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Animal Fats and Vegetable Oils—Promising Resources for Obtaining Effective Corrosion Inhibitors for Oil Refinery Equipment

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Abstract: The equipment of refineries and oil production facilities is subject to corrosion due to the supply of crude oils with a high content of mineralized water. The use of inhibitors is one of the most common corrosion protection methods. However, increasing requirements of environmental standards give impetus to developing new types of corrosion inhibitors from natural raw materials. The article deals with the synthesis conditions of new corrosion inhibitors (CIs) produced from distilled higher acids of beef fat (DHFAs) or vegetable oils (VO), as well as research on the protective effect of the synthesized corrosion inhibitors compared with industrial inhibitors (5 samples). The gravimetric method studied the protective effect in a solution of salts and jet fuel using a St20 steel plate. At 50 °C and a CIs content of 100 ppm, the protective effect of corrosion inhibitors based on VO and triethanolamine was 9.7–75.6%. Under similar conditions, CIs obtained from DHFAs and diaminoethyl exhibited a protective effect of 81.6–94.1%. When DHFAs and diethanolamine were used to synthesize CIs, the protective effect was 93.0–95.6%. CI synthesized at 130 °C and a DHFAs: diethanolamine ratio of 72:28 showed a 99.2% protective effect at 50 °C and a CI content of 200 ppm, which was higher or equal to the impact of using industrial inhibitors (91.6–99.5%). The results prove the possibility of alternative use of animal fats and waste from their production as new resources for obtaining highly effective equipment corrosion inhibitors. Using alternative inexpensive raw materials (fats, vegetable oils, waste from their output) to obtain CIs will improve the economic performance of inhibitor production. In addition, at least the fatty (oil) part of organic CIs is biodegradable and will not harm the environment.

Keywords: biological resources; corrosion inhibitor; protective effect; higher fatty acids; vegetable oil

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1. Introduction

The sustainable process of waste and low-quality minerals engineering and reuse and valorization of biomass are the main directions of creating new raw materials and resource sources. This significantly increases the circular economy's role and improves the ecology of the environment [1–6].

On the other hand, the refining industry and other fuel industries face significant corrosion challenges due to exposure to aggressive media, including mineralized water, acids,

and other corrosive components [7]. This requires effective corrosion inhibitors to protect equipment and increase its service life. The use of inhibitors is one of the most critical and widespread corrosion control methods [8]. Currently, many corrosion inhibitors are known to protect metals in hydrocarbon media. However, traditional corrosion inhibitors based on synthetic chemical compounds often contain toxic elements that harm the environment and human health. Amides (diamides), amines, imidazoline bases, and their mixtures make up the most significant part of the global production of corrosion inhibitors, which are the basis of most modern corrosion inhibitors [9,10]. Most compounds contain heteroatoms: nitrogen, sulfur, oxygen, phosphorus, and silicon [11].

According to the oil companies' requirements, the inhibitors must provide maximum protective effect at a sufficiently low concentration, be technological (not to disrupt the normal technological mode of operation of the plant), and not degrade the quality of products and the operation of catalysts of secondary processes. The inhibitors must also be economical, resistant to oxidation and reduction, non-toxic for operating personnel, and not pose a threat to environmental pollution.

However, most of the inhibitors being developed and researched are selective inhibitors with a relatively narrow spectrum of action; laboratory samples represent them, but they have no production capacity and depend on imported raw materials. Given these problems, developing inhibitors produced from organic, renewable raw materials is advisable to reduce the existing deficit in the inhibitor market [12]. In this context, the use of corrosion inhibitors produced from natural raw materials is becoming increasingly important, as such products comply with the principles of sustainable development and reduce the negative environmental impact of oil refining activities. It is known that organic inhibitors, particularly those based on vegetable oils and animal fats, not only provide adequate corrosion protection for metals but are also biodegradable, non-toxic, and often have a low environmental impact [13–18]. This makes them an essential alternative to traditional petrochemical-based corrosion inhibitors.

The main objective of S. Marzorati et al. [18] is to study plant materials and biomass waste that can be sources of green inhibitors. These raw materials are rich in various organic compounds, such as alkaloids, flavonoids, tannins, and other metabolites, which can effectively slow down the corrosion process. The paper describes in detail how these natural substances inhibit corrosion. The basic process involves the adsorption of molecules on the metal surface, creating a protective layer that prevents contact with aggressive media (e.g., acids or water). This reduces the rate of electrochemical corrosion. The authors conduct a comparative analysis of the effectiveness of natural inhibitors and traditional synthetic agents. It is noted that natural substances can be no less effective and, in some cases, even exceed the efficacy of synthetic inhibitors. In addition to being less toxic, these inhibitors are readily available and low-cost, as they can be produced from agricultural waste and other biomass sources. Although green inhibitors are promising, the authors note some challenges, such as the need for large-scale testing, optimization of production processes, and standardization for industrial use. Nevertheless, the potential for reduced environmental impact and economic benefits makes this area very promising.

Barreto et al. [19] investigated the use of vegetable waste, such as garlic peel (*Allium sativum* L.) and cocoa peel (*Theobroma* L.), as well as their synergy as a corrosion inhibitor for carbon steel in a 0.5 mol·L^{-1} hydrochloric acid solution. It was also found that the effectiveness of different vegetable residues varies depending on their chemical composition. Still, some types of waste, such as potato (Solanum tuberosum) and carrot (Daucus carota) peels, were particularly effective. The authors also noted that the effect of these inhibitors was compared with commercial synthetic corrosion inhibitors, and in some cases, their effectiveness was comparable.

Sun et al. [20] used pomelo peel (Citrus maxima) to develop corrosion inhibitors. Natural plant inhibitors, such as pomelo peel extract, provide high efficiency (up to 97%) in protecting N80 steel in aggressive media.

Ginkgo biloba leaf extract was used as a CO_2 corrosion inhibitor for carbon steel [21]. The study was conducted under conditions where the solution was saturated with CO_2, which simulates the medium in oil and gas pipelines. The results showed that Ginkgo biloba leaf extract was an effective corrosion inhibitor for carbon steel in a CO_2-saturated solution. The level of inhibitory effectiveness depended on the extract concentration: the higher the concentration, the greater the effect. In some cases, a significant reduction in corrosion rate was achieved compared to untreated steel samples.

Organic inhibitors act as anodic, cathodic, or mixed inhibitors by forming a film on the metal surface. The mechanisms of organic inhibitor action often depend on their adsorption properties on the metal surface. As noted by Pogrebova et al. [22], the adsorption of organic compounds on metal surfaces occurs through the interaction of polar groups with the metal, forming a stable protective film. Such films' formation prevents corrosive agents' penetration into the metal, effectively reducing the corrosion rate. An effective organic inhibitor usually contains polar functional groups with S, O, or N atoms in the molecule and a hydrophobic fragment that repels corrosive agents from the metal surface. Amide corrosion inhibitors act via the interaction of carboxyl groups of fatty acids with amino groups, which allows the formation of protective films on metal surfaces. As noted by Diaz et al. [23], inhibitors based on imidazoline amides demonstrate high efficiency in aggressive media, such as a 3% NaCl solution, due to the stability of their adsorption layer and the presence of hydrophobic radicals that repel corrosive agents.

Abd El-Lateef et al. synthesized new natural surfactants based on soybean oil [24]. Soybean oil was hydrolyzed with a 20% sodium hydroxide solution for 8 h at 85–90 °C. The yield of fatty acid sodium salts was 87%. Then, the salts reacted with a concentrated hydrochloric acid solution (37%) to extract the fatty acids. The resulting product is sulfated fatty acid with 81% yield. In this study, the protective effect of soybean oil-based surfactants was tested using various morphological and electrochemical studies, which were in good agreement, showing that the protective effect of soybean oil-based corrosion inhibitors reaches maximum values of 97.6–98.6% at 150 ppm, and the presence of nitrogen (N) atoms in the inhibitor structure plays a vital role in adsorption.

Green corrosion inhibitors are also used to protect equipment during well drilling. Thus, the inhibitory effect of environmentally friendly inhibitors based on fatty acids, polyethylene glycol oleamide-2 (PEG-2 oleamide), glycerol myristate (GM), and glycerol linoleate (GL) is observed for drilling fluids [25]. This study demonstrates the superior effectiveness of green inhibitors, especially PEG-2 oleamide, which shows 99.7% effectiveness. The high inhibitory capacity results from the formed protective layer that blocks corrosive ions from attacking the steel surface.

