**CAAP Quarterly Report 3**

**06/30/2024**

*Project Name: "Bio-Inspired Rational Design of Bio-Based Inhibitors for Mitigating Internal Corrosion in Metal Pipelines"*

*Contract Number: 693JK32350003CAAP*

*Prime University: University of Miami*

*Prepared By: Dr. Ali Ghahremaninezhad;* [*a.ghahremani@miami.edu*](mailto:a.ghahremani@miami.edu)*; 305-284-3465*

*Reporting Period: 03/30/2024-06/30/2024*

**Project Activities for Reporting Period:**

Student recruitment: One Ph.D. student was recruited, who will engage in several tasks/activities including literature review, experiment design and implementation, and data analysis. One undergraduate research student is being recruited to be involved in the project.

Corrosion inhibition characteristics of some amino acids and proteins on mild steel immersed in 0.5M HCl solutions were investigated. In this report, their electrochemical characteristics along with physical changes have been documented. The efficiency of the inhibitors was assessed using electrochemical measurements, specifically, electrochemical impedance spectroscopy (EIS) to allow a comparison among all used inhibitors. Fourier transform infrared spectroscopy (FTIR) of some proteins was examined to shed light onto the corrosion inhibition behavior of the inhibitors. Moreover, the corrosive solutions for the case of some inhibitors were analyzed by UV–visible spectrometry (UV–vis). The surface of mild steel that is polished, and immersed in HCl solution with and without inhibitor was analyzed by 3D profilometry and atomic force microscopy (AFM) analysis.

# **Materials and Methods**

## **Materials**

As described in detail in the 2nd quarter report, the chemical composition of the mild steel used in the experiments consisted of C: 0.059, Si: 0.18, Mn: 0.4610, P: 0.01, S:0.011, and Fe: remainder. The test specimens included mild steel with a size of 10mm x 10mm x 2mm. Before experiments, the specimen’ surfaces were mechanically polished with silicon carbide (SiC) papers with a grit size of #180, #320 and #600. This was followed by rinsing with distilled water and acetone, and finally drying in air.

The electrolyte solution of 0.5M HCl was prepared from dilution of 37% analytical grade HCl. The inhibitors were dissolved in 0.5 M HCl to obtain the desired concentration of 0.008% and 0.02% wt.

Amino acids, proteins and chitosan were used as the inhibitors. The amino acids (reagent grade ≥ 98%) and chitosan (from shrimp shells ≥ 75%) were purchased from Sigma-Aldrich and used with no further purification. The proteins studied in this investigation were obtained from various commercial vendors and used as received. Due to the considerable quantity of proteins required for both experiments and practical applications, for inhibiting steel corrosion, acquiring extremely pure proteins at the necessary scale was too expensive, resulting in the proteins being obtained in bulk with anticipated impurities. The used inhibitors and their abbreviations are listed in Table 1.

Lysozyme is a globular protein obtained from egg whites (Savadkoohi & Kasapis, 2016), serving distinct roles in biological processes. Additionally, NFMP is derived from removing moisture from non-fat milk, comprising of predominantly whey and casein protein families (Borcherding et al., 2009), which play crucial roles in various physiological functions. Collagen peptide, another vital protein abundant in mammals, constitutes a significant portion (around 25–30%) of the body's total protein makeup (Znidarsic et al., 2009) , essential for structural integrity and various cellular functions. Hemoglobin, key protein within the body, exhibits unique surface activity, making them subjects of considerable research interest (Elbaum et al., 1976).

**Table 1:** List of inhibitors and their abbreviations used in the study

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Name** | **Abb.** | **Name** | **Abb.** | **Name** | **Abb.** |
| **Amino Acids** | | | | | |
| L-Methionine | MET | L- Cysteine | CYS | L- Isoleucine | ILE |
| L-Arginine | ARG | Glycine | GLY | L- Phenylalanine | PHE |
| L-Glutamic Acid | GLU | L-Aspartic Acid | ASP | L- Alanine | ALA |
| L- Threonine | THR | L- Histidine | HIS | L-Leucine | LEU |
| L- Proline | PRO | L- Valine | VAL | L- Lysine | LYS |
| L- Tryptophan | TRP | L- Asparagine | ASN | L- Serine | SER |
| L- Tyrosine | TYR | L- Glutamine | GLN | L- Ornithine monohydrochloride | H-ORN |
| **Proteins** | | | | | |
| Lysozyme | LYS | Albumin | ALB | Mild Silver Protein | MSP |
| Whey Protein | WP | Soy Protein | SP | Bovine Serum Albumin | BSA |
| Sodium Caseinate | SC | Trypsin | TRY | Non-fat Milk Powder | NFMP |
| Collagen Peptides | CP | Pepsin | PEP | Hemoglobin Powder | HEM |

