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INHIBITIVE EFFECT OF HYPTIS SUAVEOLENS (L) POIT EXTRACT AND NATURAL HONEY ON CORROSION OF MILD STEEL IN H_2SO_4 SOLUTION

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Abstract: In this present study, inhibitive effects of a hybrid corrosion inhibitor, formulated from hyptis suaveolens poit extract and honey, on mild steel in H_2SO_4 solution was investigated using potentiodynamic polarization method. The extract and honey were characterized using Gas chramatogahy - Spectrometer (GC - MS) to determine the active components responsible for corrosion inhibition. Hyptis Suaveolens L Poit extract and Honey were blended in percentage ratios (extract: honey) of 25:75, 50:50, and 75:25 accordingly. A test electrolyte of 1M solution of H_2SO_4 was used in the absence and presence of varying concentrations of the inhibitor (0, 2, 4, 6, 8 and 10 %) were carried out. Linear Tafel of the anodic and cathodic curves were extrapolated using corrosion potential to obtain the corrosion current densities (I_{corr}), corrosion potential (E_{corr}), anodic Tafel slope (βa) and cathodic Tafel slopes (βc). GC - MS spectra of hyptis suaveolens poit extract and honey revealed 13 (13 peaks) different compounds for the extract and 11 (11 peaks) for honey which are compounds that were found to be responsible for corrosion inhibition. The anodic and cathodic current densities for the blends in different ratios, were found to decrease by increasing the blended inhibitor's concentrations. The blend with 75% Extract and 25% Honey gave the highest inhibitors efficiency of 87.5 % at a concentration of 6 % with minimum corrosion rate. The absorption of the hybrid inhibitors on the mild steel were observed to obey Langmuir adsorption isotherm.
Keywords: Hybrid, Corrosion inhibition, Honey, Hyptis Suaveolens L Poit extract, Potentiodynamic polarization

1. INTRODUCTION

Recently, much attention has been focused on the need to design and develop corrosion inhibitors that will replace toxic ones for sustainable development by combining at least two or more different organic inhibitors, [1]. A single inhibitor can only inhibit the corrosion of few metals. When the environment involves multi-metal systems, the inhibitive action may sometimes cause adverse effects to other metals. Mixed type inhibitors (anodic and cathodic) can be combined and optimized for better performance [2]. According to Karahan et al [3] the use of plant extracts/organic compounds as corrosion inhibitors are justified by chemical substances with molecular and electronic structures bearing close similarity to those of conventional molecules. The authors maintained that even though there is a wide spectrum of organic/naturally occurring compounds as corrosion inhibitors, they are generally used in combination with other ones and various additives to provide multiple effects necessary for effective corrosion inhibition. This has led to several studies by researchers to determine cooperation between different combinations of corrosion inhibitors known as synergism [4]. The phenomenon is referred to as synergism and normally considered between organic and halides ions, organic/organic, inorganic/organic as well as inorganic/inorganic.

Radojcic et al [5] studied the influence of natural honey and natural honey with black radish juice, on corrosion of tin in aqueous and sodium chloride solutions using weight loss and polarization techniques. The inhibition efficiency of honey was lower than that of honey mixed with black reddish juice. The efficiency of honey increased from 85 % to 90 % with the addition of black radish juice at a concentration of 1000 ppm using polarization method.

The increase in inhibition effect of was attributed to the formation of multilayer adsorbed film on the tin surface. The adsorption of honey with black radish on tin was found to follow the Langmuir adsorption isotherm. The synergistic action caused by iodide ions on the corrosion inhibition of mild steel in 1 M H_2SO_4 by leaves and stem extracts of Sida acuta was studied by [6] using weight loss and hydrogen evolution methods at 30–60 ^{0}C. It was found that the leaves and stem extracts of S. acuta inhibited the acid induced corrosion of mild steel. Addition of iodide ions enhances the inhibition efficiency to a considerable extent. The authors explained that the trend was due to the radii and electronegativity of the halide ions which play a significant role in the adsorption process. The inhibition efficiency increases with increase in the iodide ion concentration.