The sustainable use of bioproducts is a good alternative for synthesizing environmentally friendly inhibitors with high corrosion inhibition efficiency [26]. Literature data show that fatty acid-based inhibitors are effective due to the presence of long hydrophobic chains that form protective films on metals, blocking corrosive agents. The effect of the mentioned inhibitors is due to adsorption on the metal surface and the formation of a hydrophobic barrier. For example, studies [27] based on palmitic and stearic acid derivatives have confirmed that these compounds reduce corrosion in water-oil media. It was also found [28] that the protective ability depends on the inhibitor consumption, synthesis temperature, and time. The surface and adsorption characteristics are also important. The studies show that compounds with high protective properties have significant surface activity and excellent inhibition efficiency [29].

As raw materials, the green inhibitors were synthesized using citric acid, L-histidine, and cerium nitrate hexahydrate. The corrosion inhibition rate (IE) for metal was up to 90–96% [30–32].

Various corrosion test methods were used to determine the effectiveness of corrosion inhibition: weight tests to assess the mass loss of steel due to corrosion, Fourier transform infrared spectroscopy, potential dynamic polarization, electrochemical impedance spectroscopy, scanning electron microscopy (SEM), scanning electrochemical microscopy (SECM), quantum chemical calculations, and electrochemical methods, including polarization curves and electrochemical impedance spectroscopy (EIS), and analysis of the degree of adsorption. The corrosion depth also depends on the type and temperature of the aggressive medium. Therefore, the conditions for studying the effectiveness of inhibitors (corrosive medium, temperature) are usually selected depending on the further scope of its application [17,20,21,33–36].

On the other hand, large stocks of oils, fats, and waste from their production are being created in Ukraine and worldwide. In 2022, animal fat was the 971st most-sold product in the world, with a total trade volume of $ 834 million. Between 2021 and 2022, animal fat exports decreased by −8.62% from $ 913 million to $ 834 million. Trade in animal fat accounts for 0.0035% of total world trade [37]. By 2026, global animal fat consumption will reach 16,250 thousand metric tons. This is a slight increase of 0.3% per year compared to 16,010 thousand metric tons in 2021. Since 2017, demand for animal fats has grown by 0.2% per year [38].

Global production of vegetable oils has also been steadily increasing since the beginning of the century, reaching a peak of 210.4 million metric tons in 2022/2023. Ukrainian enterprises process up to 800 thousand tons of oils per year. The most common vegetable oils worldwide include palm, soybean, canola, and sunflower oil [39,40].

The processing of oils (and fats) generates about 1.2–1.5% of waste [40], approximately 190–240 thousand metric tons of animal fats, and 2.5–3.1 million metric tons per year worldwide as of 2021/2022. Therefore, the production volumes of fats and oils or their waste are sufficient to obtain alternative environmentally friendly products, including corrosion inhibitors.

Given the above, it is advisable to study the production of corrosion inhibitors based on the most common vegetable oils, animal fats, or their production wastes in Ukraine and the world. Also, the above-mentioned studies on the production of corrosion inhibitors from natural raw materials do not compare the production efficiency of vegetable and animal fats. Our previous work [17] described exploratory studies using compounds based on vegetable oils and animal fats with di- and triethanolamine as corrosion inhibitors. Comparative tests of corrosion inhibitors from well-known companies and corrosion inhibitors based on renewable raw materials showed a relatively high protective effect of the latter. Therefore, this work aims to continue the above experiments using amino derivatives to synthesize green corrosive inhibitors from raw plant and animal materials. Investigating their protective effects in a highly corrosive medium and comparing their efficiency with known inhibitors of world manufacturers is also necessary. Given that much of the research is devoted to synthesizing corrosion inhibitors from different types of raw materials at various temperatures, the simplest way to analyze their effectiveness (weight tests to assess the mass loss) is to select 1–3 optimal inhibitors. This will allow valorizing oils, animal fats, and waste from their production as potential raw materials for producing highly effective, inexpensive compounds used in the oil industry to reduce equipment corrosion.

2. Materials and Methods

2.1. Materials

Unsaturated acids-based corrosion inhibitors are believed to have a more significant protective effect than those based on saturated acids [41]. Therefore, we investigated raw materials with a high content of unsaturated acids (Table 1). Corn (Clavus) and sunflower (*Heliánthus ánnuus*) were chosen among vegetable oils. Coconut oil was used for the comparison because it contains quite a small amount of unsaturated acids. Instead, the content of saturated acids in it is pretty high and amounts to 49 wt%. Beef fat containing unsaturated acids of 51.0 wt% was chosen among animal fats. Vegetable oils and distilled saturated fatty acids from beef fat were obtained from Ukrainian industrial enterprises (Dnipro Agro Group, Dnipro, Ukrainian and Barcom LLC, Lviv region, village of Pidbirtsi, Ukraine). The company uses the hydrolysis of beef fats in the presence of water and NaOH as the catalyst to obtain the higher fatty acids. The fatty acids are separated from glycerol. Distillation at 150–200 °C under a 5–10 mm Hg vacuum is used to purify and concentrate fatty acids.

Table 1. Content of acids in the investigated samples [17].

Raw Material	Content of Acids, wt%								
	Lauric $C_{12}H_{24}O_2$	Myristic $C_{14}H_{28}O_2$	Palmitic $C_{16}H_{32}O_2$	Stearic $C_{18}H_{36}O_2$	Oleic $C_{18}H_{34}O_2$	Erucic $C_{22}H_{42}O_2$	Linoleic $C_{18}H_{32}O_2$	Linolenic $C_{18}H_{30}O_2$	Average Amount of Unsaturated Acids
Corn oil	-	-	9–19	1–3	40	-	40	1	80
Sunflower oil	-	-	-	6	35	-	56	-	91
Coconut oil	49	16	9	2	6	-	2	-	8
Beef fat	-	-	32	14	48	-	3	-	51

The average content of acids in natural raw materials under study is represented in Table 1.

To compare the protective effect of the synthesized inhibitors and those used today in oil refining, we used corrosion inhibitors manufactured by Chimec S.p.A. (Rome, Italy), SUEZ Group (Paris, France), Clariant AG (Muttenz, Switzerland), Nalco Water (An Ecolab Company)—Naperville, IL, USA, Barva LLC—(Ivano-Frankivsk, Ukraine). The active substance of inhibitors is dissolved in a hydrocarbon solvent. The list of commercial inhibitors is given in Table 2.

Table 2. The list of corrosion inhibitors from different manufacturers.

Sample No.	Manufacturer	Active Substance	Solvent	Product Name
1	Chimec S.p.A.	Alkyl imidazoline	Heavy aromatic hydrocarbons	Chimec 1839W
2	SUEZ Group	n-9-octadecyl 1,3-propane diamine	C_{10} hydrocarbons, heavy aromatic hydrocarbons	PhilmPlus 5068E
3	Clariant AG	Amides of polyamine naphthenic acids	C_{10} hydrocarbons, heavy aromatic hydrocarbons	Dodigen 481
4	Nalco Water	Tallow oil hydroxyethyl imidazoline	Heavy aromatic hydrocarbons	Nalco EC1021A
5	Barva LLC	Diethanol-aminoethyl heptadecenyl imidazoline	C_8 aromatic hydrocarbons	Carbosoline OT-2

The physical and chemical properties of commercial inhibitors usually used by oil refineries to prevent corrosion are given in Table 3.

Table 3. Properties of the commercial inhibitors.

Index	Sample No. According to Table 2				
	1	**2**	**3**	**4**	**5**
Physical state	liquid	liquid	liquid	liquid	liquid
Pour point, °C	−31	−34	−32	−25	−20
Initial boiling point, °C	180	177	200	180	139
Density at 20 °C, kg/m^3	980	890	940	918	910
Viscosity at 20 °C, mm^2/s	100	86	94	15	92
Flashpoint, °C	>61	61	85	68	35

The data show that all corrosion inhibitors have similar physical and chemical characteristics. All of them are liquids with a solidification temperature varied from −20 °C to −34 °C, a density of 890–980 kg/m^3, and an initial boiling point of 139–200 °C.

The corrosion studies were performed on samples of St20 steel with a total area of 30 cm^2 and a rectangular shape. The characteristics of the plate are shown in Table 4.

Table 4. The content of micro components in the metal plate used in the study [42].

	C	**Si**	**Mn**	**Ni**	**Cr**	**Cu**	**P**	**S**	**As**
wt%	0.17–0.24	0.17–0.37	0.35–0.65	≤0.3	≤0.25	≤0.3	≤0.035	≤0.04	≤0.08

Diethanolamine, diaminoethanol, and triethanolamine used in the study were of 99.7% purity.