## **Electrochemical Measurements**

Electrochemical experiments, including open circuit potential (OCP) and electrochemical impedance spectroscopy (EIS), were conducted in a conventional three-electrode glass cell, using a Gamry Reference 600 and Gamry 1010E potentiostats. Mild steel specimens were used as the working electrode. The saturated calomel electrode (SCE) and platinum sheet electrode were used as reference electrode and counter electrode, respectively. The details of the experimental setup have been provided in the 2nd quarter report. All the electrochemical experiments were repeated three times to examine the reproducibility of the electrochemical data. The obtained EIS data were interpreted with Gamry Echem Analyst. With the EIS results, the corrosion inhibition efficiency was calculated according to Equation 1.

|  |  |
| --- | --- |
|  | (1) |

where and are the charge transfer resistance without and with inhibitor, respectively.

## **Characterization Techniques**

### **1.3.1 FTIR**

The FTIR analysis was performed using a PerkinElmer Frontier spectrometer with an Attenuated Total Reflectance (ATR) accessory, to determine the structure and bond configuration of the Albumin protein and the formed film on the mild steel surface. To this end a 12% concentration of protein by mass in a 0.5M HCl solution was prepared. The Albumin-HCl solution was mixed using a stirring rod for 30 min to ensure total dissolution of protein particles prior to testing. The mild steel specimens with dimensions of 10mm x 10mm x 2mm were used. Mild steel specimens’ surfaces were mechanically polished with silicon carbide (SiC) papers with a grit size of #180, #320 and #600. This was followed by rinsing with distilled water, acetone, and drying in air. FTIR was carried out on ALB in HCl solution, and on mild steel surfaces after 24h immersion in 0.5M HCl solution in the presence and absence of 0.1% of ALB. The transmission infrared spectra of the specimens were recorded in the range between 650 cm-1 and 4000 cm-1 at a resolution of 4 cm-1 with 3 scans per specimen. An average of three replicates is reported in this study. The background noise was also collected and removed from both the protein and mild steel spectra. After obtaining the spectra, baseline correction was applied on the spectra to fix both the sloping shape of the spectra and the offset in absorbance.

### **1.3.2 UV–vis**

UV–vis analysis was carried out using a Shimadzu UV-2600 spectrophotometer in a range of 200–800 nm. The UV–vis spectra were collected for the solutions of the 0.02% Albumin in the 0.5M HCl recorded prior to immersion of the mild steel, and solutions of 0.02% Albumin in the 0.5M HCl after 2h immersion of the mild steel. The spectral profiles were then compared to predict whether a complex is formed with the metal surface. The mild steel specimens were prepared similar to that described in the FTIR section.

### **1.3.3 3D Profilometry**

The 3D profilometry analysis was performed using a Nanovea CHR 150 chromatic confocal profilometer. It measures the surface profile and topology of the mild steel specimens. The mild steel specimens with dimension of 20mm x 20mm x 2mm were used in this test. Mild steel specimens’ surfaces were mechanically polished with silicon carbide (SiC) papers with a grit size of #180, #320, #600 and #1200. This was followed by rinsing with distilled water, acetone, and finally drying in air. The surface of the metal specimens was measured for the polished specimen and the mild steel specimens that were immersed in the 0.5M HCl without and with 0.1% of ALB for 24h. An area of 3mm x 3mm on the specimen surface was scanned with the step size of 1.5 μm in both 2D directions. Scan velocity was 1.50 mm/s. The data were processed with Professional 3D software to calculate surface topology before and after corrosion.

### **1.3.4 AFM Analysis**

The AFM technique was used to investigate the morphological characteristics of the mild steel surface in the corrosive solution without and with ALB. The Cypher S AFM from Oxford Technologies (former Asylum Research) was used for the analysis. The mild steel specimens were prepared in a similar way to that used in the 3D profilometry analysis and inserted in the corrosive solution without and with 0.1% of ALB for 24h. After 24h, the specimens were removed, carefully rinsed with DI water and dried in air. The surface examination was performed in tapping mode (intermittent contact), and the topographic AFM images of 256 by 256 pixels for the scanned area of 10x10 μm were obtained at 1 Hz per line. The images were obtained using the probe (AC160) from Oxford Technologies with a spring constant of 26 N/m. The image analysis was processed using Igor software to determine surface roughness of the specimens before and after corrosion.

