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

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Project Activities for Reporting Period:

In this report, the primary goal was to identify and evaluate eco-friendly green corrosion inhibitors for gas pipeline protection. To this end, 10 bio-based surfactants were tested in two different corrosion media. Their efficiency was evaluated by weight loss analysis. The study utilized 0.5 M HCl and 3.5 % NaCl solutions as corrosive environments to compare the inhibition efficiencies of the inhibitors in two corrosive media. Additionally, A36 steel specimens were exposed to dynamic flow conditions within a pipeline system to evaluate the influence of specimen positioning and the corresponding inhibition efficiency of selected inhibitors under these conditions. Two types of inhibitors were tested: protein-based inhibitors and one commercially available organic inhibitor.

1. Conducting Weight Loss Tests in Two Different Corrosive Media to Compare the Efficiency of Bio-based Surfactants

1.1. Materials and Methods

Ten commercially available surfactants were used as inhibitors. The test inhibitors are listed in Table 1.

Table 1: List of inhibitors used in the weight loss analysis.

No	Inhibitor (Bio-based Surfactants)	No	Inhibitor (Bio-based Surfactants)
1	Adogen 464	6	Makon TD-3
2	Makon NF-12	7	Kao Findet MB212
3	Biosoft TA-2	8	Makon UD-5
4	Makon NF-5	9	Biosoft N91-6

5	Ecosurf EH6	10	Igepal CA-720

A36 steel specimens (McMaster-Carr, US) with the composition of C: 0.19 %, Cr: 0.04 %, Cu: 0.03 %, Mn: 0.76 %, Mo: 0.01 %, Ni: 0.01 %, Si: 0.019 %, P: 0.01 %, S:0.008 %, V: 0.001 % and Fe: remainder were used in all the experimental studies. The specimen dimensions used in the weight loss experiment were 20 mm x 10 mm x 1.5 mm. Unpolished steel specimens were used for this study.

Two different corrosive media were prepared as follows:

1. **0.5 M HCl solution**: The electrolyte solution of 0.5 M HCl was prepared by diluting 37 % analytical-grade HCl (Sigma-Aldrich) with deionized water.
2. **3.5 % NaCl solution:** The solution was prepared by dissolving 35 g of NaCl in 1 L of deionized water.

The ten bio-based surfactant inhibitors were dissolved separately in the 0.5 M HCl solution and the 3.5 % NaCl solution to achieve concentrations of 0.05 %.

1.2. Weight Loss Measurements

The weight loss measurements were performed to assess and compare the corrosive behavior and inhibition efficiencies of test inhibitors on A36 steel specimens exposed to various corrosive environments, which are 0.5 M HCl solution and 3.5 % NaCl solution. These measurements provide quantitative data on the material degradation due to corrosion, facilitating an understanding of how different environments influence the corrosion rate. By evaluating weight loss over time, it is possible to establish a correlation between environmental factors and the rate of corrosion, offering insights into the performance and durability of A36 steel in different conditions.

First, A36 steel specimens (20 mm x 10 mm x 1.5 mm) were immersed in corrosive solutions in the absence and presence of bio-based surfactant inhibitors for 7 days of measurements. After the immersion period, the steel specimens were rinsed with deionized water and acetone, dried in air, and reweighed. The weight loss was calculated as the difference between the weight of the specimens before and after 7 days of immersion.

Three replicates were used for each test. The average relative mass loss of the A36 steel specimens was determined from three individual measurements. All the measurements were taken at room temperature. The corrosion rate (CR) and inhibition efficiency (IE) were calculated by the following equations:

$$CR\ (mmy) = \frac{KW}{\rho A t} \tag{1}$$

where W is the weight loss (in g), ρ is the density (gcm^{-3}), A is the exposed area of the specimen (cm^2), and t is the exposure time (h). K is a constant that can be varied to calculate the corrosion rate in various units. For the case of mm/year for CR calculation, K is equal to $8.75x10^4$.

$$IE_{WL}(\%)=\frac{CR_0\text{-}CR_i}{CR_0}\times 100 \qquad (2)$$

where CR_0 and CR_i are the corrosion rates of A36 steel in the absence and presence of inhibitors respectively.