Isopropyl alcohol and hydrocarbon solvent were of PA grade.

2.2. Synthesis of Corrosion Inhibitors and Preparation of Working Solution

The high protective effect of corrosive inhibitors is caused by the interaction of higher fatty acids in the composition of raw materials with amines [43–46]. That is why natural raw materials and amines were used for the synthesis. A flow diagram of the preparation of the corrosion inhibitor working solution is shown in Figure 1.

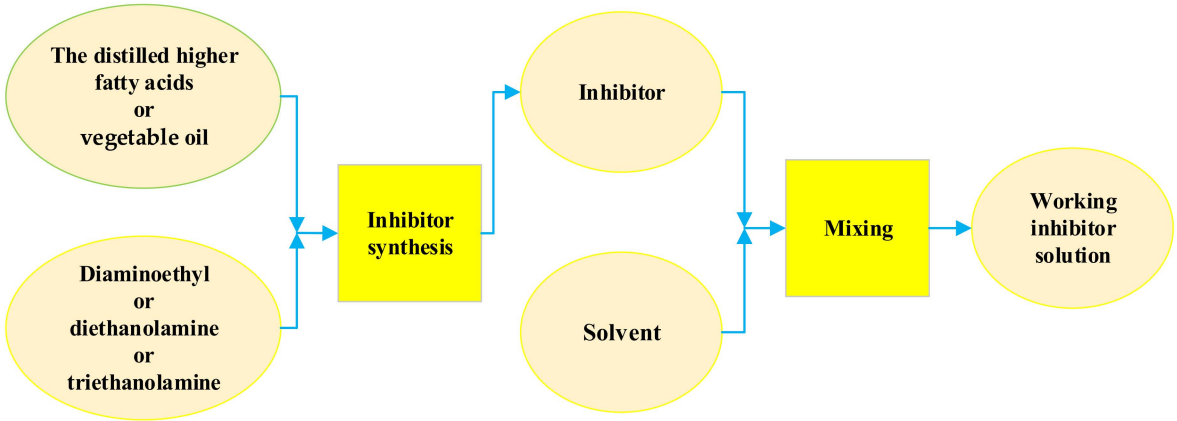


Figure 1. Flow diagram of the preparation of the corrosion inhibitor working solution.

Vegetable oils predominantly contain unsaturated fatty acids. They are more reactive and can interact with amines through adduct reactions, complexes, esters, and amide formation (if possible). On the other hand, the studies used different types of vegetable oils (with higher and lower content of unsaturated acids than animal fats). Using tertiary amines in reactions with vegetable oils containing various amounts of unsaturated acids made it possible to establish which groups tertiary amines react with. Animal fats usually contain more saturated fatty acids, which are less reactive but form more stable amides.

Therefore, secondary amines, capable of forming amides, were used for reactions with animal fats.

For the synthesis of inhibitors, the distilled higher fatty acids (DHFAs) or vegetable oils (sunflower, coconut, or corn) derived from the raw materials were loaded into a 250-mL three-necked flask with a diameter of 64 mm. The oil and fat were purified from impurities and water by pre-filtration. Then diethanolamine or diaminoethanol (for beef fat) and triethanolamine (for vegetable oils) were added. The amount of additives was calculated based on the molecular weight of the components and their ratio in the mixture. After the reaction was completed, the mixture was gradually cooled to room temperature while maintaining stirring. The density of the reaction products was determined. The amount of inhibitors formed was 150 ± 20 g. Since all inhibitors are highly viscous liquids, 5% solutions in a mixture of isopropanol and hydrocarbon solvent (working inhibitor solution) were introduced into the corrosive environment.

The flask was placed on a heating device, raising the required reaction temperature. The synthesis time was 4 h. Stirring was performed using an OS20 laboratory stirrer with a 25 mm wing tip at a stirring speed of 180 rpm. The ratio of the reaction vessel's diameter to the stirrer's diameter was 1.3:1. Other synthesis variables are presented in Tables 5 and 6. The processing time, stirring intensity, temperature intervals, and ratios of raw material components were taken based on exploratory and previous studies [17].

Table 5. Synthesis conditions for corrosion inhibitor from vegetable oils.

Sample No.	Synthesis Temperature, °C	Oil: Triethanolamine Ratio, wt/wt
	Sunflower oil	
6.1	120	69.3:30.7
6.2	130	69.3:30.7
6.3	140	69.3:30.7
6.4	150	69.3:30.7
	Corn oil	
7.1	120	65.3:34.7
7.2	130	65.3:34.7
7.3	140	65.3:34.7
7.4	150	65.3:34.7
	Coconut oil	
8.1	120	67.0:33.0
8.2	130	67.0:33.0
8.3	140	67.0:33.0
8.4	150	67.0:33.0

Table 6. Synthesis conditions for corrosion inhibitor from DHFA.

Sample No.	Synthesis Temperature,°C	DHFA: Amine Ratio, wt/wt
	DHFA: diaminoethyl	
9.1	120	82:18
9.2	130	82:18
9.3	140	82:18
10.1	120	90:10
10.2	130	90:10
10.3	140	90:10
	DHFA: diethanolamine	
11.1	120	72:28
11.2	130	72:28
11.3	140	72:28

2.3. Methods of Analysis

The physicochemical properties of the research objects were determined according to international standards [47–51].

As mentioned above, there are various approaches to analyzing the degree of corrosion and the effectiveness of inhibitors. The gravimetric method determined the inhibitor effect based on our developed methodology [52], which consists of determining the weight loss of a metal plate arranged in the medium with and without an inhibitor.

The two-phase medium consisted of an aqueous salt solution and jet fuel. The composition of the aqueous salt solution was as follows: NaCl—163 g/L, $MgCl_2 \cdot 6H_2O$—17 g/L, $Ca(HSO_4)_2 \cdot 2H_2O$—0.14 g/L, $CaCl_2$—34 g/L. The water: jet fuel ratio was 1:9 (wt/wt). This medium simulates water formation in oil production facilities or the corrosive environment formed in water tanks after electric dehydrators.

The inhibitor introduced into the medium was 100 and 200 ppm of the active substance. Under the experimental conditions, this amounted to 0.65 mL and 1.3 mL of a 5% working inhibitor solution per 300 mL medium.

Figure 2 shows the laboratory setup for the investigation of the inhibitor effect. A magnetic stirrer heating element and a contact thermometer regulated and maintained the process temperature within the specified limits. The mixing intensity was controlled by changing the rotation speed of the magnetic stirrer.

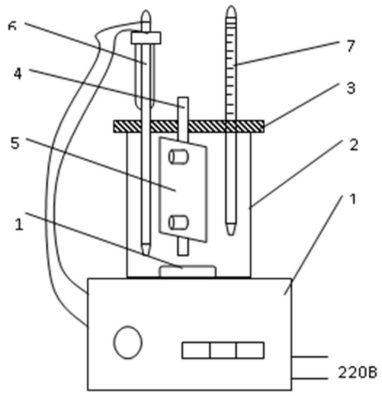


Figure 2. Setup for studying the anticorrosive ability of inhibitors using the gravimetric method. 1—magnetic stirrer; 2—chemical beaker; 3—teflon lid; 4—glass rod; 5—metal plate; 6—contact thermometer; 7—thermometer.

Quantitative assessment of the inhibitor effect (at a specific concentration) on the rate of the corrosion process is characterized by the protective effect Z, which was determined at temperatures of 50, 60, and 70 °C. The protective effect Z is the ratio of the difference in metal corrosion rates in the media without and with an inhibitor to the metal corrosion rate in an aggressive medium without an inhibitor expressed as a percentage:

$$Z = \frac{V_0 - V}{V_0} \cdot 100 \quad (1)$$

where V_0 is the metal corrosion rate in an aggressive environment, $g/(m^2 \cdot h)$, and V is the metal corrosion rate after the addition of inhibitor, $g/(m^2 \cdot h)$.

Corrosion rate V (V_0) $[g/(m^2 \cdot h)]$ was determined as the ratio of the plate weight loss due to corrosion to the plate surface area over a certain period:

$$V\ (V_0) = \Delta m/(S \cdot t), \quad (2)$$

where Δm is the decrease in the metal plate weight due to corrosion, [g]; t is the time of the experiment, [h], equal to 2 h; S is the surface area of the metal plate, [m^2], equal to 0.003 m^2.

To confirm the reliability of the results obtained, the protective effect of inhibitors under certain conditions was determined 3 times using this method. The deviation of the values of the obtained results was no more than 5%, confirming these studies' reproducibility. The average value for each survey was taken as accurate.