Karahan et al [3] carried out an investigation on the development of a hybrid type inhibitor by a mixture of Hypericum Perforatum (HP) plant extract and nitrite (TP) based inorganic inhibitor on EN 10204 Steel in H_2SO_4. Inhibitive properties of nitrite containing inorganic substance and total plant extract of Hypericum Perforatum at various concentrations were investigated individually as well as in mixed conditions using potentiodynamic polarization technique. The results showed that inhibition efficiency of HP and TP tested separately was significantly different with values of 52 % and 91 % respectively. However, inhibition efficiency (98 %) of HP-TP blends was found to be better than that of the individual inhibitors on EN boiler steel. The synergistic effect observed for the mixture of the inhibitors caused large decrease in corrosion density current (I_{corr}) compared to the individual inhibitors. This was possible because in more acidic environments, nitrite decomposed forming volatile nitric oxide and nitrogen as nitrite acts as a passivating anodic site. Turhan et al. (2014) investigated a hybrid type inhibitors made of total plant extract Vaccinium myrtillus (VM) mixed with nitrite (NO2-) based inorganic inhibitors at different ratios in fully de-aerated 10^{-4} M H_2SO_4+0.25M K_2SO_4 blank solution by Tafel extrapolation, Potentiodynamic anodic polarization and optical microscopy methods. The results revealed an increase in inhibition efficiency as high as 94-99% at different mixtures of (TP+VM) concentrations compared to the individual efficiencies of 82 % and 85 % respectively for Vaccinium myrtillus and nitrite.

Ameh and Eddy [7] investigated joint effect of Halide ions and Ficus glumosa gum exudate on the inhibition of corrosion on mild steel in 0.1 M HCl using weight loss and gasometric methods. The results obtained indicated that the inhibition efficiency of Ficus glumosa gum exudate increases with increase in concentration and with increasing temperature. Synergistic combination of the gum and 0.005 M KI, KCl and KBr respectively, led to enhancement of the inhibition efficiency of the gum at 303 K. Application of the transition state equation indicated that the adsorption of the gum, halides and gum-halide mixture was an endothermic and occurred with an increase in orderliness. The formation of multiple layers of inhibitor on the surface of the metal was confirmed by slope values greater than unity for adsorption isotherms.

Honey has been reported as effective corrosion resistant on mild steel, Al-Mg-Si alloy, and tin by [8] and [5] respectively, in various solutions. In their separate investigations honey proved to be an effective corrosion inhibitor in both media. Honey is an organic compound containing polar groups such as nitrogen (N), sulphur (S) and oxygen (O) as well as heterocyclics containing conjugated double bonds that have made it suitable as good corrosion inhibitor due to the presence of the –C=C–group, N, S and O atoms in its molecule. According to [1] Hyptis suaveolens L Poit is a well-known pseudo-cereal plant in the Latin American region and in many regions of Africa including Nigeria and it has been used as corrosion inhibitor. The authors in their study proved that extract from Hyptis suaveolens L Poit was effective for the inhibition of corrosion on mild steel in acidic medium. However, for the literatures reviewed so far no work has been carried out using the blends of Hyptis suaveolens L Poit extract and honey as a corrosion inhibitor on a mild steel in acidic media. The present study investigate corrosion inhibition effects of a hybrid, formulated using Hyptis suaveolens L Poit and natural honey on mild steel in 1M H_2SO_4 solution

2. MATERIALS AND METHODS

— Characterization and Preparation of Hyptis Suaveolens L Poit extract and Honey

The extract of Hyptis Suaveolens L Poit was obtained using solvent extraction method with the aid of ethanol according to the work done by [1]. Pure honey (4 litres) was procured from Jato-Aka market in Kwande Local government area of Benue State. Prior to the blending of the two inhibitors, the Hyptis Suaveolens L Poit extract and honey were characterized using GC-MS Hewlet Packard Model 6890 Series to identify active components present in them according to procedure reported by [1]. The blending was done in the percentage ratios (extract: honey) of 25:75, 50:50, and 75:25.