2. Experimental Investigation of Corrosion Inhibition Efficiency of Test Inhibitors in Dynamic Pipeline Conditions

2.1. Materials

The inhibitors selected for this study included a soy protein, chosen for its potential to form a protective layer on the steel surface, and a commercially available organic inhibitor (Halox 330), which is used for comparison purposes. Halox 330 is classified as a film-forming amine-based corrosion inhibitor, incorporating amino-phosphate and amino-borate functional groups. A36 steel specimens with dimensions of 20 mm x 10mm x 1.5mm were used for the experiments. 0.5 M HCl solution was used to simulate an aggressive acidic environment.

The corrosion mitigation on A36 steel using inhibitors was analyzed within a laboratory-scale pipeline system. A custom-designed pipeline circulation setup was used to simulate industrial flow conditions and to evaluate the effectiveness of test inhibitors under dynamic flow conditions. The experimental setup is shown in Figure 1. The setup comprises a PVC pipe with an internal diameter of 1.278 inches. The corrosion medium, 0.5 M HCl solution, circulated through the pipeline at a flow rate of 3.5 gallons per minute (GPM) using a vacuum pump. A blue container served as the reservoir for the corrosive solution.

For the test setup, the A36 steel specimens were strategically positioned diametrically on the inner walls of the pipe, corresponding to the top, bottom, left, and right orientations. Each steel specimen was securely attached to the pipe using external magnets, as illustrated in Figure 1. The purpose of this placement was to investigate positional variations in corrosion behavior along the pipeline under consistent flow conditions. The setup allowed for precise control of solution flow and specimen positioning. The weight loss tests were also evaluated in a beaker for comparative tests under static conditions.

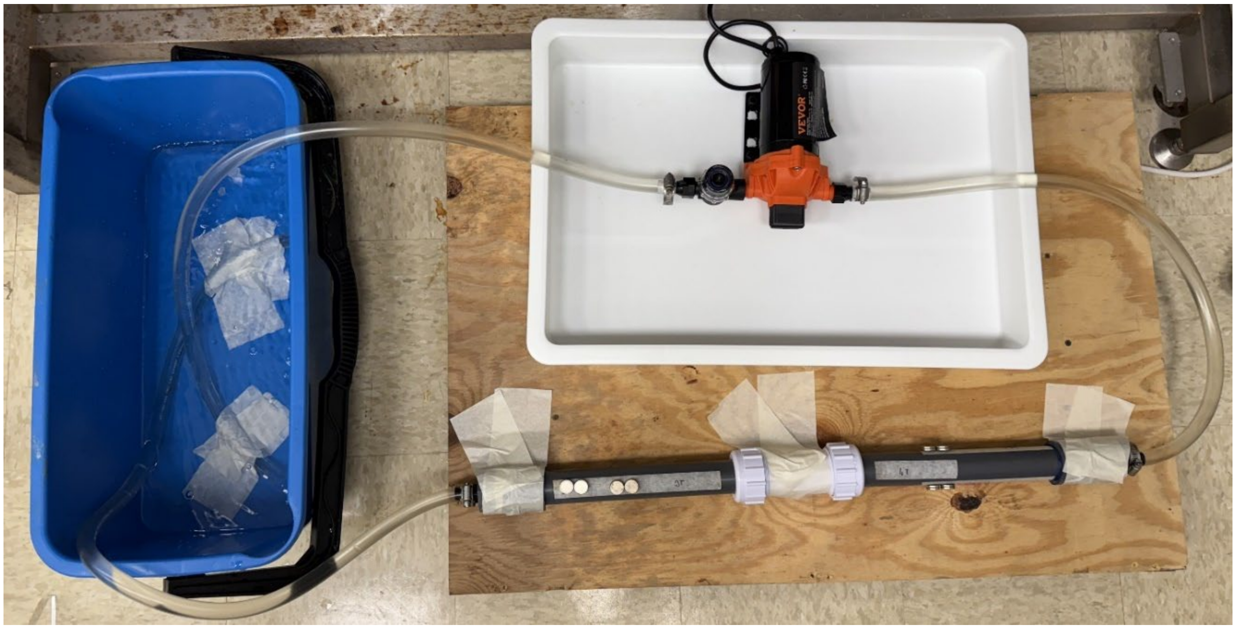

Figure 1: A laboratory-scale pipeline setup.