The surface microstructure of the studied plates covered with a layer of inhibitor and without it was carried out on a desktop scanning electron microscope CEN NeoScop (Japan). For the study of corrosion inhibitors, an accelerating voltage of about 10 kV was chosen to ensure an optimal balance between image detail and surface integrity. The surface samples were magnified by 5000 times.

3. Results and Discussion

The first series of studies was carried out with the addition of a minimal amount of inhibitor (100 ppm). The protective effect Z was determined at a temperature of 50 °C. This temperature is typical for refinery equipment exposed to corrosive media. The study of the properties of inhibitors based on vegetable oils is given in Table 7.

Table 7. Properties of the synthesized inhibitors based on vegetable oils and triethanolamine.

Sample No.	Reaction Medium Density, kg/m^3	V, g/(m^2·h)	Z, %
Blank (V_0)	-	1.1470 ± 5%	-
	Sunflower oil		
6.1	919 ± 1	1.0360 ± 5%	9.7 ± 5%
6.2	970 ± 1	0.3292 ± 5%	71.3 ± 5%
6.3	978 ± 1	0.2799 ± 5%	75.6 ± 5%
6.4	984 ± 1	0.8820 ± 5%	23.1 ± 5%
	Corn oil		
7.1	975 ± 1	0.9956 ± 5%	13.2 ± 5%
7.2	981 ± 1	0.3498 ± 5%	69.5 ± 5%
7.3	982 ± 1	0.5597 ± 5%	51.2 ± 5%
7.4	985 ± 1	0.7456 ± 5%	35.0 ± 5%
	Coconut oil		
8.1	940 ± 1	0.6331 ± 5%	44.8 ± 5%
8.2	958 ± 1	0.3452 ± 5%	69.9 ± 5%
8.3	975 ± 1	0.6022 ± 5%	47.5 ± 5%
8.4	980 ± 1	0.4003 ± 5%	65.1 ± 5%

The inhibitor consumption per 300 mL of corrosive medium was 0.65 mL (100 ppm).

Among raw plant materials, the highest protective effect, 75.6%, was found for sample 6.3 (Table 7). This inhibitor was synthesized from sunflower oil at 140 °C for 4 h with an oil: triethanolamine ratio of 69.3:30.7 (wt/wt). The inhibitor synthesized from corn oil at the same temperature (sample 7.3, Table 7) shows less protective effect by almost 24.5%. Interestingly, the decrease in the synthesis temperature by 10 °C increases its protective effect to 69.4% (sample 7.2, Table 7). At the same temperature, the protective effect of coconut oil (sample 8.2, Table 7), which has the lowest content of unsaturated acids, only eight wt%, is unexpectedly high and reaches 70%. This differs from the literature data [41]. Perhaps the polar groups of the "coconut" inhibitor form bonds with metal atoms, and the long hydrophobic alkyl chains are oriented outward, creating a barrier that prevents the penetration of water, oxygen, and ions. Thus, the coconut oil-based inhibitor provides long-term protection of metal surfaces through a combination of hydrophobicity and adsorption ability. This is practically the level of effect shown by sunflower oil (cf. 71.3%).

So, it is evident that the protective effect of inhibitors synthesized from vegetable oils and triethanolamine strongly depends on the synthesis temperature; for sunflower oil, the

maximum impact is achieved at the synthesis temperature of 140 °C; for corn and coconut oils—at 130 °C.

The difference in corrosion protection efficiency at different synthesis temperatures for each type of oil can be explained by several factors related to the chemical and physical properties of the inhibitor molecules formed at these temperatures.

As the synthesis temperature increases, the rate of chemical reactions between the oil and triethanolamine increases, which can lead to the formation of inhibitors with better adsorption properties on the metal surface. However, beyond a specific temperature, excessive heating can lead to partial oxidation of the inhibitor and/or reactions between acids, reducing the number of active sites and ultimately reducing the inhibitor's effectiveness. The above assumption is confirmed by the increase in the density of the reaction mixture with increasing temperature (molecular weight increases and, consequently, density increases). Therefore, for each type of oil, the efficiency of the inhibitor is achieved at certain synthesis temperatures, which may indicate the optimal ratio between the polar and nonpolar parts of the molecules that form a stable film. The molecules may not be active enough at low synthesis temperatures for effective adsorption on a metal surface. At too high temperatures, the molecules may lose their properties due to the increased molecular weight of the fatty acid alkyl chain (oxidation, ester formation, oligomerization along double bonds).

The properties and protective effect of inhibitors synthesized from beef fat are shown in Table 8. The protective effect of these samples is significantly higher than that of inhibitors from vegetable oils. Depending on synthesis conditions, the value of Z varies from 83.3% (sample 10.2, Table 8) to 95,6% (sample 11.2, Table 8). The best results were obtained for inhibitor synthesized at the temperature of 130 °C and DHFA:diaminoethyl ratio of 82:18 (sample 9.2), DHFA:diaminoethyl ratio of 90:10 (sample 10.2, Table 8), and DHFA: diethanolamine ratio of 72:28 (sample 11.2, Table 8). The protective effect of these samples was 94.1%, 83.3%, and 95,6%, respectively.

Table 8. Properties of the synthesized inhibitors based on beef fat and diaminoethyl or diethanolamine.

Sample No.	Reaction Medium Density, kg/m^3	V, g/(m^2·h)	Z, %
Blank (V0)	-	1.1470 ± 5%	-
	DHFA: diaminoethyl		
9.1	974 ± 1	0.0734 ± 5%	93.6 ± 5%
9.2	979 ± 1	0.0677 ± 5%	94.1 ± 5%
9.3	980 ± 1	0.0860 ± 5%	92.5 ± 5%
10.1	982 ± 1	0.2053 ± 5%	82.1 ± 5%
10.2	984 ± 1	0.1915 ± 5%	83.3 ± 5%
10.3	989 ± 1	0.2110 ± 5%	81.6 ± 5%
	DHFA: diethanolamine		
11.1	975 ± 1	0.0631 ± 5%	94.5 ± 5%
11.2	978 ± 1	0.0505 ± 5%	95.6 ± 5%
11.3	979 ± 1	0.0803 ± 5%	93.0 ± 5%

The inhibitor consumption per 300 mL of corrosive medium was 0.65 mL (100 ppm).

The effect of synthesis temperature on the quality of DHFA-based inhibitors is similar to that of vegetable oils-based inhibitors:

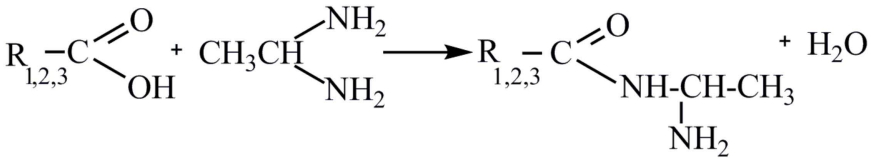
- with increasing temperature, the density (and, accordingly, the molecular weight) of the products increases;
- the temperature of 130 °C is optimal for achieving maximum molecular activity, which contributes to forming a stable protective film.

The polar end of the molecule containing amino groups is adsorbed to the metal surface through electrostatic and chemical interactions, mainly through the formation of donor-nor-acceptor bonds between the nitrogen atoms of amine molecules and the metal. The hydrophobic end of the molecule (hydrocarbon chain) helps to shield the metal surface from aggressive corrosive agents.

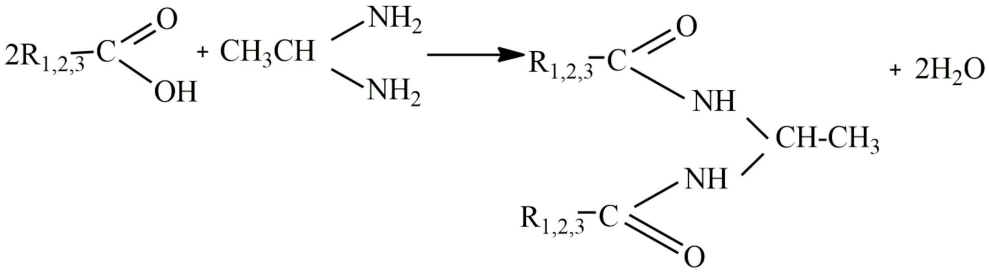
With a higher content of amines in the reaction mixture, the protective effect of the resulting product improves. Samples with a DHFA: diaminoethyl ratio equal to 72:28 (No. 9) show a higher level of efficiency, as they provide a better adsorption protective effect than samples with a lower amine content (No. 10). The corrosion inhibitor containing alcohol-amine groups (DHFA+diethanolamine, No. 11) shows better protective properties than the inhibitors based on DHFA+diaminoethyl (No. 9).