— **Potentiodynamic Polarization Measurements (Electrochemical Measurements)**

The electrochemical experiment was carried out using AUTOLAB PGSTAT 204N instrument. Twenty-six (26) pieces of mild steel with surface area 0.76 cm^2 were used as working electrodes, saturated silver/silver chloride as reference electrode, and platinum rod as counter electrode. An insulated copper wire was attached to one face of each mild steel sample specimen using an aluminum conducting tape, and cold mounted using a resin to expose the surface area. The test electrolyte was 1M solution of H_2SO_4 in the presence and absence of the blended inhibitor (Hyptis Suaveolens L Poit extract and Honey) in varying concentrations of 0, 2, 4, 6, 8 and 10 %. All electrochemical experiments were conducted at room temperature (25°C±2°C) using 100 ml of electrolyte in a stationary condition. The working electrode was immersed in a test solution for 30 minutes until a stable open circuit potential was attained. Potentiodynamic polarization measurements were carried out using a scan rate of 1.0 mV/s at a potential initiated at -250mV to + 250mV. After each experiment, the electrolyte and the test sample were replaced. The linear Tafel of the anodic and cathodic curves were extrapolated to corrosion potential to obtain the corrosion current densities (Icorr) and corrosion potential (Ecorr). Anodic Tafel slope (βa) and cathodic Tafel slopes (βc) were determined from the experimental curve. The IE_{Icor}(%)was calculated using the current densities [9].

$$IE_{\ Icor}(\%) = \frac{I^{o}_{corr} - I_{cor}}{I^{o}_{corr}} \times 100 \qquad (1)$$

where,i^{o}_{corr} and icorr are the corrosion current density values in the absence and presence of inhibitor respectively.

An iterative procedure using several absorption isotherms such as Temkin, Frumkin, Flory-Huggins and Langmuir was employed to investigate the interaction of the blends with the mild steel coupons. Each of these adsorption isotherms was tested in terms of their descriptions of the adsorption behavior of extracts on mild steel surface in 1M H_2SO_4 solution. The Langmuir absorption isotherm was selected and carried out by plotting $\frac{C}{\theta}$ vs C, where C was the concentration and θ , the surface coverage.

Langmuir adsorption isotherm was mathematically expressed in equation (2) [10]:

$$\frac{C}{\theta} = c + \frac{1}{K_{ad}} \qquad (2)$$

where, C is the concentration of the inhibitor θ is the fractional surface coverage, and K is the adsorption equilibrium constant.

Surface coverage (θ) was calculated using the expression given in equation (3) [6]

$$\theta = \frac{IE\ \%}{100} \qquad (3)$$

where IE % is the inhibitor's efficiency.

3. RESULTS AND DISCUSSION

— **Characterization of Hyptis Sauveolens Poit Extract and Honey**

The phytochemical analysis conducted in this study revealed types, quantity and qualities of the bioactive compounds present in Hyptis Sauveolens Poit Extrac and honey which are capable of corrosion inhibition. Table 1 revealed the presence of tannins, alkaloids flavonoids, and plytosteriods in the Hyptis Sauveolens Poit Extract. However, saponins, glycoside, phenols were not detected in the extract and the compounds present were found to be low, moderate and high for plytosteriods and alkaloids, tannins, and flavoids respectively. In Table 2 the presence of glycoside, Saponins, Phenols, alkaloids flavonoids, and plytosteriods was revealed, but Tannin, Saporin and Plytosteriods, were not detected. The presence of these compounds have been reported to promote the inhibition of mild steel in aggressive acidic media [9].

Table 1: Phytochemical Constituents of Hypis Suaveolens Poit Leaf extract.

Phytochemical constituents	Results
Tannin	++
Alkaloids	+
Plytosteriods	+
Flavonoids	+++
Saponins	-
Glycoside	-
Phenols	-

Table 2: Phytochemical Constituents of Honey

Phytochemical constituents	Results
Tannin	-
Alkaloids	+
Plytosteriods	-
Flavonoids	++
Saponins	+
Glycoside	+
Phenols	+
Saporin	+
Steroid	-