2.2. Methods

For the case without inhibitors (control), the A36 steel specimens were individually weighed to establish their initial mass and attached to the pipeline setup. Then, A36 steel specimens were exposed to the circulating 0.5 M HCl solution for three days. After the exposure period, the specimens were removed, cleaned, and reweighed to determine weight loss due to corrosion. This initial test provided baseline data on corrosion rates under uninhibited conditions. Additionally, the effects of flow dynamics on corrosion rates were evaluated based on the position of the steel specimens within the pipeline.

In addition, two different methodologies were employed to assess the corrosion inhibition performance of the selected inhibitors in the dynamic flow condition as described below:

2.2.1. Pre-Treatment Method (Surface Coating Approach)

In this method, the steel specimens were first weighed and pre-treated by immersing them in an inhibitor solution for three hours to form a protective coating on the surface. Following this pre-treatment, the specimens were positioned at different locations within the pipeline system, including the top, bottom, and sides (right and left) of the pipe. The pipeline was then subjected to continuous circulation of 0.5 M HCl solution for three days under controlled flow conditions. After a three-day circulation period, the specimens were removed, cleaned, and reweighed to determine weight loss due to corrosion. Then, the corrosion rate and inhibition efficiency of the system were calculated according to Equation 1 and Equation 2 to evaluate the effectiveness of the pre-formed inhibitor layer under flow conditions.

2.2.2. Direct Addition Method (Inhibitor in Solution Approach)

In the second approach, the steel specimens were initially weighed and placed inside the pipeline at the same designated positions (top, bottom, and sides). However, instead of pre-treating the specimens, the inhibitor was added directly to the circulating 0.5 M HCl solution. The pipeline system was then operated under identical dynamic conditions for three days. After the three-day circulation period, the steel specimens were removed, cleaned, and reweighed to quantify weight loss due to corrosion. The corrosion rate and inhibition efficiency of the system were then calculated using Equation 1 and Equation 2, respectively. These calculations were performed to assess the effectiveness of the direct addition of the inhibitor to the corrosive solution under flow conditions and to compare its performance with the pre-treatment method.

2.2.3. Static Condition Comparison

Additionally, to compare the effects of dynamic and static conditions, a separate set of experiments was conducted under static conditions. In these tests, the same pre-treatment and direct addition methodologies were applied, but instead of using a pipeline system, the specimens were fully immersed in the 0.5 M HCl solutions within a beaker. The weight loss analysis was applied to the beaker system too. The results obtained from the dynamic pipeline environment were then compared to those from the static immersion tests to assess the influence of flow conditions on inhibitor performance.

3. Results and Discussion

3.1. Weight Loss Measurements

3.1.1. Weight Loss Measurements in 0.5 M HCl Solution

The corrosion behavior of A36 steel specimens in 0.5 M HCl solution in the absence and presence of 0.05 % of bio-based surfactant inhibitors was studied using a weight loss technique and data obtained after 7 days of immersion are shown in Table 2. It can be stated that the corrosion rate of A36 steel is reduced in the presence of inhibitors as compared to the absence of the inhibitor in the solutions. For all test inhibitors, the inhibition efficiency increases with the presence of the inhibitor in the corrosive solution. The increased inhibition efficiency indicates that the inhibitor molecules are adsorbed on the A36 steel surface, leading to greater surface coverage and hence the formation of a protective film [1]. The maximum inhibition efficiency was observed to be 95.28% with the addition of Adogen 464 in 0.5 M HCl at a concentration of 0.05 %.

Table 2: The weight loss parameters obtained for A36 steel specimens in 0.5 M HCl solution without and with the 0.05 % bio-based surfactant inhibitors.