# **Results and discussion**

## **Electrochemical Measurements**

The inhibition performance of amino acids, proteins and chitosan for mild steel corrosion in 0.5M HCl solution was investigated using the EIS measurements. The obtained results in EIS were analyzed using an electrical equivalent circuit as shown in Figure 1. In this circuit, RS is the solution resistance between the reference and the working electrodes, Rct represents the charge-transfer resistance at the metal-electrolyte interface, and Cdl is the double layer capacitance. In calculation, the constant phase element (CPE) instead of Cdl was used. The use of CPE allows to compensate for the deviation from the ideal dielectric behavior caused by the inhomogeneous nature of the electrode surface (Guo et al., 2022). The impedance function of CPE can be described by the equation:

|  |  |
| --- | --- |
|  | (5) |

where is the magnitude of CPE, *j* is an imaginary number , is the angular frequency (=2πƒ) and exponent is the deviation parameter and takes on values between -1 to 1. Based on the values of , CPE can represent: inductance ( = -1), resistance ( = 0), Warburg impedance ( = 0.5), and capacitance ( = 1) (Farag et al., 2018). The can be obtained by the following equation:

|  |  |
| --- | --- |
|  | (6) |

where is the frequency at which the imaginary impedance has the highest value.

|  |
| --- |
| A diagram of a circuit  Description automatically generated |

**Figure 1:** Electrochemical equivalent circuit used to fit the impedance spectra.

In Table 2, the electrochemical parameters obtained from the EIS tests are presented. Moreover, their inhibition efficiencies with respect to the control specimen are summarized. For all the tested inhibitors, inhibition efficiencies increased with an increase in their concentration in the 0.5M HCl solution. In Table 2, the inhibitors are sorted by increasing inhibition efficiency, and all results are presented for 0.02% concentration of inhibitors.

**Table 2:** EIS parameters for mild steel in 0.5 M HCl and the presence of different concentrations of the investigated inhibitors.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **#** | **Inhibitors** | **Rs (Ω cm2)** | **Rct (Ω cm2)** | **IE (%)** |
| 0 | Control | 3.56 | 196.09 | - |
| 1 | Albumin | 4.52 | 539.91 | 63.68 |
| 2 | Lysozyme | 4.39 | 502.23 | 60.61 |
| 3 | Collagen Peptides | 4.11 | 492.35 | 60.17 |
| 4 | Soy Protein | 3.98 | 487.97 | 59.82 |
| 5 | Pepsin | 4.05 | 413.89 | 52.62 |
| 6 | Chitosan | 3.71 | 408.90 | 52.04 |
| 7 | Non-fat Milk Powder | 3.84 | 391.91 | 49.97 |
| 8 | Mild Silver protein | 4.20 | 390.56 | 49.79 |
| 9 | Trypsin | 4.53 | 373.57 | 46.86 |
| 10 | L-Methionine | 3.87 | 364.73 | 46.24 |
| 11 | Whey-Protein | 3.72 | 345.99 | 43.32 |
| 12 | Bovine Serum Albumin | 4.18 | 345.59 | 43.26 |
| 13 | Hemoglobin | 4.37 | 292.82 | 33.03 |
| 14 | L-Asparagine | 4.18 | 290.52 | 32.50 |
| 15 | L-Arginine | 3.49 | 284.20 | 31.00 |
| 16 | L-Cysteine | 4.28 | 279.12 | 29.75 |
| 17 | L-Histidine | 3.90 | 256.03 | 23.41 |
| 18 | Sodium Caseinate | 4.06 | 253.07 | 22.51 |
| 19 | L-Tryptophan | 3.68 | 249.39 | 21.37 |
| 20 | L-Valine | 3.71 | 245.27 | 20.05 |
| 21 | L-Lysine | 3.81 | 236.28 | 17.01 |
| 22 | L-Tyrosine | 3.86 | 233.13 | 15.89 |
| 23 | L-Isoleucine | 4.15 | 230.84 | 15.05 |
| 24 | L-Glutamine | 3.54 | 229.93 | 14.72 |
| 25 | L-Aspartic Acid | 3.84 | 225.04 | 12.86 |
| 26 | L-Glycine | 4.80 | 218.20 | 10.13 |
| 27 | L-Leucine | 3.54 | 220.88 | 9.40 |
| 28 | L-Phenylalanine | 5.98 | 213.32 | 8.08 |
| 29 | L-Proline | 4.91 | 215.09 | 8.83 |
| 30 | L-Threonine | 5.42 | 210.98 | 7.06 |
| 31 | L-Glutamic Acid | 4.66 | 203.07 | 3.44 |
| 32 | L-Alanine | 4.19 | 201.63 | 2.75 |
| 33 | DL-Serine | 3.79 | 178.91 | -9.60 |

From Table 2, it is observed that there was a significant enhancement in the change of Rct for most of the inhibitors. An increase in Rct manifests the formation of a protective layer on the metal surface, which provides higher resistance toward the charge transfer reactions occurring at the metal-electrolyte interface (Satpati et al., 2020). The obtained Rct allowed to calculate their efficiency in terms of inhibition of corrosion. For example, proteins LYS and ALB, and amino acids MET and ASN showed positive effects for corrosion inhibition with an increase in their charge transfer resistance.