Key: - = not detected, + = Low, ++ = Moderate, +++ = High

Gas chromatography - Mass spectroscopy (GC-MS) spectra of hyptis suaveolens poit extract and honey shown in (Tables 3 and 4 respectively) identified 13 (13 peaks) different compounds in the extract as well as 11 (11 peaks) for honey representing about 100% of the compounds in the extract. Table 3 further showed the percentages of compounds in the extract such as terpinolene (14.1%), beta-caryophyllene (12.3%), terpinen-4-01 (9.8%), beta-Ocimene (9.2%), 1,8-cinerle (8.7 %) and biclyclogermacrene (7.1%) as the major components of the extract while beta-phellandrene (5.6%), eucalptol (5.2%), limonene (5.0%), sabinene (5.0%), beta-pinene (4.5%) and fenchone (4.1%) were shown as the compounds in smaller quantities. Table 4 showed Acetic acid, Toliene, Butanoic acid 3-methyl, Batyrolactone, Benzeneaceta-aidehyde and Acetophenone as the major components in honey while Furtural, Benzaldehyde, Benzenemethanol, Nonanal and Benzeneethanol were shown as the compounds in smaller quantities. These results are similar to the one obtained by by [11] for extract of Asteriscus gravveolens utilized for corrosion inhibition of mild steel in sulphuric acidic medium. This implies that the compounds present in both extract and honey are capable of inhibiting corrosion.

Table 3: Chemical composition of Hyptis Sauveolens L Poit

Peak No	Component name	Percentage (%)
1	Sabine	5.0
2	Limonene	5.0
3	Biclyclogermcrene	7.1
4	Beta-phellandrene	5.6
5	1, 8 – Cinerle	8.7
6	Menthe - 2, 4 – diene	9.2
7	Eucalptol	5.2
8	Beta-caryophyllene	12.5
9	Terpinolene	14.1
10	Fenchone	4.1
11	Beta- pinene	4.5
12	Beta- ocimene	9.2
13	Terpinen -4, o1	9.8

Table 4: Chemical composition of Honey

Peak No	Componet Name	Time (min)
1	Acetic acid	1.009
2	Toliene	1.134
3	Furtural	15.007
4	Butanoic acid, 3-methyl	18.415
5	Batyrolactone	18.578
6	Benzaldehyde	20.248
7	Benzenemethanol	20.538
8	Benzeneacetaaidehyde	21.11
9	Acetophenone	22.01
10	Nonanal	24.087
11	Benzeneethanol	25.133

— **Synergistic Effect Caused by the use of Hyptis Suaveolens Leaf Extract- Honey Blends on Inhibition**

Figures 1, 2 and 3 present the anodic and cathodic current densities for the blends of hyptis suaveolens leaf extract and honey in the ratios of 25% extract-75% honey, 50% extract-50% honey, and 75% extract-25% honey, respectively. The anodic and cathodic polarization curves of mild steel in the H_2SO_4 solution in the absence and presence of the various concentrations of the blends were found to decrease by increasing the inhibitor's concentrations.

