QO‘QON DAVLAT PEDAGOGIKA INSTITUTI ILMIY XABARLARI
(2026-yil 1-son)

TABIIY FANLAR

NATURAL SCIENCES

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SYNTHESIS AND THERMODYNAMIC PROPERTIES OF THE PFAQ CORROSION INHIBITOR

https://doi.org/10.70728/qdpi.v08.i01.011

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Abstract.A novel oligomer-type corrosion inhibitor (PFAQ) was synthesized from p-phenylenediamine, formalin, and alpha amino succinate under an inert nitrogen atmosphere. Optimization of the synthesis conditions revealed that the highest yield (≈86–88%) was obtained at a molar ratio of 1:2:2 and a temperature range of 40–65 °C, while higher temperatures significantly reduced the yield. Thermodynamic studies based on Arrhenius kinetics revealed that the activation energy increases with increasing inhibitor concentration, indicating that the corrosion inhibition mechanism is primarily governed by physical adsorption on the metal surface. Negative entropy values imply that the rate-determining step involves association rather than dissociation, leading to a decrease in disorder. Adsorption studies using various isotherms showed that the Langmuir model best

describes the adsorption behavior, with a correlation coefficient close to unity. The adsorption equilibrium constant (K_{ads}) and standard Gibbs free energy ($\Delta G°\_ads$) were calculated in the temperature range of 293–333 K. The negative $\Delta G°\_ads$ values confirm that adsorption is spontaneous, and the magnitude of $\Delta G°\_ads$ indicates a mixed adsorption mechanism involving both physical and chemical adsorption. Overall, PFAQ demonstrates strong adsorption capability and effective corrosion inhibition, making it a promising candidate for protecting steel in aggressive acidic environments.

Keywords: p-phenylenediamine, formalin, alpha amino succinate, FT-IR spectroscopy, semi-empirical quantum chemical methods

Annotatsiya. Inert azot atmosferasida p-fenilendiamin, formalin va alfa-aminokislotalar yordamida yangi oligomer tipidagi korroziya inhibitori (PFAQ) sintez qilindi. Sintez sharoitlarini optimallashtirish shuni ko'rsatdiki, eng yuqori hosil (≈86–88%) 1:2:2 molyar nisbatda va 40–65 °C harorat oralig'ida olingan, yuqori haroratlar esa unumni sezilarli darajada kamaytirgan. Arrenius kinetikasiga asoslangan termodinamik tadqiqotlar shuni ko'rsatdiki, faollashuv energiyasi inhibitor konsentratsiyasining ortishi bilan ortadi, bu esa korroziyani ingibirlash mexanizmi asosan metall yuzasida fizik adsorbsiya bilan boshqarilishini ko'rsatadi. Salbiy entropiya qiymatlari tezlikni belgilovchi bosqich dissotsiatsiya o'rniga assotsiatsiyani o'z ichiga olishini va tartibsizlikning pasayishiga olib kelishini anglatadi. Turli izotermlardan foydalangan holda o'tkazilgan adsorbsiya tadqiqotlari shuni ko'rsatdiki, Langmuir modeli adsorbsiya xatti-harakatlarini eng yaxshi tasvirlaydi, ya’ni korrelyatsiya koeffitsienti birga yaqin. Adsorbsiya muvozanat konstantasi (K_{ads}) va standart Gibbs erkin energiyasi ($\Delta G°_{ads}$) 293–333 K harorat oralig'ida hisoblab chiqilgan. Manfiy $\Delta G°_{ads}$ qiymatlari adsorbsiyaning o'z-o'zidan sodir bo'lishini tasdiqlaydi va $\Delta G°_{ads}$ kattaligi ham fizik, ham kimyoviy adsorbsiyani o'z ichiga olgan aralash adsorbsiya mexanizmini ko'rsatadi. Umuman olganda, PFAQ kuchli adsorbsiya qobiliyatini va samarali korroziya ingibirlashini namoyish etadi, bu esa uni agressiv kislotali muhitda po'latni himoya qilish uchun istiqbolli nomzodga aylantiradi.