No	Inhibitor	CR (mm/year)	IE (%)
Control - 0.5M HCl	-	5.65 ± 0.43	-

1	Adogen 464	0.27 ± 0.05	95.28 ± 0.86
2	Makon NF-12	0.36 ± 0.02	93.62 ± 0.34
3	Biosoft TA-2	0.45 ± 0.04	91.95 ± 0.74
4	Makon NF-5	0.54 ± 0.01	90.49 ± 0.24
5	Ecosurf EH6	0.60 ± 0.07	89.39 ± 1.31
6	Makon TD-3	0.62 ± 0.03	88.99 ± 0.51
7	Kao Findet MB212	0.65 ± 0.02	88.54 ± 0.41
8	Makon UD-5	0.66 ± 0.01	88.22 ± 0.04
9	Biosoft N91-6	0.67 ± 0.01	88.06 ± 0.21
10	Igepal CA-720	0.70 ± 0.01	87.61 ± 0.14

In acidic environments, iron dissolution as well as hydrogen evolution occur [2]. Visual observations showed that the hydrogen evolution decreased (i.e., an increase in the inhibition effect of inhibitors) upon the addition of the inhibitor. Therefore, the corrosion rate of A36 steel specimens decreased in the presence of the inhibitors. This could be attributed to the corrosion inhibition mechanism of inhibitors, which can be identified with the adsorption of the molecules of inhibitors at the steel/aggressive solution interface [3].

3.1.2. Weight Loss Measurements in 3.5 % NaCl Solution

The corrosion behavior of A36 steel specimens in 3.5 % NaCl solution, both in the absence and presence of 0.05 % bio-based surfactant inhibitors, was investigated using the weight loss technique. The data obtained after 7 days of immersion are presented in Table 3. The results indicate that the addition of some of the bio-based surfactant inhibitors significantly reduced the corrosion rate compared to the control (uninhibited) solution. This reduction suggests a higher inhibition efficiency for the test inhibitors. The increased inhibition efficiency is attributed to the adsorption of inhibitor molecules onto the A36 steel surface, leading to enhanced surface coverage and the subsequent formation of a protective film. The maximum inhibition efficiency was observed to be 43.68 % with the addition of Kao Findet MB212 in 3.5% NaCl at a concentration of 0.05 %.

Table 3: The weight loss parameters obtained for A36 steel specimens in 3.5 % NaCl solution without and with the 0.05 % bio-based surfactant inhibitors.

No	Inhibitor	CR (mm/year)	IE (%)
Control - 0.5M HCl	-	0.062 ± 0.003	-

1	Adogen 464	0.081 ± 0.005	-29.56 ± 7.73
2	Makon NF-12	0.056 ± 0.001	9.28 ± 1.25
3	Biosoft TA-2	0.070 ± 0.001	-12.82 ± 1.65
4	Makon NF-5	0.066 ± 0.001	-6.13 ± 2.83
5	Ecosurf EH6	0.081 ± 0.005	-30.71 ± 8.31
6	Makon TD-3	0.077 ± 0.004	-23.21 ± 5.58
7	Kao Findet MB212	0.035 ± 0.003	43.68 ± 4.00
8	Makon UD-5	0.075 ± 0.002	-20.03 ± 0.67
9	Biosoft N91-6	0.060 ± 0.002	3.15 ± 4.60
10	Igepal CA-720	0.072 ± 0.003	-15.97 ± 2.46

The corrosion behavior of metals varies significantly between HCl and NaCl solutions due to differences in their chemical conditions. HCl, a strong acid, dissociates completely in aqueous solutions, providing a high concentration of hydrogen ions (H^+), accelerating the anodic dissolution of metals. In contrast, NaCl is a neutral salt that dissociates into sodium (Na^+) and chloride (Cl^-) ions, with the chloride ions primarily contributing to localized corrosion, such as pitting. Studies have shown that metals exhibit higher corrosion rates in HCl compared to NaCl solutions [4]. This increased rate in HCl is attributed to its strong acidic nature, which leads to more aggressive uniform corrosion. Conversely, in NaCl solutions, corrosion tends to be less severe but can result in localized forms such as pitting.