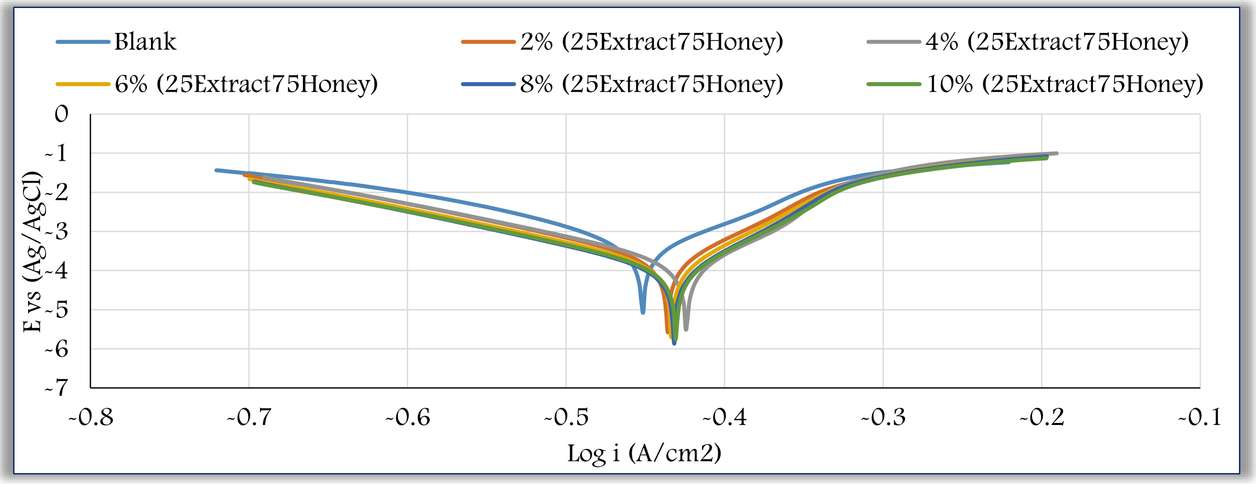

Figure 1: Tafel Polarization Curves for the Mild Steel in the Absence and Presence of 25% Extract and 75% Honey

It was also noted in Figures 1 that the addition or increase in concentrations of the 25% extract-75% honey blended inhibitor was accompanied by a parallel shift in corrosion potential (rightward) indicating displacement in the cathodic and anodic branch of the curves towards the areas with high current densities. It may be related to more stable protective film on the surface of mild steel as reported by [12]. However, the shift in corrosion potential for the blends of 50%

extract-50% honey, and 75% extract-25% honey moved towards positive direction (leftward) with corresponding leftward displacement in the anodic and cathodic curves that leads to lower current densities.

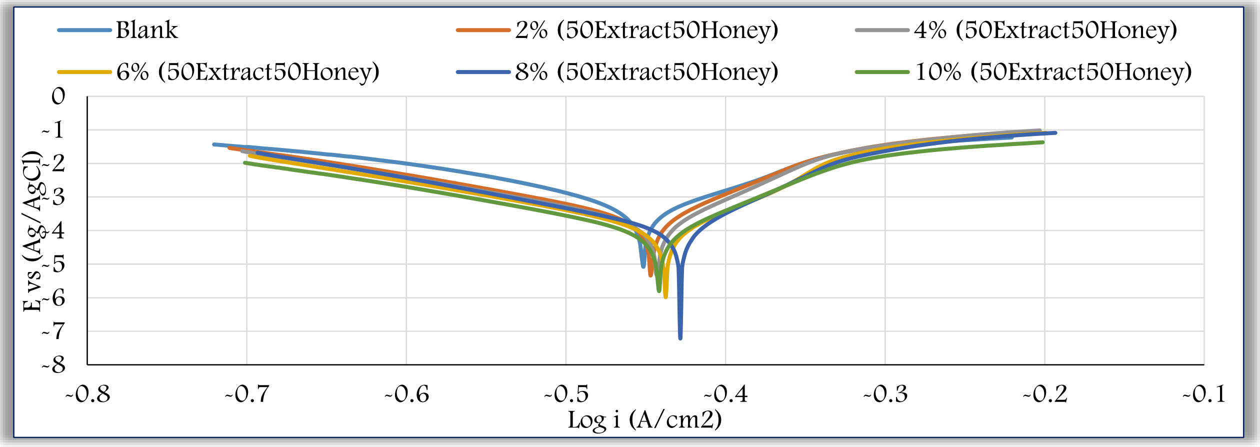

Figure 2: Tafel Polarization Curves for Mild Steel in the Absence and Presence of 50% Extract and 50% Honey