The primary reaction during the synthesis occurs between the carboxyl group of fatty acids and amino groups of amines (triethanolamine, diaminoethanol, or diethanolamine). During the condensation process, the carboxyl group (-COOH) interacts with the amino group (-NH_2) to form an amide bond (-CONH) and release water. This reaction requires elevated temperatures (120–140 °C), which activates dehydration processes and facilitates the formation of stable amides.

The amide bond formed due to the condensation reaction contains a polar amino group (-NH) with a high adsorption capacity on metal surfaces. The nitrogen atom, which is part of the amide group, has a free electron pair, which allows it to interact with active centers on the metal surface through π-orbitals as a result of the reaction of acid and ethyl diamine, monosubstituted or disubstituted ethylamide can be obtained (see Scheme 1).



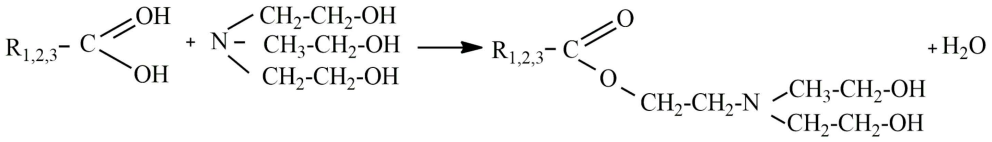
(**a**)



(**b**)

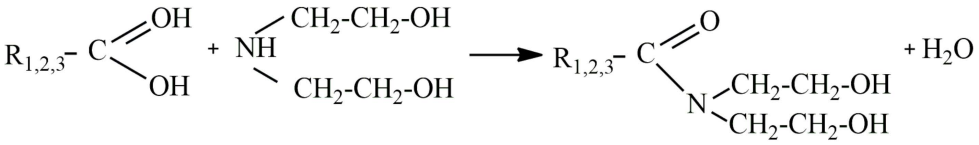
Scheme 1. Reaction of fatty acid and ethyl diamine with the production of monosubstituted (**a**) or disubstituted ethylamide (**b**): R_1 is C_nH_{2n+1}, R_2 is C_nH_{2n-1}, and R_3 is C_nH_{2n-3}—fatty acid alkyl chain.

According to the results presented in this paper and our previous results [17], the participation of triethanolamine in the synthesis process has less impact on the protective ability of resulting compounds. The esterification reaction prevails when fatty acids and triethanolamine interact at 130–150 °C. As a result, triethanolamine ester is formed (see Scheme 2).



Scheme 2. Reaction of fatty acids and triethanolamine with the production of triethanolamine ester: R_1 is C_nH_{2n+1}, R_2 is C_nH_{2n-1}, and R_3 is C_nH_{2n-3}—fatty acid alkyl chain.

The reaction of DHFA and diethanolamine has a more significant effect due to the formation of dihydroxyethylamide of higher fatty acids (see Scheme 3).



Scheme 3. Reaction of fatty acids and diethanolamine with the production of dihydroxyethylamide: R_1 is C_nH_{2n+1}, R_2 is C_nH_{2n-1}, and R_3 is C_nH_{2n-3}—fatty acid alkyl chain.

Thus, the synthesized inhibitors act on the principle of forming a multilayer protective film consisting of the polar and hydrophobic layers. In the polar layer, the amide group is strongly adsorbed on the metal surface through the bond between the nitrogen and metal atoms. In other words, as mentioned above, the protective film formation occurs with the help of the π-orbitals of nitrogen molecules. Nitrogen, part of the inhibitors, is the polar end of the inhibitor molecule, which, "according to the theory of the three-layer mechanism" [18], provides a connection between the polar end of the molecule and the metal surface. The protective effect depends on the strength of this bond.

The hydrophobic layer is a hydrocarbon chain of fatty acids that forms a non-polar outer layer protecting the metal from contact with corrosive agents. The degree of wetting or surface shielding determines its impact on the protective effect. A mixture of higher fatty acids provides the middle protective layer. The hydrocarbon radical, which has hydrophobic properties, is directed toward the aggressive medium and repels corrosive particles. It also shields the metal surface and enhances its blocking. The hydrophobic layer further reduces the diffusion of corrosive particles and prevents the release of metal ions, such as Fe^{2+}, which can catalyze corrosion processes.

Given the better performance of animal fat-based inhibitors, further studies were conducted with DHFA-based inhibitors.

It is well known that the higher the temperature, the greater the corrosive activity of the medium [53,54]. Considering relatively high values of Z, we decided to examine the protective effect of the DHFA-based inhibitors at higher temperatures. The experimental results are shown in Table 9.

As expected, the increase in temperature from 50 °C to 70 °C decreases the protective effect by an average of 3–5%. However, even the lowest value of protective effect observed for animal fat-based inhibitors is comparable with the highest value obtained for inhibitors synthesized from vegetable oils (76.0% for beef fat vs. 75.6% for sunflower oil).

Given the above results, further investigations were carried out with the samples based on HDFA from beef fat.

So, three samples showing the highest value of Z were selected to ensure which one was the best. They were compared under the same conditions, but their consumption changed. It was increased to 1.3 mL per 300 mL of corrosive medium (200 ppm) to maximize

the protective effect while maintaining the economic feasibility of inhibitor use. The results are shown in Table 10.

Table 9. Protective effect of the synthesized inhibitors at different temperatures.

Sample No. According to Table 5	50 °C		60 °C		70 °C	
	V, g/(m²·h)	Z, %	V, g/(m²·h)	Z, %	V, g/(m²·h)	Z, %
Blank(V0)	1.1470 ± 5%	-	1.1960 ± 5%	-	1.2007 ± 5%	-
9.1	0.0734 ± 5%	93.6 ± 5%	0.1017 ± 5%	91.5 ± 5%	0.1237 ± 5%	89.7 ± 5%
9.2	0.0677 ± 5%	94.1 ± 5%	0.0945 ± 5%	92.1 ± 5%	0.1213 ± 5%	89.9 ± 5%
9.3	0.0860 ± 5%	92.5 ± 5%	0.1124 ± 5%	90.6 ± 5%	0.1381 ± 5%	88.5 ± 5%
10.1	0.2053 ± 5%	82.1 ± 5%	0.2380 ± 5%	80.1 ± 5%	0.2618 ± 5%	78.2 ± 5%
10.2	0.1915 ± 5%	83.3 ± 5%	0.2260 ± 5%	81.1 ± 5%	0.2642 ± 5%	78.0 ± 5%
10.3	0.2110 ± 5%	81.6 ± 5%	0.2404 ± 5%	79.9 ± 5%	0.2882 ± 5%	76.0 ± 5%
11.1	0.0631 ± 5%	94.5 ± 5%	0.0849 ± 5%	92.9 ± 5%	0.1105 ± 5%	90.8 ± 5%
11.2	0.0504 ± 5%	95.6 ± 5%	0.0730 ± 5%	93.9 ± 5%	0.0997 ± 5%	91.7 ± 5%
11.3	0.0802 ± 5%	93.0 ± 5%	0.1076 ± 5%	91.0 ± 5%	0.1417 ± 5%	88.2 ± 5%

The inhibitor consumption per 300 mL of corrosive medium was 0.65 mL (100 ppm).

Table 10. Comparison of the synthesized inhibitors with the highest protective effect.

Sample No. According to Table 5	50 °C		60 °C		70 °C	
	V, g/(m²·h)	Z, %	V, g/(m²·h)	Z, %	V, g/(m²·h)	Z, %
Blank (V0)	1.1470 ± 5%	-	1.1960 ± 5%	-	1.2007 ± 5%	-
9.2	0.0206 ± 5%	98.2 ± 5%	0.0466 ± 5%	96.1 ± 5%	0.0756 ± 5%	93.7 ± 5%
10.2	0.1503 ± 5%	86.9 ± 5%	0.1854 ± 5%	84.5 ± 5%	0.2149 ± 5%	82.1 ± 5%
11.2	0.0092 ± 5%	99.2 ± 5%	0.0347 ± 5%	97.1 ± 5%	0.0504 ± 5%	95.8 ± 5%

The inhibitor consumption per 300 mL of corrosive medium was 1.3 mL (200 ppm).

The increase in inhibitor consumption increases the protective effect but does not change the previously observed regularities. The inhibitor synthesized at 130 °C and DHFA: diethanolamine ratio of 72:28 (sample 11.2, Table 10) exhibits the best protective properties at all tested temperatures. This inhibitor was selected for comparison with five commercial corrosive inhibitors. The results are represented in Table 11.