The Nyquist and Bode plots for the mild steel in 0.5M HCl without and with ALB, LYS, MET, and ASN are presented in Figures 2 (a) and (b), respectively. The Nyquist plots are characterized by one capacitive semi-circular arc which corresponds to one time-constant in the Bode plots over the entire range of frequency. This shows that the corrosion mechanism is mainly controlled by charge transfer processes (Guo et al., 2022; Haruna et al., 2018).

|  |  |
| --- | --- |
| (a) |  |
| (b) | A graph of a number of different colored dots  Description automatically generated with medium confidence |

**Figure 2:** (a) Nyquist and (b) Bode plots for mild steel in 0.5M HCl without and with 0.02% concentration of LYS, ALB, MET, and ASN.

In the Nyquist plots, the diameter of the semicircle represents Rct. A larger Rct indicates a stronger resistance to corrosion. As illustrated in Figure 2 (a), the diameters of the Nyquist semicircles in the presence of various inhibitors were larger than that without inhibitor, control specimen. Binding of inhibitors onto the metal surface makes the migration of charge to the electrode surface more difficult (Wang et al., 2023). This implies that the inhibitors form a protective film on the surface of the metal thereby increasing the impedance of the metal surface to electrochemical corrosion (Haruna et al., 2018). The inhibitor molecules suppress the dissolution of the carbon steel by forming an inhibitor - metal complex. This complex adsorbs onto the surface and prevents it from being affected by the corrosive environment (Paramasivam et al., 2016).

The Bode impedance modulus plots in Figure 2(b) show the linear portions at intermediate frequencies. The linearity at intermediate frequencies is more pronounced in the presence of the inhibitors (amino acids and protein), and the inhibitor cases have higher slopes than the control specimen. Moreover, having higher absolute impedance values (|Z|) at higher concentrations resulted from the alteration of the double layer on the metal surface due to the adsorption of inhibitor molecules by forming metal complexes (Udayappan & Veawab, 2022).

## **Characterization Techniques**

### **2.2.1 FTIR**

The mild steel surface was analyzed using FTIR to observe the formation of the protective layer. The spectra for the ALB in HCl solution, and the surface of mild steel immersed in 0.5M HCl without and with 0.1% ALB are presented in Figure 3. The FTIR spectra of the mild steel immersed in solution containing ALB were similar to that of ALB in HCl solution. This indicates that the adsorption of the ALB on the mild steel surface could form a film on metal specimen (Haruna et al., 2018).

|  |
| --- |
| (a)  (b)  (c) |

**Figure 3:** FTIR spectra of (a) ALB in HCl solution, (b) surface-adsorbed layer of the mild steel immersed in 0.5M HCl (c) surface-adsorbed layer of mild steel immersed in 0.5M HCl in the presence of 0.1% ALB.