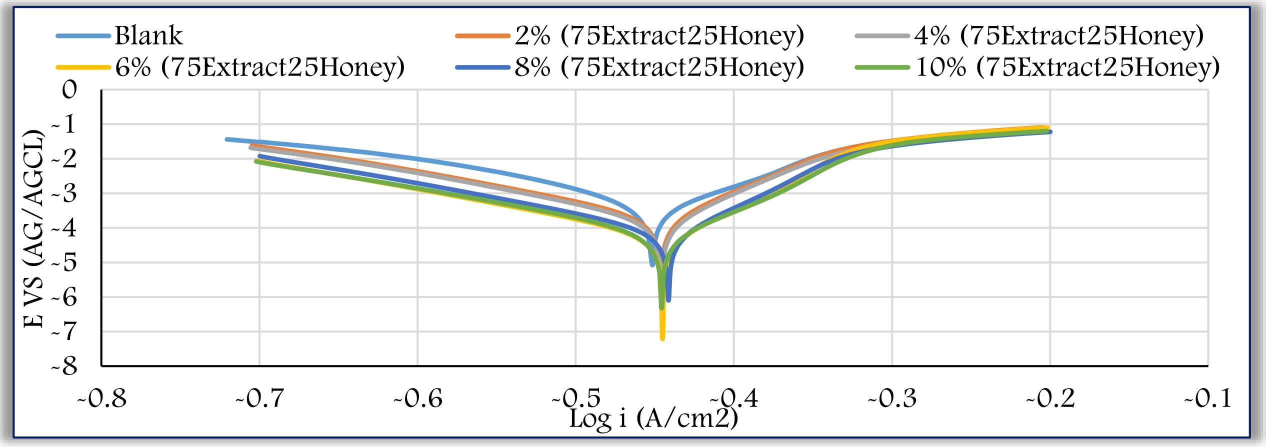

Figure 3: Tafel Polarization Curves for Mild Steel in the Absence and Presence of 75% Extract and 25% Honey

The cathodic curves were the most affected to a greater extent and this confirms the early findings by [8] that the presence of increasing amount of studied compounds leads to a dramatic decrease in anodic and cathodic current densities. These results suggested that the inhibitor suppressed both the anodic and cathodic reactions, although mainly the anodic one. Ashassi-Sorkhabi et al [13] stated that the organic compounds cannot be generally designed specifically as anodic or cathodic inhibitors and most of organic compounds are mixed type inhibitors that affect both anodic and cathodic reactions. This confirmed that the inhibitor obtained using blends of hyptis suaveolens leaf extract and honey in the ratios of 25% extract-75% honey, 50% extract-50% honey, and 75% extract-25% honey is a mixed-type inhibitor.

The electrochemical parameters [corrosion potential (E_{corr}), corrosion current density (i_{corr}), cathodic Tafel slope (Bc), and anodic Tafel slope (Ba)] obtained from the polarization curves and the corresponding inhibition efficiency (IE) and polarization resistance (P_R)values at different concentrations of the blends of hyptis suaveolens leaf extract and honey (25% extract-75% honey, 50% extract-50% honey, and 75% extract-25% honey) are reported in Tables 5, 6 and 7 respectively. The corrosion potential values ($-E_{corr}$) varied from 424-452 mV, 427-452 mV and 442-452 mV/SCE for the blends (25% extract-75% honey, 50% extract-50% honey, and 75% extract-25% honey respectively. It was observed that (Ecorr) value did not change in a regular manner in the presence of different concentrations of inhibitor and Ecorr value shows a marginal change; indication that the inhibitor acts as a mixed-type inhibitor. The corrosion current densities (i_{corr}) varied from 95-415 μA/cm², 81.3-415 μA/cm² and 51.6 – 415 μA/cm², for the blends of 25% extract-75% honey, 50% extract-50% honey, and 75% extract-25% honey respectively (Tables 5-7). It was observed that corrosion current densities (i_{corr}) decreased with increasing concentration of the blends indicating that adsorption of inhibitor blends modified the mechanism of anodic dissolution as well as cathodic hydrogen evolution. [13] reported that the electrochemical processes on the metal surface are likely to be closely related to the adsorption of the inhibitor and the adsorption was known to depend on the chemical structure of the inhibitor.

The anodic Tafel slope (Ba) values as shown in Table 5-7 for hybrid inhibitors were more than the values of cathodic Tafel slopes (Bc) indicating that the inhibitors are mixed type. However, the results indicated that the hybrid inhibitor formulation retards both the anodic dissolution of carbon steel and oxygen reduction at cathodic sites in the corrosion inhibition process with the effect or reaction more pronounced on anodic. The values of cathodic Tafel slopes as observed shown in Tables 5 ,6 and 7 were approximately constant, indicating that the inhibitive action occurred by simple blocking of available surface areas mostly anodic as reported by [14].