Kalit so'zlar: p-fenilendiamin, formalin, alfa aminoksinat, FT-IR spektroskopiyasi, yarim empirik kvant kimyoviy usullar

Аннотаци.Новый ингибитор коррозии олигомерного типа (PFAQ) был синтезирован из п-фенилендиамина, формалина и альфа-аминосукцината в инертной азотной атмосфере. Оптимизация условий синтеза показала, что наибольший выход (≈86–88%) был получен при молярном соотношении 1:2:2 и диапазоне температур 40–65 °C, в то время как более высокие температуры значительно снижали выход. Термодинамические исследования, основанные на кинетике Аррениуса, показали, что энергия активации увеличивается с увеличением концентрации ингибитора, что указывает на то, что механизм ингибирования коррозии в основном определяется физической адсорбцией на поверхности металла. Отрицательные значения энтропии

подразумевают, что лимитирующей стадией является ассоциация, а не диссоциация, что приводит к уменьшению разупорядоченности. Исследования адсорбции с использованием различных изотерм показали, что модель Лангмюра наилучшим образом описывает поведение адсорбции с коэффициентом корреляции, близким к единице. Константа адсорбционного равновесия (Kads) и стандартная свободная энергия Гиббса ($\Delta G°_{ads}$) были рассчитаны в диапазоне температур 293–333 К. Отрицательные значения $\Delta G°_{ads}$ подтверждают спонтанный характер адсорбции, а величина $\Delta G°_{ads}$ указывает на смешанный механизм адсорбции, включающий как физическую, так и химическую адсорбцию. В целом, PFAQ демонстрирует высокую адсорбционную способность и эффективное ингибирование коррозии, что делает его перспективным кандидатом для защиты стали в агрессивных кислых средах.

Ключевые слова: р-фенилендиамин, формалин, альфа-аминосукцинат, FT-IR - спектроскопия с преобразованием Фурье, полуэмпирические квантово-химические методы

INTRODUCTION. Metal corrosion is a widespread problem that reduces service life and increases maintenance costs. Traditional synthetic inhibitors can be toxic and environmentally harmful, motivating the search for greener solutions. Plant extracts and plant-based nanoparticles offer promising, sustainable corrosion inhibition due to their natural active constituents and low toxicity[1,2]. Three amino acids with different functional groups—L-methionine, L-arginine, and L-aspartic acid—were investigated as corrosion inhibitors for carbon steel in 0.5 M HCl in the presence of potassium iodide. Electrochemical measurements, surface analyses, and theoretical calculations revealed a pronounced synergistic inhibition effect between the amino acids and KI, leading to significantly enhanced inhibition efficiency, particularly at elevated temperatures. The synergistic mechanism and the influence of amino acid molecular structure on inhibition performance were systematically analyzed[3,4]. Two amino acid–based green corrosion inhibitors, 4-(tert-butylbenzoyl)methionine and 4-(tert-butylbenzoyl)cysteine, were synthesized via a one-step acylation method and evaluated for Q235 steel in 1 M HCl. Both inhibitors significantly reduced corrosion rates by chemical adsorption, with P-Meth exhibiting higher inhibition efficiency, confirmed by electrochemical, surface, and molecular dynamics analyses[5,6]. Amino acid alkali salts are eco-friendly, stable, and low-cost additives for acidic corrosion inhibitors. This study shows that taurine and aminohexanoic acid reduce Co and Ni leaching and enhance the performance of carboxylic and phosphonic acid inhibitors. Thus, they are promising sustainable alternatives to conventional alkaline additives[7,8]. Metal corrosion causes significant economic losses and safety hazards, yet effective and water-soluble inhibitors remain limited. This study evaluates two quinoxaline derivatives, BrSQX and MeSQX, as inhibitors for mild steel in

1.0 M HCl using weight loss, electrochemical, surface, and theoretical analyses. Both compounds showed high inhibition efficiency, with MeSQX performing slightly better, and their adsorption followed the Langmuir isotherm, indicating chemisorption and protective film formation[9,10].

This work aims to study the synthesis and structure of a new type of corrosion inhibitor based on p-phenylenediamine.

MATERIALS. Compounds of p-paraphenylenediamine, formalin, and alanin were used for this study. All chemical reagents were purchased as "chemically pure" from "Merit Chemicals" company.

METHODS. ***IR- analysis***. The IR spectra of the synthesized compounds were recorded using a Bruker Tensor 27 FTIR spectrometer (Germany) in the range of 4000–400 cm^{-1}.