The difference in corrosion behavior between HCl and NaCl solutions is evident from the corrosion rate values presented in Table 2 and Table 3. In the HCl solution, the corrosion rate was determined to be 5.65 mm/year, whereas in the NaCl solution, it was significantly lower, measuring only 0.06 mm/year. This substantial disparity highlights the aggressive nature of HCl, which promotes rapid uniform corrosion, in contrast to NaCl, where the corrosion process is comparatively slower and primarily localized.

Studies have shown that the effectiveness of inhibitors and their mechanism of inhibition depend on multiple factors, including the presence of corrosive ions, the chemical structure of the inhibitor, the number of adsorption sites available on the metal surface, and other related parameters. Moreover, it is stated in most studies that organic inhibitors are highly effective in acidic environments, as they strongly adsorb onto the metal surface, forming a protective barrier that mitigates corrosion [5,6]. However, their performance in saline environments, such as a 3.5% NaCl solution, is often limited due to the aggressive nature of chloride ions (Cl^-), which can penetrate and destabilize the inhibitor film, leading to localized corrosion, particularly pitting corrosion [7]. This could explain, based on the obtained data from Table 2 and Table 3, why certain inhibitors exhibited a positive effect in HCl, significantly reducing the corrosion rate, while in NaCl, they demonstrated a negative impact, leading to an increase in the corrosion rate.

In addition, the inhibition is caused by forming a monomolecular film-adsorbed surface, which blocks the direct contact between the metal and a corrosive environment [8]. This film is formed by chemical or physical adsorption of the inhibitors onto the metal surface with the formation of a coordinate covalent bond or electrostatic interaction, respectively. At the same concentration of the inhibitors, having a higher inhibition efficiency of an inhibitor could be attributed to the polymers' ability to form a dense film on the A36 steel specimen, which mainly comes from the functional group in their molecular structure [9]. Since organic inhibitors work by attaching themselves to the metal surface, their effectiveness is heavily influenced by their ability to form a complex film on the metal surface [10]. The presence of heteroatoms containing N, O, P, and/or S, as well as aromatic rings, and the π electrons in their bond structure are the fundamental characteristics of the organic inhibitors [11].

3.2. Flow Analysis in Pipeline System

3.2.1. Flow Analysis of Pre-Treatment Method

The experimental results, shown in Table 4, indicate that the soy protein inhibitor exhibited higher inhibition efficiency compared to Halox 330 when both were used at a 2 % concentration. Specifically, for soy protein, the corrosion rate ranged from 5.0 mm/year to 5.7 mm/year, with inhibition efficiency values between 30.1 % and 35.4 %, depending on the position of the specimen in the pipe. In contrast, Halox 330 showed a higher corrosion rate, ranging from 6.8 mm/year to 7.4 mm/year, with lower inhibition efficiency values of 11.0 % to 14.5 %. These values clearly demonstrate that the soy protein inhibitor provided significantly better corrosion protection in all tested positions within the pipeline system.

Furthermore, tests conducted with soy protein at two different concentrations (0.05 % and 2 %) revealed that increasing the inhibitor concentration led to an enhanced inhibition efficiency, indicating a greater adsorption coverage on the metal surface. This trend suggests that higher concentrations of the inhibitor result in greater adsorption onto the metal surface, thereby forming a more effective protective film [12].

Table 4: Corrosion rate and inhibition efficiency parameters of A36 steel specimens in a flow system with 0.5 M HCl solution for pre-treatment method with soy protein and Halox 330 inhibitors.