The inhibition efficiencies (Tables 5, 6 and 7) varied from 57.1 – 76.6 %, 52.1 – 80.4 % and 56.1-85.7% % for the blends of 25% extract-75% honey, 50% extract-50% honey, and 75% extract-25% honey, respectively and increased with increasing concentrations of the blends. The results revealed that there were increased in efficiencies with the addition of extract on honey. The inhibition efficiency of 76.6 % (25% extract-75 % honey blend) at 10 % concentrations was better than the value of 63.6 % reported by [8]. The inhibition efficiency of 80.4% at 10% concentration of blends was also obtained by the blend of 50% extract-50% honey. This implies that the addition of plant extract to the honey has improved the corrosion inhibition on the mild steel. The blend of 75% extract-25% honey gave the highest inhibition efficiency of 87.5% at a concentration 10 % which was better than the value of 85 % reported by [5] for natural honey with black radish juice on corrosion of tin in aqueous and sodium chloride solutions. The value was also better than the value of 85.8 % reported by [1] for their study of hyptis suaveolen l poit leaves extract as corrosion inhibitor on mild steel in H_2SO_4 solution. This indicated that the blends acted as a good inhibitors for mild steel in 1M H_2SO_4; due to the fact that honey and the extract are multicomponent systems, consisting of various compounds that were able to form protective layer on mild steel surface, thereby interacting mutually as reported by [8]. The reason could also be the increased in the formation of films on the surface of the mild steel which effectively protects the steel from corrosion as reported by [10]. The authors maintained corrosion inhibition property of plant/root extract is normally due to the presence of complex organic species such as tannins, alkaloids and nitrogen bases, carbohydrates, amino acids and proteins as well as hydrolysis products which are equally found in the inhibitors. These organic compounds contain polar functions with N, S and O atoms as well as conjugated double bonds or aromatic rings in their molecular structures, which are the major adsorption centres

The corrosion rate as shown in Tables, 5-7 for the blends obviously, decreased with increasing concentrations. The decrease in the corrosion rate can be explained by the inhibition efficiency of the blends on the cathodic part of polarization curves through the reduction of hydrogen ions H+ and also its effectiveness on the anodic part due to adsorption of the extract components on the surface of mild steel sample which contain a barrier that hinders the process of hydrogen gas evolution and metal dissolution [7].

Table 5 : The Electrochemical Parameters of Mild Steel at various Concentrations of 25% Extract and 75% Honey

25% extract and 75% honey	Ba (mV/decade)	Bc (mV/ decade)	$-E_{corr}$ (mv/SCE)	I_{corr} (μA/cm²)	CR (mmpy)	PR (kΩ cm²)	IE_{Icor}(%)
Blank	86.5	88.6	452	415	4.82	45.8	
2	103.5	61	437	178	2.06	93	57.1
4	101.3	66	424	147	1.71	118	64.5
6	104	56	433	128	1.48	124	69.2
8	100	55	431	95	1.11	161	77.1
10	97	56	431	97	1.12	159	76.6

Table 6 : The Electrochemical Parameters of Mild Steel at various Concentrations of 50% Extract and 50% Honey

50% extract and 50% honey	Ba (mV/decade)	Bc (mV/decade)	$-E_{corr}$ (mv/SCE)	I_{corr} (μA/cm²)	CR (mmpy)	PR (kΩ cm²)	IE_{Icor}(%)
Blank	86.5	88.6	452	415	4.82	45.8	
2	102	57	445	199	2.31	80	52.1
4	101.8	55	442	148	1.71	105	64.3
6	93	60	437	95.9	1.14	165	76.9
8	112	50	427	105	1.21`	144	74.6
10	103	58.6	441	81.3	0.94	200	80.4

Table 7: The Electrochemical Parameters of Mild Steel at Concentrations of 75% Extract and 25% Honey

75% extract and 25% honey	Ba (mV/decade)	Bc (mV/decade)	$-E_{corr}$ (mv/SCE)	I_{corr} (μA/cm²)	CR (mmpy)	PR (kΩ cm²)	IE_{Icor}(%)
Blank	86.5	88.6	452	415	4.82	45.8	
2	101	57	446	182	2.11	87	56.1
4	95	53	446	142	1.64	105	65.7
6	95	56	445	51.6	0.59	299	87.5
8	95	54	442	70	0.81	216	83.1
10	98	64	445	59	0.68	284	85.7

— **Adsorption consideration of Hyptis Suaveolens Leaf Extract- Honey Blends on mild steel**