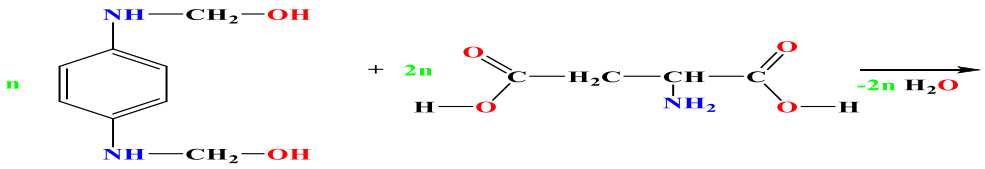
SYNTHESIS OF THE CORROSION INHIBITOR (PFAQ)

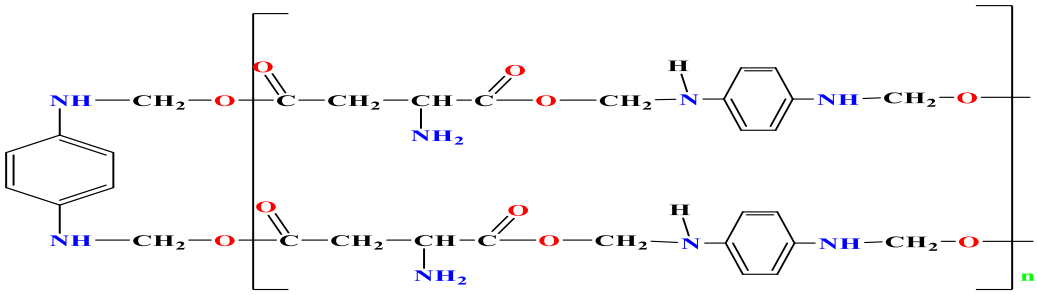
In the synthesis of this corrosion inhibitor, 0.1 mol of p-phenylenediamine and 0.2 mol of formalin were stirred under reflux in a nitrogen atmosphere for 30 minutes at a temperature range of 44–50 °C. Then, 0.1 mol of the initially formed compound and 0.2 mol of alpha amino succinic acid solution dissolved in double-distilled water were slowly added dropwise while stirring. During this process, the temperature was maintained in the range of 55–65 °C.

Table-1.

Dependence of the yield of PFAQ corrosion inhibitor synthesis on the molar ratio of the initial reactants and temperature

p-phenylenediamine *formalin*+ alpha amino succinate	Temperature 0C	Yield %	Temperature 0C	Yield %
1:1:1	40÷65	56.67	65≤t	41.15
1:2:2		86.37		82.36
2:2:1		73.21		61.26
2:1:3		55.62		32.56
1:2:1		69.43		42.25





As shown in Table 1, the highest yield was obtained at temperatures in the range of 40–65 °C and an initial molar ratio of 1:2:2. When the temperature exceeded 65 °C, the product yield decreased significantly.

Results and Its Discussion

Kinetic Study Results of the Inhibitors

Knowing the thermodynamic energy of the system is very important for determining the mechanisms of corrosion inhibitors. Accordingly, the energy of the thermodynamic system in which corrosion occurs is measured in both inhibited and uninhibited states at different inhibitor concentrations. This can be determined using the Arrhenius equation.

$$CR = A\exp\left(\frac{-\mathrm{Ea}}{\mathrm{RT}}\right) \qquad (2.6)$$

Here, Ea represents the activation energy expressed in kJ/mol, RRR is the universal gas constant with a value of 8.314 J/mol·K, TTT is the temperature expressed in Kelvin, and AAA is the pre-exponential factor.

When comparing the activation energy (Ea) of inhibited solutions with that of the uninhibited solution, it can be observed that the addition of the inhibitor increases the activation energy, and as the inhibitor concentration increases, the activation energy also increases. A higher activation energy is indicative of physical adsorption, whereas unchanged or lower activation energy suggests chemical adsorption.

The activation energy (E_a) values increased significantly with increasing inhibitor concentration. Therefore, in corrosion prevention, the primary role of the inhibitor is to adsorb physically onto the metal surface. From the highly negative values of entropy, it can be inferred that during the rate-determining step of corrosion, the formation of the activated complex is more associated with association rather than dissociation, which leads to a decrease in disorder.

The adsorption process can be defined as the adsorption of inhibitor molecules on the metal surface accompanied by the desorption of water molecules, and it can also be described as an exchange process. From this, it can be understood that the inhibitor adsorbs

onto the metal surface and covers it; as the inhibitor concentration increases, the surface coverage (θ) also increases, leading to higher coverage and improved efficiency. The surface coverage θ is mainly a parameter that reflects the inhibitor’s effectiveness and is considered up to 100%. Several types of isotherms are used to describe this process. The Freundlich adsorption isotherm was obtained and can be expressed as follows:

$$\theta = K_{ads}C^{n} \qquad (2.7)$$

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$$log\theta = logK_{ads} + nlogC \qquad (2.8)$$

Here, 0<n<1; θ–sirt is the surface coverage; C is the inhibitor concentration; and K_{ads}-is the equilibrium constant of the adsorption–desorption process.