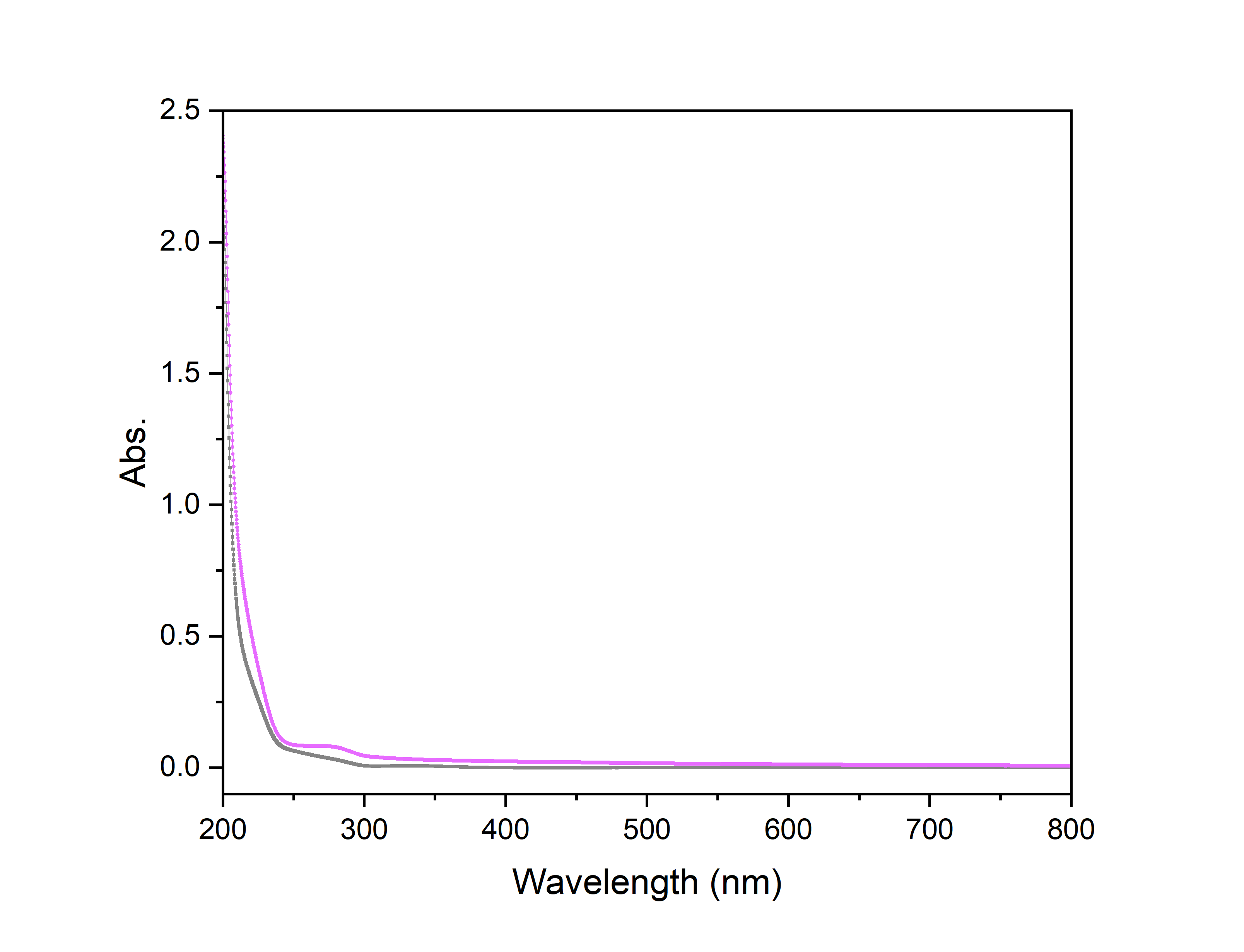
The formation of the protective layer containing Albumin on the mild steel surface was analyzed and confirmed by comparing the FTIR spectra of ALB in HCl with 0.1% ALB adsorbed on mild steel in 0.5M HCl solution. It can be said that the characteristics amide groups (-CO/NH-) were the main adsorption band of Albumin (Pal et al., 2016). For the ALB in HCl (Figure 3a), the characteristic peaks were observed at 1631 cm-1 (C=O stretching) due to amide I band and 1535 cm-1 (C-N stretch with N-H bending mode) due to amide II band which show the presence of protein (Mahobia et al., 2016). The band at 1366 cm-1 is attributed to the C-H vibrations. The broad band observed at 3290 cm-1 is associated with the O-H stretching of water stretching overlapped by an N-H stretching mode (Hemapriya et al., 2020). The band at 2973 cm-1 is associated with the C-H stretching (Ghaderi et al., 2022).

For the FTIR spectra of mild steel immersed in 0.5M HCl with 0.1% ALB (Figure 3c), the band intensities were found to be lower than that of ALB in HCl solution. The peak for C=O stretching vibration was shifted to a higher frequency (1657 cm−1), indicating the formation of a bond between the oxygen atom in the ALB and the metal surface (Boskey & Pleshkocamacho, 2007). The band for C-N stretching and N-H bending was shifted to higher frequency at 1539 cm-1, and the band for C-H vibrations was shifted to a higher frequency at 1374 cm-1. This also provides evidence of the interaction between ALB and mild steel surface and the film formation (Haruna et al., 2018).

The FTIR spectra for the mild steel that was immersed in 0.5M HCl without inhibitors were also presented in Figure 3b. A comparative analysis of the spectra of metal specimens with the spectra of ALB in HCl revealed the shift of the characteristic band of ALB to higher frequency and presence of additional bands other than the mild steel immersed in only 0.5M HCl (Chung et al., 2019). The observations from FTIR analysis showed that specific interactions had occurred between the inhibitor and the metal surface. Moreover, the obtained results indicated that ALB was adsorbed by mild steel surface through the amide groups of the protein chain (Pal et al., 2016).