For the plant/organic extract to inhibit the corrosion of mild steel, there must have to be an adsorption of the components of the plant extracts on the metal surface leading to greater surface coverage as the first step of the inhibition mechanism [6]. The degree of surface coverage of the hybrid inhibitors on the mild steel in the acidic medium are presented in Figure 4. Of all the isotherms investigated Langmuir adsorption isotherms was found to fit well with the experimental data. This implies that there was formation of layer of insoluble complex of the metal on the surface due to the presence of the hybrid inhibitors which acts as a barrier between the metal surface and the corrosive medium - usually known as physisorption. This was confirmed by the higher values of coefficient of correlation given as 0.9951, 0.9939 and 0.9803 for 25 % extract-75% honey, 50 % extract-5% honey and 75 % extract-25% honey respectively. The values of the degree of surface coverage (h) defined as the fraction of the mild steel surface that was covered by the inhibitors were quite useful for the determination of inhibitor adsorption characteristic. These values were better than the values of 0.9424 - 0.9934 reported by [9] in their study of Corrosion inhibition and adsorption characteristics of rice husk extracts on mild steel in 1M H_2SO_4 and HCL solutions.

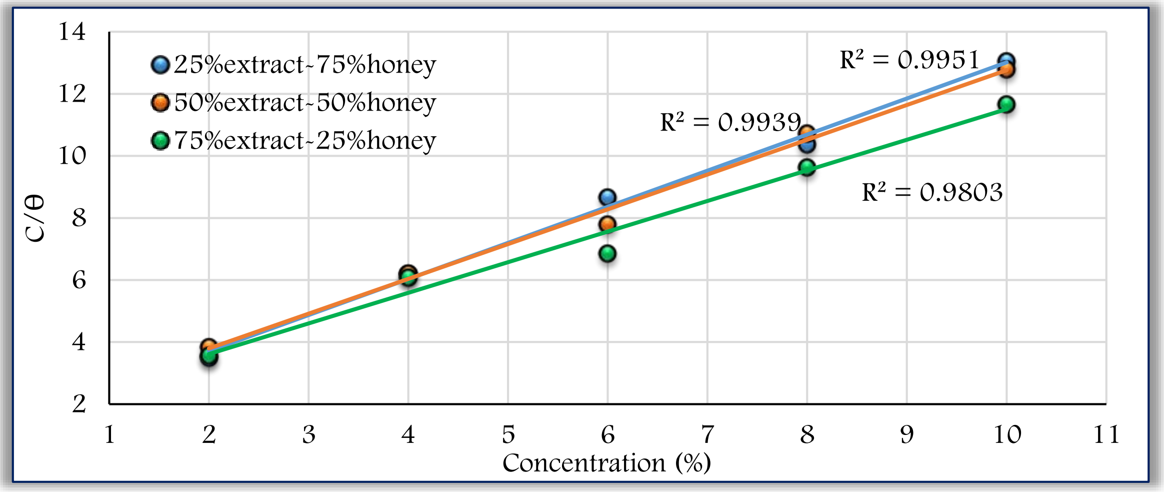

Figure 4: Langmuir adsorption plots of mild steel in H_2SO_4 in the presence of the blends of extract and honey

4. CONCLUSION

The following conclusions were drawn from the study;

- Potentiodynamic polarization results confirm that the combination of hyptis suaveolens leaves extract and honey show a much better inhibitive performance than that of a sole inhibitor. The blends of hyptis suaveolens leaves extract and honey acted as a good mixed-type inhibitors on mild steel in H_2SO_4 solution by preventing anodic metal dissolution and cathodic hydrogen evolution reaction.
- Electrochemical kinetic parameters such as corrosion potential (E_{corr}), cathodic and anodic slope (Bc and Ba), corrosion current density (i_{corr}) and percentage of inhibition efficiency confirmed that inhibition has taken place using the blends of hyptis suaveolens leaves extract and honey. The blend of the extract and honey in the ratio of 75% to 25 % gave the highest inhibitors efficiency of 87.5 % at 6 % concentration.
- The inhibitive action of the extract was attributed to the physical adsorption of its compounds onto the steel surface and obeyed Langmuir adsorption isotherm.

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