Inhibitor	Position	CR (mm/year)	IE (%)
0.5M HCl (Control)	Top	8.2 ± 0.3	-
	Bottom	7.8 ± 0.4	-

	Sides (Right and Left)	8.3 ± 0.4	-
Soy Protein (2 %)	Top	5.3 ± 0.4	35.3 ± 4.6
	Bottom	5.0 ± 0.4	35.4 ± 4.6
	Sides (Right and Left)	5.7 ± 0.3	30.1 ± 3.6
Soy Protein (0.05 %)	Top	7.1 ± 0.2	13.0 ± 1.9
	Bottom	7.0 ± 0.1	10.0 ± 0.9
	Sides (Right and Left)	7.4 ± 0.1	10.7 ± 1.1
Halox 330 (2 %)	Top	7.0 ± 0.3	14.5 ± 0.5
	Bottom	6.8 ± 0.4	12.9 ± 1.3
	Sides (Right and Left)	7.4 ± 0.4	11.0 ± 1.1

3.3. Flow Analysis of Direct Addition Method

The findings presented in Table 5 illustrate the corrosion rate and inhibition efficiency values obtained for soy protein and Halox 330 when they were directly added to the 0.5 M HCl solution. In this method, Halox 330 was introduced into the solution at a 2% concentration, in accordance with the specifications provided by the supplier. In contrast, soy protein was used at a significantly lower concentration of 0.05 %, aiming to evaluate its effectiveness with a reduced inhibitor dosage.

Despite the lower concentration, soy protein demonstrated significantly higher inhibition efficiency compared to Halox 330, indicating its superior performance as a corrosion inhibitor even at reduced dosages. For soy protein (with a concentration of 0.05 %), the corrosion rate varied between 1.4 mm/year and 1.9 mm/year, while the inhibition efficiency ranged from 77.7 % to 82.2 %, depending on the specimen's placement within the pipeline. Conversely, Halox 330 (with a concentration of 2 %) exhibited a higher corrosion rate, between 3.3 mm/year and 3.8 mm/year, with a lower inhibition efficiency of 53.7 % to 60.0 %. This result suggests that soy protein exhibits strong adsorption behavior, leading to enhanced surface coverage and corrosion protection [13].

Table 5: Corrosion rate and inhibition efficiency parameters of A36 steel specimens in a flow system with 0.5 M HCl solution for direct addition method with soy protein and Halox 330 inhibitors.

Inhibitor	Position	CR (mm/year)	IE (%)
0.5M HCl (Control)	Top	8.2 ± 0.3	-

	Bottom	7.8 ± 0.4	-
	Sides (Right and Left)	8.3 ± 0.4	-
Soy Protein (0.05 %)	Top	1.5 ± 0.04	82.2 ± 0.5
	Bottom	1.4 ± 0.05	81.5 ± 0.6
	Sides (Right and Left)	1.9 ± 0.04	77.7 ± 0.4
Halox 330 (2 %)	Top	3.3 ± 0.2	60.0 ± 2.4
	Bottom	3.3 ± 0.2	57.9 ± 2.3
	Sides (Right and Left)	3.8 ± 0.1	53.7 ± 1.5

Furthermore, the direct addition method yielded higher inhibition efficiency for both inhibitors compared to the pre-treatment approach. This enhancement can be attributed to the continuous availability of the inhibitor molecules in the solution, which facilitates more effective adsorption onto the metal surface, thereby forming a stronger and more protective film.

3.4. Static Condition Comparison

The experimental data presented in Table 6 reveal that specimens subjected to static conditions exhibited higher inhibition efficiencies for both inhibitors and both pre-treatment and direct addition methods compared to those under dynamic flow conditions.

Table 6: Inhibition efficiency parameters of A36 steel specimens in a flow system and static condition in 0.5 M HCl solution for pre-treatment and direct addition method with soy protein and Halox 330 inhibitors.

Inhibitor	Position	IE / Flow Condition (%)	IE / Static Condition (%)
Soy Protein (0.05 % / direct addition)	Top	82.2 ± 0.5	88.5 ± 0.3
	Bottom	81.5 ± 0.6	
	Sides (Right and Left)	77.7 ± 0.4	
Halox 330 (2 % / direct addition)	Top	60.0 ± 2.4	80.8 ± 1.25
	Bottom	57.9 ± 2.3	
	Sides (Right and Left)	53.7 ± 1.5	
Soy Protein (2 % / pre-treatment)	Top	35.3 ± 4.6	59.6 ± 2.5
	Bottom	35.4 ± 4.6	