### **2.2.2 UV-Vis**

The UV-vis spectra for Albumin were shown in Figure 4. The spectra were obtained for the solution that contains 0.02% Albumin in 0.5M HCl before and after the immersion of the mild steel specimen for 2h. It was shown that after immersion of the mild steel specimen, the obtained absorption spectra in the UV-Visible region shifted to a lower absorbance value. This implies that there might be an interaction between Fe2+ and the inhibitor molecules in the solution (Finšgar & Jackson, 2014). This is explained by having some electronic transitions between the metal surface and the inhibitor molecules, thus, the formation of a film complex on the surface of the mild steel. The electronic transition can be classified as n → π or n → π\* (involving the non-bonding electrons of the ALB O and N atoms) (Haruna et al., 2018). Having an adsorbed protective film, which was formed by interaction between the ALB molecules and mild steel surface, can reduce the acid attack on the metal surface. Therefore, corrosion on the surface can be prevented.



(b)

(a)

**Figure 4:** UV-vis spectra of (a) the solution with 0.02% ALB in the 0.5M HCl recorded prior to immersion of the mild steel specimen and (b) solution with 0.02% ALB in the 0.5M HCl after 2h immersion of the mild steel specimen.

### **2.2.3 3D Profilometry**

Surface topology of the metal specimens was measured on the polished mild steel specimen and the mild steel specimens that were immersed in the 0.5M HCl with and without ALB. The scanned area was 3x3 mm2 for all the specimens. Mild steel specimens were immersed in the solution of 0.5M HCl without and with 0.02% ALB. Figure 5 shows the 3D-profiles of the polished mild steel specimen and treated mild steel specimens in non-inhibited and ALB-inhibited solution.

The parameter of root mean square deviation of the roughness (Rq) was obtained from the 3D profilometry test scan and presented in Table 3.

For the mild steel specimen immersed in 0.5M HCl solution with 0.02% ALB had lower value of Rq than the mild steel immersed in 0.5M HCl without any inhibitor. This implies that the ALB molecules could create a bond with the mild steel surface, and this could suppress the corrosion of the metal (Finšgar, 2013). In other words, having ALB in the solution helped to form a complex film on the mild steel surface to prevent corrosion.

|  |  |  |  |
| --- | --- | --- | --- |
| A blue and green square with measuring tape  Description automatically generated with medium confidence (a) | A blue and green gradient on a square  Description automatically generated (b) | A colorful pattern on a white surface  Description automatically generated with medium confidence  (c) | A yellow and green bar with black text  Description automatically generated |

**Figure 5:** Surface topology of (a) polished mild steel, (b) mild steel specimen immersed in 0.5M HCl, and (c) mild steel specimen immersed in 0.5M HCl with 0.02% ALB

**Table 3:** Surface roughness parameters obtained by profilometer of the polished mild steel, and mild steel specimen immersed in 0.5M HCl with and without 0.1% ALB.

|  |  |
| --- | --- |
| **Specimen** | **(Rq)** |
| Polished mild steel | 600 nm |
| Mild steel immersed in 0.5M HCl | 900 nm |
| Mild steel immersed in 0.5M HCl + 0.1% ALB | 600 nm |

### **2.2.4 AFM**

AFM is a widely recognized and highly effective tool for examining the formation of inhibitor films at the nano to micro scales. It is commonly employed to quantify surface roughness in metal analysis and to visualize the three-dimensional surface morphology of materials (Vengatesh & Sundaravadivelu, 2019). The two-dimensional (2D) and three-dimensional (3D) images of the surface topology of the polished mild steel and the mild steels that were immersed in 0.5M HCl solution with and without 0.1% ALB are shown in Figure 6.

The values for the parameter of root mean square roughness (Rq) are presented in Table 4. From Table 4, Rq for polished mild steel surface, inhibited and uninhibited mild steel surface were 16.76 nm, 32.53 nm and 114.37 nm respectively. The results showed that Rq for the mild steel surface immersed in 0.5M HCl with 0.1% ALB solution is lower than that of the steel surface immersed in 0.5M HCl without inhibitor. This indicates that the use of ALB controlled the corrosion process by the formation of a film on the mild steel surface. The reduced value of Rq for the treated surface with ALB also indicated the homogeneity of the film on the surface. Moreover, the formed film prevented the metal from corrosion (Vengatesh & Sundaravadivelu, 2019). The AFM results seem to be in a good agreement with the FTIR, UV-vis and 3D profilometry analyses.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| (a) | A close-up of a graph  Description automatically generated | A close-up of a graph  Description automatically generated | A close-up of a screen  Description automatically generated | A close-up of a graph  Description automatically generated |
| (b) | A close-up of a graph  Description automatically generated | A close-up of a graph  Description automatically generated |
| (c) | A close-up of a red and yellow image  Description automatically generated | A close-up of a red and yellow image  Description automatically generated |

**Figure 6:** 2D and 3D images of the profiles obtained by AFM of (a) polished mild steel, (b) mild steel specimen immersed in 0.5M HCl, and (c) mild steel specimen immersed in 0.5M HCl with 0.02% ALB.