Table 11. Comparison of the protective effect of commercial and synthesized inhibitors at different temperatures.

Sample No. According to Tables 2 and 5	50 °C		60 °C		70 °C	
	V, g/(m²·h)	Z, %	V, g/(m²·h)	Z, %	V, g/(m²·h)	Z, %
Blank (V0)	1.1470 ± 5%	-	1.1960 ± 5%	-	1.2007 ± 5%	-
1	0.0963 ± 5%	91.6 ± 5%	0.1304 ± 5%	89.1 ± 5%	0.1561 ± 5%	87.0 ± 5%
2	0.0401 ± 5%	96.5 ± 5%	0.0610 ± 5%	94.9 ± 5%	0.0828 ± 5%	93.1 ± 5%
3	0.0057 ± 5%	99.5 ± 5%	0.0251 ± 5%	97.9 ± 5%	0.0504 ± 5%	95.8 ± 5%
4	0.0528 ± 5%	95.4 ± 5%	0.0742 ± 5%	93.8 ± 5%	0.0961 ± 5%	92.0 ± 5%
5	0.0252 ± 5%	97.8 ± 5%	0.0490 ± 5%	95.9 ± 5%	0.0756 ± 5%	93.7 ± 5%
11.2	0.0092 ± 5%	99.2 ± 5%	0.0347 ± 5%	97.1 ± 5%	0.0504 ± 5%	95.8 ± 5%

The inhibitor consumption per 300 mL of corrosive medium was 1.3 mL (200 ppm).

The comparison showed that the protective effect of the inhibitor synthesized from beef fat is close to that of the inhibitor Dodigen 481 (No. 3, see Table 2) and even higher than other known inhibitors (95.8–99.2% vs. 87.5–97.8%).

The surface microstructure of the studied plates was studied using an electron microscope at a magnification of 5000 times. Microscopic studies of the surface are presented in Figure 3.

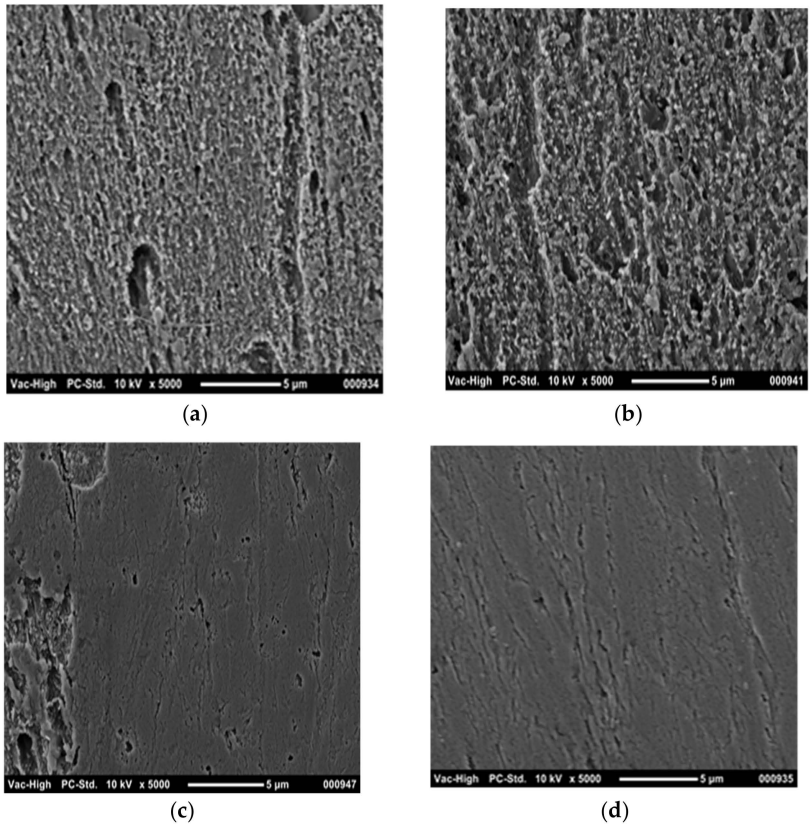


Figure 3. Microscopic studies of the metal surface at a magnification of 5000 times: (**a**) metal before experiments; (**b**) in a corrosive environment without an inhibitor; (**c**) in an environment with a synthesized inhibitor (No. 10.2); (**d**) in an environment with the inhibitor Dodigen 481 (No. 3).

At a magnification of 5000 times, it is seen that the surface of the plate, which was in an environment without an inhibitor, is uniformly corroded (Figure 3a,b). At the same time, even the surface of the metal (Figure 3a), which was stored in the air, was corroded. When the synthesized inhibitor is introduced into the environment, the surface of the plate looks solid without corrosion damage (Figure 3c). Notably, the degree of protection of the synthesized inhibitor is relatively high and close to the degree of protection of the industrial corrosion inhibitor Dodigen 481 (Figure 3d).

Microscopic studies also confirmed the possibility of the synthesized inhibitors' sorption on the metal surface. The inhibitor was adsorbed on the metal surface by the functional groups of nitrogen and oxygen adjacent to the skeletal structure of the molecule. Side branches in the form of oxyethylene links intertwine on the surface, forming an impermeable protective film that provides insulation of the cathodic and anodic sections, and hydrocarbon radicals hydrophobized the surface and limit the access of electrolyte ions to the steel surface. The sorbed film of the corrosion inhibitor formed on the surface of the steel sample fills the steel surface with colloidal particles, forming a protective layer that has the appearance of dense chains.

In the case of using the synthesized inhibitor, the number density of such chains is relatively high. The photographs of the sample (Figure 3c), which was in an environment with a synthesized inhibitor, show two areas of the surface: smooth, which did not corrode due to the adsorption of the inhibitor, and corroded, where it was not adsorbed. The results of microscopic studies confirmed the conclusions drawn based on the results of gravimetric studies about the ability of the studied substances to protect the metal surface from corrosion, creating an adsorption protective layer on the metal surface. Therefore, DHFA-based corrosion inhibitors' effectiveness depends on amide groups' ability to form a

strong polar bond with the metal surface and the hydrophobic properties of hydrocarbon chains that ensure the effective blocking of corrosive agents.

Finally, the environmental and economic aspects of the work should be considered. The price of industrial corrosion inhibitors is a trade secret. However, the authors can provide approximate costs for the studied compounds based on their cooperation experience with Ukrainian oil refineries and inhibitor manufacturers. A corrosion inhibitor based on polyamine acid amides costs 6500–7200 euros/ton. At the same time, the price of a corrosion inhibitor made of beef fat can be 3500–4000 euros/ton. That is, using alternative natural resources will allow the utilization of animal waste and the production of bio-friendly compounds and provide a significant economic effect. This, in turn, makes it attractive to introduce large-scale production and use of the corrosion inhibitors under study.

Organic corrosion inhibitors (based on natural raw materials), in turn, have several significant advantages that can make them more effective under certain conditions. Natural inhibitors derived from vegetable or animal fats are biodegradable and do not harm the environment as microorganisms decompose. This significantly reduces the risk of contamination of water and soil resources, unlike synthetic inhibitors that can accumulate in natural environments, causing toxic effects.

Thus, due to their environmental safety, biodegradability, and self-healing ability, organic corrosion inhibitors can be more effective than synthetic ones in most cases, especially when maintaining stability at low and medium temperatures or in environments with low chemical activity. They are economically advantageous due to lower wastewater treatment costs and reduced risks of ecosystem pollution.

4. Conclusions

This study emphasizes the prospects of using inhibitors based on organic raw materials in the industry, which contributes to the development of sustainable technologies and compliance with environmental requirements. New corrosive inhibitors based on natural raw materials were obtained under different conditions and with varying ratios of the components. The inhibitors synthesized from vegetable oils and triethanolamine were found to have a slight protective effect against metal corrosion compared with inhibitors based on distilled higher fatty acids derived from beef fat and diethanolamine. The best results were obtained for the sample with DHFA: amine ratio of 72:28 (wt/wt) synthesized at a temperature of 130 °C and time of 4 h. It demonstrates a 99% protective effect at the corrosive medium temperature of 50 °C. The increase in temperature to 70 °C slightly decreases the impact to 95.6%.

Synthesized inhibitors are as good as, in some cases, even better than well-known commercial inhibitors. Using inexpensive alternative resources (fats, vegetable oils, waste from their production and processing) to obtain effective corrosion inhibitors will reduce their price by approximately half. The lower cost of the studied corrosion inhibitors makes the possibility of their further industrial implementation extremely promising.