	Sides (Right and Left)	30.1 ± 3.6	
Soy Protein (0.05 % / pre-treatment)	Top	13.0 ± 1.9	34.4 ± 2.5
	Bottom	10.0 ± 0.9	
	Sides (Right and Left)	10.7 ± 1.1	
Halox 330 (2 % / pre-treatment)	Top	14.5 ± 0.5	29.9 ± 1.3
	Bottom	12.9 ± 1.3	
	Sides (Right and Left)	11.0 ± 1.1	

The observed data suggests that the presence of flow conditions facilitates the continuous replenishment of corrosive ions at the metal surface, thereby sustaining the corrosion process. Unlike static conditions, where the diffusion of aggressive species such as H^+ and Cl^- ions is relatively slow, flow conditions promote mass transport, leading to higher availability of these ions at the metal interface. Consequently, the protective inhibitor film may experience greater mechanical disruption due to the movement of the solution, reducing its overall stability and effectiveness. As a result, corrosion tends to progress more rapidly in a flowing system compared to a static environment, where the inhibitor molecules can remain more uniformly adsorbed on the metal surface, providing enhanced protection [14].

Additionally, the data indicates that the position of the specimens within the pipeline system did not result in significant variations in corrosion rates, as the measured values exhibited minimal differences across different locations.

4. Conclusions

The effect of inhibitors, including ten bio-based surfactants, soy protein and Halox 330, on A36 steel in corrosive solutions (0.5 M HCl solution and 3.5 % NaCl solution) was investigated using weight loss analysis and under flow conditions within a pipe system. The obtained results showed that most of the used inhibitors showed exceptional inhibition efficiency for A36 steel in a corrosive solution. The mechanism for the inhibition could be explained by the adsorption of the inhibitor molecules on the metal surface by their functional groups. 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 lab-scale experimental pipe model provides a framework for investigating the effects of corrosion inhibitors under controlled conditions. By simulating pipeline environments, this study contributes to the broader understanding of corrosion dynamics and the development of effective strategies for corrosion mitigation in industrial applications. It represents the initial phase of ongoing research aimed at understanding the mechanisms of corrosion inhibition and optimizing inhibitor performance in dynamic environments. Subsequent experiments will investigate the long-term effects of the inhibitor, varying concentrations of the corrosive medium, and different flow rates. The influence of other environmental factors and the development of novel inhibitor formulations will also be explored.

Project Financial Activities Incurred during the Reporting Period:

One Graduate Research Assistant (GRA) at the University of Miami.

Materials and Supplies

Advanced Materials Characterization User Fee

Project Activities with Cost Share Partners:

N/A

Project Activities with External Partners:

Collaboration with industry partners has been established to explore the practical application of bio-based corrosion inhibitors. This partnership aims to integrate industry insights into the experimental design, ensuring the research tackles real-world challenges and applications. By working closely with industry stakeholders, the research methodologies will be refined, enhancing the relevance of the findings to practical situations and facilitating the successful implementation of these innovative corrosion prevention solutions.

Potential Project Risks:

N/A

Future Project Work:

Future research will focus on the evaluation of different types of corrosion inhibitors, including proteins, synthesized molecules, and commercially available formulations, under varying flow rates and chemical environments.

For future investigation:

- Long-Term Performance Assessment – Examining the stability and durability of inhibitors over extended exposure periods to understand their effectiveness in prolonged industrial applications.
- Influence of Flow Rate in Pipeline System – Investigating how increased turbulence impacts the adsorption and efficiency of inhibitors in dynamic systems.

- Adsorption Behavior Analysis – Utilizing electrochemical techniques and surface characterization methods to analyze inhibitor adsorption in both HCl and NaCl solutions.
- Development of Optimized Inhibitor Formulations – Exploring the synergistic effects of combining bio-based and synthetic inhibitors to enhance corrosion resistance under extreme conditions.

Potential Impacts to Pipeline Safety:

The outcomes of this research have the potential to contribute significantly to the development of advanced corrosion inhibition technologies to address internal corrosion in oil and gas pipelines.

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