**Table 4:** Roughness parameter obtained by AFM measurement of the polished mild steel, and mild steel specimens immersed in 0.5M HCl with and without 0.1% ALB.

|  |  |
| --- | --- |
| **Specimens** | **(Rq)** |
| Polished mild steel | 16.76 nm |
| Mild steel immersed in 0.5M HCl | 114.37 nm |
| Mild steel immersed in 0.5M HCl + 0.1% ALB | 32.53 nm |

## **Conclusions**

The effect of selected inhibitors, including different amino acids, different proteins and chitosan, on mild steel in a 0.5 M HCl was investigated using electrochemical measurements. The film formation on the mild steel surface was studied using FTIR and UV-vis. The surface topology was evaluated using 3D profilometry and AFM. The obtained results showed that most of the amino acids and proteins used as inhibitors showed higher inhibition efficiency with increasing their concentration. The mechanism for the inhibition could be explained by the adsorption of the inhibitor molecules on the metal surface. The adsorbed molecules of inhibitors formed a complex film on the metal and effectively blocked the steel surface from being attacked by the corrosive media. The obtained results from FTIR and UV-vis analysis revealed the protein (ALB) molecules adsorbed on the mild steel surface through interaction between atoms of ALB and the metal surface to form the mild steel-protein complex. Moreover, 3D profilometry and AFM analysis further indicated the corrosion inhibition property of ALB.

.

# **References**

Borcherding, K., Lorenzen, P. C. H. R., & Hoffmann, W. (2009). Effect of protein content, casein–whey protein ratio and pH value on the foaming properties of skimmed milk. *International Journal of Dairy Technology*, *62*(2), 161–169. https://doi.org/10.1111/j.1471-0307.2009.00472.x

Boskey, A., & Pleshkocamacho, N. (2007). FT-IR imaging of native and tissue-engineered bone and cartilage. *Biomaterials*, *28*(15), 2465–2478. https://doi.org/10.1016/j.biomaterials.2006.11.043

Chung, I.-M., Kim, S.-H., Hemapriya, V., Kalaiselvi, K., & Prabakaran, M. (2019). Inhibition behavior of Tragia involucrata L. phenolic compounds against acidic medium corrosion in low carbon steel surface. *Chinese Journal of Chemical Engineering*, *27*(3), 717–725. https://doi.org/10.1016/j.cjche.2018.10.008

Elbaum, D., Harrington, J., Roth, E. F., & Nagel, R. L. (1976). Surface activity of hemoglobin S and other human hemoglobin variants. *Biochimica et Biophysica Acta (BBA) - Protein Structure*, *427*(1), 57–69. https://doi.org/10.1016/0005-2795(76)90285-3

Farag, A. A., Ismail, A. S., & Migahed, M. A. (2018). Environmental-friendly shrimp waste protein corrosion inhibitor for carbon steel in 1 M HCl solution. *Egyptian Journal of Petroleum*, *27*(4), 1187–1194. https://doi.org/10.1016/j.ejpe.2018.05.001

Finšgar, M. (2013). 2-Mercaptobenzimidazole as a copper corrosion inhibitor: Part I. Long-term immersion, 3D-profilometry, and electrochemistry. *Corrosion Science*, *72*, 82–89. https://doi.org/10.1016/j.corsci.2013.03.011

Finšgar, M., & Jackson, J. (2014). Application of corrosion inhibitors for steels in acidic media for the oil and gas industry: A review. *Corrosion Science*, *86*, 17–41. https://doi.org/10.1016/j.corsci.2014.04.044

Ghaderi, M., Ramazani S. A., A., Kordzadeh, A., Mahdavian, M., Alibakhshi, E., & Ghaderi, A. (2022). Corrosion inhibition of a novel antihistamine-based compound for mild steel in hydrochloric acid solution: Experimental and computational studies. *Scientific Reports*, *12*(1), 13450. https://doi.org/10.1038/s41598-022-17589-y

Guo, L., Luo, Y., Huang, Y., Yang, W., Zheng, X., Lin, Y., & Marzouki, R. (2022). Imidazolidiny Urea as a Potential Corrosion Inhibitor for Mild Steel in HCl Medium: Experimental and Density-Functional Based Tight-Binding Methods. *International Journal of Electrochemical Science*, *17*(7), 220748. https://doi.org/10.20964/2022.07.34