Studies have also shown that the content of unsaturated compounds in the feedstock of plant origin has virtually no effect on the protective properties of the synthesized compounds. Therefore, vegetable oils can also be a promising raw material for producing N-containing corrosion inhibitors in the case of obtaining amides based on them. Thus, future research will aim to achieve higher protective properties of compounds synthesized based on Ukraine's most common vegetable oils (e.g., sunflower, rapeseed) and diethanolamine. Moreover, based on 1–2 most effective corrosion inhibitors, it is necessary to study the mechanism of their action and the effectiveness of equipment protection using a different range of studies described in Section 1. Introduction. It is equally important to compare the biodegradation rate of natural inhibitors with industrial ones. Finally, the research will

aim to integrate natural inhibitors into industrial processes, including equipment operation under challenging conditions (high temperatures, extremely aggressive environment).

Author Contributions: S.P.: Conceptualization, Methodology, Formal analysis, Data curation, Writing—original draft, Writing—review and editing, Supervision; O.R.: Conceptualization, Methodology, Investigation; P.T.: Methodology, Resources, Project administration; V.R.: Validation, Writing—review and editing, Software, Writing—original draft; D.M.: Formal analysis, Data curation, Writing—review and editing; Y.R.: Resources, Validation; H.O.: Resources, Validation; Y.P.: Software, Formal analysis. All authors have read and agreed to the published version of the manuscript.

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References

1. Pyshyev, S.; Miroshnichenko, D.; Chipko, T.; Donchenko, M.; Bogoyavlenska, O.; Lysenko, L.; Miroshnychenko, M.; Prysiazhnyi, Y. Use of Lignite Processing Products as Additives to Road Petroleum Bitumen. *Chem. Eng.* **2024**, *8*, 27. [CrossRef]
2. Casau, M.; Dias, M.F.; Matias, J.C.O.; Nunes, L.J.R. Residual Biomass: A Comprehensive Review on the Importance, Uses and Potential in a Circular Bioeconomy Approach. *Resources* **2022**, *11*, 35. [CrossRef]
3. Pstrowska, K.; Łużny, R.T.; Fałtynowicz, H.; Jaroszewska, K.; Postawa, K.; Pyshyev, S.; Witek-Krowiak, A. Unlocking sustainability: A comprehensive review of up-recycling biomass waste into biochar for environmental solutions. *Chem. Chem. Technol.* **2024**, *18*, 211–231. [CrossRef]
4. Filho, J.J.d.S.; Gaspar, P.D.; Souza, A.C.d.; Paço, A.d. Circular Economy in Guaiamum and Uçá Crab Waste in Brazil: Potential By-Products—A Systematic Literature Review. *Resources* **2024**, *13*, 46. [CrossRef]
5. Szpilko, D.; de la Torre Gallegos, A.; Jimenez Naharro, F.; Rzepka, A.; Remiszewska, A. Waste Management in the Smart City: Current Practices and Future Directions. *Resources* **2023**, *12*, 115. [CrossRef]
6. Rai, M.; Pant, G.; Pant, K.; Aloo, B.N.; Kumar, G.; Singh, H.B.; Tripathi, V. Microplastic Pollution in Terrestrial Ecosystems and Its Interaction with Other Soil Pollutants: A Potential Threat to Soil Ecosystem Sustainability. *Resources* **2023**, *12*, 67. [CrossRef]
7. Bannikov, L.; Miroshnichenko, D.; Pylypenko, O.; Pyshyev, S.; Fedevych, O.; Meshchanin, V. Coke quenching plenum equipment corrosion and its dependents on the quality of the biochemically treated water of the coke-chemical production. *Chem. Chem. Technol.* **2022**, *16*, 328–336. [CrossRef]
8. Saji, V.S.; Umoren, S.A. (Eds.) *Corrosion Inhibitors in the Oil and Gas Industry*; John Wiley & Sons: Hoboken, NJ, USA, 2020; Available online: https://onlinelibrary.wiley.com/doi/book/10.1002/9783527822140 (accessed on 14 February 2020).
9. Sriplai, N.; Sombatmankhong, K. Corrosion inhibition by imidazoline and imidazoline derivatives: A review. *Corros. Rev.* **2023**, *41*, 237–262. [CrossRef]
10. Kousar, K.; Ljungdahl, T.; Show, A.W. An Exemplar Imidazoline Surfactant for Corrosion Inhibitor Studies: Synthesis, Characterization, and Physicochemical Properties. *JSD* **2019**, *23*, 225–234. [CrossRef]
11. Jalab, R.; Saad, M.; Benali, A.; Hussein, I.A.; Khaled, M. Biodegradable polysaccharide grafted polyacrylamide inhibitor for corrosion in CO_2- saturated saline solution. *Heliyon* **2023**, *9*, e20304. [CrossRef]
12. Lavanya, M.; Avryl, A. Surfactants as biodegradable sustainable inhibitors for corrosion control in diverse media and conditions: A comprehensive review. *Sci. Total Environ.* **2024**, *908*, 168407. [CrossRef]
13. Obot, I.B.; Moses, M.S.; Umoren, S.A.; Suleiman, R.; Elanany, M.; Alanazi, N.M.; Sorour, A.A. Progress in the development of sour corrosion inhibitors: Past, present, and future perspectives. *JIEC* **2019**, *79*, 1–18. [CrossRef]
14. Obot, I.B.; Ikenna, B.; Onyeachu, S.A.; Umoren, M.A.; Quraishi, A.A.; Sorour, T.; Aljeaban, N.; Wang, Q. High temperature sweet corrosion and inhibition in the oil and gas industry: Progress, challenges and future perspectives. *J. Pet. Eng.* **2020**, *185*, 106469. [CrossRef]
15. Goni, L.; Mazumder, M.; Green Corrosion Inhibitors. 30 April 2019. Available online: https://www.intechopen.com/chapters/63755 (accessed on 30 April 2019).
16. Shang, Z.; Zhu, J. Overview on plant extracts as green corrosion inhibitors in the oil and gas fields. *J. Mater. Res. Technol.* **2021**, *15*, 5078–5094. [CrossRef]
17. Topilnytskyy, P.; Romanchuk, V.; Yarmola, T. Production of Corrosion Inhibitors for Oil Refining Equipment Using Natural Components. *Chem. Chem. Tech.* **2018**, *12*, 400–404. [CrossRef]