Haruna, K., Obot, I. B., Ankah, N. K., Sorour, A. A., & Saleh, T. A. (2018). Gelatin: A green corrosion inhibitor for carbon steel in oil well acidizing environment. *Journal of Molecular Liquids*, *264*, 515–525. https://doi.org/10.1016/j.molliq.2018.05.058

Hemapriya, V., Prabakaran, M., Chitra, S., Swathika, M., Kim, S.-H., & Chung, I.-M. (2020). Utilization of biowaste as an eco-friendly biodegradable corrosion inhibitor for mild steel in 1 mol/L HCl solution. *Arabian Journal of Chemistry*, *13*(12), 8684–8696. https://doi.org/10.1016/j.arabjc.2020.09.060

Mahobia, S., Bajpai, J., & Bajpai, A. K. (2016). *An In-vitro Investigation of Swelling Controlled Delivery of Insulin from Egg Albumin Nanocarriers*.

Pal, A., Dey, S., & Sukul, D. (2016). Effect of temperature on adsorption and corrosion inhibition characteristics of gelatin on mild steel in hydrochloric acid medium. *Research on Chemical Intermediates*, *42*(5), 4531–4549. https://doi.org/10.1007/s11164-015-2295-8

Paramasivam, S., Kulanthai, K., Sadhasivam, G., & Subramani, R. (2016). Corrosion Inhibition of Mild Steel in Hydrochloric Acid using4- (pyridin-2yl)-N-p-tolylpiperazine-1-carboxamide. *International Journal of Electrochemical Science*, *11*(5), 3393–3414. https://doi.org/10.1016/S1452-3981(23)17408-6

Satpati, S., Saha, S. Kr., Suhasaria, A., Banerjee, P., & Sukul, D. (2020). Adsorption and anti-corrosion characteristics of vanillin Schiff bases on mild steel in 1 M HCl: Experimental and theoretical study. *RSC Advances*, *10*(16), 9258–9273. https://doi.org/10.1039/C9RA07982C

Savadkoohi, S., & Kasapis, S. (2016). High pressure effects on the structural functionality of condensed globular-protein matrices. *International Journal of Biological Macromolecules*, *88*, 433–442. https://doi.org/10.1016/j.ijbiomac.2016.04.012

Udayappan, B., & Veawab, A. (2022). Performance analysis of methionine as an environmentally friendly corrosion inhibitor for carbon steel in the amine based carbon capture process. *International Journal of Greenhouse Gas Control*, *114*, 103565. https://doi.org/10.1016/j.ijggc.2021.103565

Vengatesh, G., & Sundaravadivelu, M. (2019). Non-toxic bisacodyl as an effective corrosion inhibitor for mild steel in 1 M HCl: Thermodynamic, electrochemical, SEM, EDX, AFM, FT-IR, DFT and molecular dynamics simulation studies. *Journal of Molecular Liquids*, *287*, 110906. https://doi.org/10.1016/j.molliq.2019.110906

Wang, Q., Zhang, Q., Zheng, H., Liu, L., Wu, X., Zhao, C., Zhou, X., Sun, Y., Yan, Z., & Li, X. (2023). Insight into anti-corrosion behavior of protein extract as eco–friendly corrosion inhibitor. *Sustainable Chemistry and Pharmacy*, *34*, 101177. https://doi.org/10.1016/j.scp.2023.101177

Znidarsic, W. J., Chen, I.-W., & Shastri, V. P. (2009). ζ-potential characterization of collagen and bovine serum albumin modified silica nanoparticles: A comparative study. *Journal of Materials Science*, *44*(5), 1374–1380. https://doi.org/10.1007/s10853-008-2998-y

**Project Financial Activities Incurred during the Reporting Period:**

|  |  |
| --- | --- |
| Category | Amount |
| Materials and Supplies | $2,500 |
| Ph.D. student Stipend and Insurance | $11,000 |
| Tuition | $0 |
| PI salary |  |

**Project Activities with Cost Share Partners:**

N/A

**Project Activities with External Partners:**

Collaboration with industry partners has been initiated to understand the practical considerations of utilizing bio-based corrosion inhibitors and to incorporate industry input in the design of the experiments.

**Potential Project Risks:**

N/A

**Future Project Work:**

Corrosion efficiency of other biopolymers will be investigated through electrochemical testing, surface topology evaluation, and surface chemical characterization. The film formation ability of the biopolymers will be investigated. The relationships between the biomolecule characteristics and their corrosion behavior will be studied.

**Potential Impacts to Pipeline Safety:**

The results of this project have the potential to revolutionize the development of eco-friendly inhibitors and methods to combat internal corrosion in pipeline systems.