18. Marzorati, S.; Verotta, L.; Verotta, L. Green Corrosion Inhibitors from Natural Sources and Biomass Wastes. *Molecules* **2019**, *24*, 48. [CrossRef] [PubMed]
19. Barreto, L.S.; de Almeida, T.F.; Santos, A.d.M.; Tokumoto, M.S.; Cotting, F.; Capelossi, V.R. Evaluation of vegetables residues as corrosion inhibitors. *Res. Soc.* **2021**, *10*, 2525–3409. [CrossRef]
20. Sun, Z.; Singh, A.; Xu, X.; Chen, S.; Liu, W.; Lin, Y. Inhibition effect of pomelo peel extract for N80 steel in 3.5% NaCl saturated with CO_2 solution. *Rev. Chem. Intermed.* **2017**, *11*, 6719–6736. [CrossRef]
21. Su, F.; Gu, M.; Zhao, J. Inhibition of carbon steel corrosion in solution saturated with CO_2 by ginkgo leaves extract. *J. Hebei Univ. Eng. Nat. Sci. Ed.* **2016**, *36*, 264–268.
22. Pogrebova, I.S. *Monograph: Model of Adsorption of Organic Compounds on Metals, Based on the Concept of Formation of Complexes with Charge Transfer, and Their Use in the Selection of Corrosion Inhibitors. Promising Materials and Processes in Applied Electrochemistry*; KNUTD: Kyiv, Ukraine, 2018; pp. 195–214. (In Ukrainian)
23. Diaz, E.F.; Gonzalez-Rodriguez, J.G.; Martinez-Villafañe, A.; Gaona-Tiburcio, C. H_2S corrosion inhibition of an ultra high strength pipeline by carboxyethyl-imidazoline. *J. Appl. Electrochem.* **2010**, *40*, 1633. [CrossRef]
24. El-Lateef, H.M.A. Novel Natural Surfactant-Based Fatty Acids and Their Corrosion-Inhibitive Characteristics for Carbon Steel-Induced Sweet Corrosion: Detailed Practical and Computational Explorations. *Front. Mater.* **2022**, *9*, 843438. [CrossRef]
25. Palimi, M.J.; Tang, Y.; Alvarez, V.; Kuru, E.; Li, D.Y. Green corrosion inhibitors for drilling operation: New derivatives of fatty acid-based inhibitors in drilling fluids for 1018 carbon steel in CO_2-saturated KCl environments. *Mater. Chem. Phys.* **2022**, *288*, 126406. [CrossRef]
26. Swathi, P.N.; Rasheeda, K.; Samshuddin, S.; Alva, V. Fatty acids and its derivatives as corrosion inhibitors for mild steel—An overview. *Asian Sci. Res.* **2017**, *7*, 301–308. [CrossRef]
27. Elabar, D.; Elgazali, A.; Gebril, M.; Haidar, F.; Esmaael, R.; Ahmad, I. The Comparative Corrosion Inhibition tendency of Imidazolines Prepared from Fatty Acids of Carbon Chain 16 or 18 with Diethylene Triamine. *IJCS* **2023**, *13*, 86–93.
28. Desimone, M.P.; Gordillo, G.; Simison, S.N. The effect of temperature and concentration on the corrosion inhibition mechanism of an amphiphilic amido-amine in CO_2 saturated solution. *Corros. Sci.* **2011**, *53*, 4033–4043. [CrossRef]
29. Solmaz, R.; Salc, A.; Dursun, Y.A.; Kardaş, G. A comprehensive study on the adsorption, corrosion inhibition efficiency and stability of acriflavine on mild steel in 1 M HCl solution. *Colloids Surf. A: Physicochem. Eng. Asp.* **2023**, *674*, 131908. [CrossRef]
30. Huang, W.; Tang, Z.; Liu, X.; Liu, L.; Zhong, H.; Yu, Y.; Chen, H.; Wang, C.; Jiang, Q.; Ye, Y.W.; et al. A green and effective anti-corrosion and anti-microbial inhibitor of citric acid-based carbon dots: Experiment and mechanism analysis. *J. Mater. Res. Technol.* **2024**, *32*, 2149–2159. [CrossRef]
31. Ye, Y.; Zhang, D.; Zou, Y.; Zhao, H.; Chen, H. A feasible method to improve the protection ability of metal by functionalized carbon dots as environment-friendly corrosion inhibitor. *J. Clean. Prod.* **2020**, *264*, 121682. [CrossRef]
32. Tang, Z.; Huang, W.; Liu, L.; Li, H.; Meng, H.; Zeng, T.; Ye, X.; Jiang, Q.; Ye, Y.W.; Liu, Y. Study on structure and molecular scale protection mechanism of green Ce, N-CDs anti-bacterial and anti-corrosive inhibitor. *J. Mater. Res. Technol.* **2024**, *28*, 3868–3881. [CrossRef]
33. Zou, C.J.; Tang, Q.W.; Zhao, P.W.; Guan, E.D.; Wu, X.; Ye, H. Further study on the inclusion complex of 2-phosphonobutane-1,2,4-tricarboxylic acid with bcyclodextrin: A new insight of high inhibition efficiency for protecting steel corrosion. *J. Petrol. Sci. Eng.* **2013**, *103*, 29–35. [CrossRef]
34. Zhang, H.H.; Chen, Y. Experimental and theoretical studies of benzaldehyde thiosemicarbazone derivatives as corrosion inhibitors for mild steel in acid media. *J. Mol. Str.* **2019**, *1177*, 90–100. [CrossRef]
35. Berdimurodov, E.; Kholikov, A.; Akbarov, K.; Guo, L.; Kaya, S.; Katin, K.P.; Verma, D.K.; Rbaa, M.; Dagdag, O.; Haldhar, R. Novel bromide–cucurbit [7] uril supramolecular ionic liquid as a green corrosion inhibitor for the oil and gas industry. *JEAC.* **2021**, *901*, 115794. [CrossRef]
36. Haldhar, R.; Raorane, C.J.; Mishra, V.K.; Periyasamy, T.; Berisha, A.; Kim, S.-C. Development of different chain lengths ionic liquids as green corrosion inhibitors for oil and gas industries: Experimental and theoretical investigations. *J. Mol. Liq.* **2023**, *372*, 121168. [CrossRef]
37. OEC. Available online: https://oec.world/en/profile/hs/animal-fat?latestTrendsYAxisSelector=log (accessed on 1 December 2024).
38. ReportLinker. Available online: https://www.reportlinker.com/clp/global/457161#block-indicator (accessed on 1 December 2024).
39. USDA. Available online: https://fas.usda.gov/data/production/commodity-group/oilseeds,%20oil (accessed on 1 December 2024).
40. Ukrainian Research Institute of Oils and Fats of the National Academy of Agrarian Sciences of Ukraine. Oil and Fat Industry of Ukraine. *Information and Analytical Bulletin of the Oil and Fat Industry of Ukraine. Scientific publication. Kharkiv, Ukraine*. 2021. Available online: https://www.fatoil.com.ua/images/document/9187574/52021.pdf (accessed on 15 December 2021).
41. Romanchuk, V.; Topilnytskyy, P. Investigation of Reagents with Different Chemical Compositions for Protection of Oil Primary Refining Equipment. *Chem. Chem. Technol.* **2010**, *3*, 231–236. [CrossRef]
42. *DSTU 7809*; Rolled long products, calibrated with special surface treatment of high-quality carbon structural steel. General technical conditions: DP "UkrNDC", Kyiv, Ukraine, 2016. (In Ukrainian)

43. Ibrahimi, B.; Jmiai, L.; Bazzi, S. El Issami Amino acids and their derivatives as corrosion inhibitors for metals and alloys. *Arab. J. Chem.* **2020**, *13*, 740–771. [CrossRef]
44. Roscher, J.; Liu, D.; Xie, X.; Holze, R. Aromatic Metal Corrosion Inhibitors. *Corros. Mater. Degrad.* **2024**, *5*, 513–560. [CrossRef]
45. Abdel-Fatah, T.M.; Abdel-Samad, H.S.; Hassan, A.A.M.; El-Sehiety, H.E.E. Effect of variation of the structure of amino acids on inhibition of the corrosion of low-alloy steel in ammoniated citric acid solutions. *Res. Chem. Intermed.* **2014**, *40*, 1675–1690. [CrossRef]
46. Al-Sabagh, A.M.; Nasser, N.M.; El-Azabawy, O.E.; Tabey, A.E.E. Corrosion inhibition behavior of new synthesized nonionic surfactants based on amino acid on carbon steel in acid media. *J. Mol. Liq.* **2016**, *219*, 1078–1088. [CrossRef]
47. *ASTM D97*; Standard Test Method for Pour Point of Petroleum Products. ASTM International: West Conshohocken, PA, USA, 2022.
48. *ASTM D86*; Standard Test Method for Distillation of Petroleum Products at Atmospheric Pressure. ASTM International: West Conshohocken, PA, USA, 2024.
49. *ASTM D1298*; Standard Test Method for Density, Relative Density, or API Gravity of Crude Petroleum and Liquid Petroleum Products by Hydrometer Method. ASTM International: West Conshohocken, PA, USA, 2023.
50. *ASTM D445*; Standard Test Method for Kinematic Viscosity of Transparent and Opaque Liquids (and Calculation of Dynamic Viscosity). ASTM International: West Conshohocken, PA, USA, 2024.
51. *ASTM D92*; Standard Test Method for Flash and Fire Points by Cleveland Open Cup Tester. ASTM International: West Conshohocken, PA, USA, 2024.
52. Pat. 64703 Ukraine MPK51 C23F 11/10, C10 G 75/00, C10 G 7/00 Method for determining the degree of protection of corrosion inhibitors for oil refinery equipment/Romanchuk V.V.; Topilnytskyi P.I.; applicant and patent owner National University "Lviv Polytechnic". - No. u 2011 06534; appl. 24.05.2011, publ. 10.11.2011, bull. No. 21. Available online: https://base.uipv.org/searchInvRevoke/search.php?action=showsearchresults&page=1&lang=ukr&qp=claims_per_page=10;ch_0=on;qe0=64703; (accessed on 10 November 2011).
53. Ha, M.-G.; Heo, C.-J.; Ahn, J.-H. Monitoring for relative effect of corrosive environmental factor on corrosion rate for steel structural details. *J. Build. Eng.* **2023**, *78*, 107565. [CrossRef]
54. Liu, Y.; Liu, M.; Lu, X.; Wang, Z. Effect of temperature and ultraviolet radiation on corrosion behavior of carbon steel in high humidity tropical marine atmosphere. *Mater. Chem. Phys.* **2022**, *277*, 124962. [CrossRef]

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