Additionally, the adsorption behavior of these corrosion inhibitors was also investigated using the following isotherms:

Lengmyur: $$\frac{C_{\text{ing}}}{\theta} = \frac{1}{K_{ads}} + C_{\text{ing}} \qquad (2.9)$$

Frumkin: $$\frac{\theta_{grav}}{1-\theta_{grav}} exp(-2f\theta_{grav}) = K_{ads}C_{ing} \qquad (2.10)$$

Tyomkin: $$exp(f\theta_{grav}) = K_{ads}C_{ing} \qquad (2.11)$$

Here, C_{ing} is the inhibitor concentration in the solution (mg/l), θ-is the degree of surface coverage, and K_{ads} is the adsorption equilibrium constant.

The standard free energy of adsorption ($\Delta G°_{ads}$) is calculated using the following equation (2.12):

$$\Delta G^{o}_{ads} = \Delta H^{o}_{ads} - T\Delta S^{o}_{ads} \qquad (2.12)$$

Here, R is the universal gas constant, T is the absolute temperature in Kelvin, and ρ_W is the density of water in g/L. The values of g/l. k_{ads} va $\Delta G°_{ads}$ are calculated using the adsorption isotherm equations given above.

The negative value of $\Delta G°_{ads}$ indicates that adsorption has reached a high level. For the Langmuir adsorption isotherm, $\Delta G°_{ads}$ ranged from −40.5 kJ mol⁻¹ to −43 kJ mol⁻¹. For the Temkin isotherm, the $\Delta G°_{ads}$ values ranged from −32 kJ mol⁻¹ to −40 kJ mol⁻¹. A value of $\Delta G°_{ads}$ around −40 kJ mol⁻¹ corresponds to a balance between chemical and physical adsorption. It is generally accepted that if $\Delta G°_{ads}$ is up to −20 kJ mol⁻¹, the adsorption is physical (physisorption), while values more negative than −40 kJ mol⁻¹ indicate chemical adsorption (chemisorption

The Frumkin isotherm for the PFAQ inhibitor in the working solution of 1 M HCl + 200 mg/L NaCl was obtained from the relationship between lg [θ/(1-θ)] logCing (Figure 3.29). The correlation coefficients (0.9134, 0.9125, 0.9387, 0.9525) are not close to 1, indicating that the inhibitor adsorption does not follow the Frumkin isotherm.

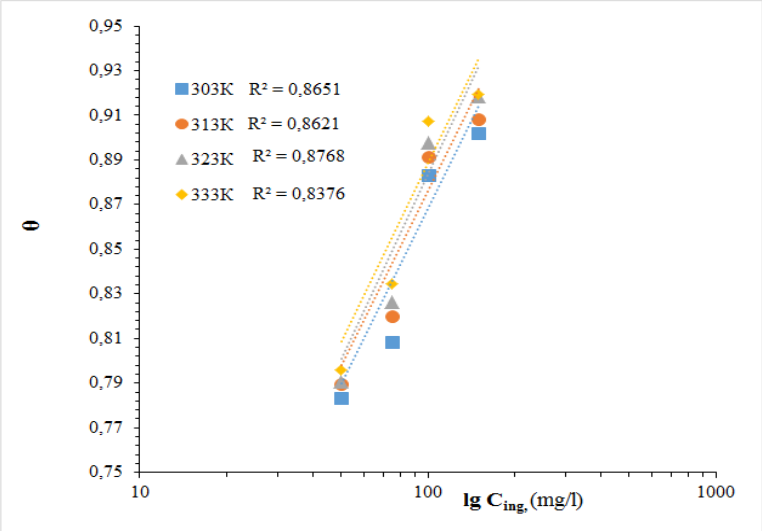

Figure 1. Temkin isotherm of the PFAQ inhibitor in a working solution of 1 M HCl + 200 mg/l NaCl

The Temkin isotherm for the PFAQ inhibitor in the working solution of 1 M HCl + 200 mg/L NaCl was obtained from the relationship between lgC$_{ing}$ning θ (Figure 1). Considering that the correlation coefficients of the PFAQ corrosion inhibitor are significantly different from 1 (0.8651 at 293 K, 0.8621 at 303 K, 0.8768 at 313 K, and 0.8376 at 333 K), it indicates that the inhibitor adsorption does not follow the Temkin isotherm.

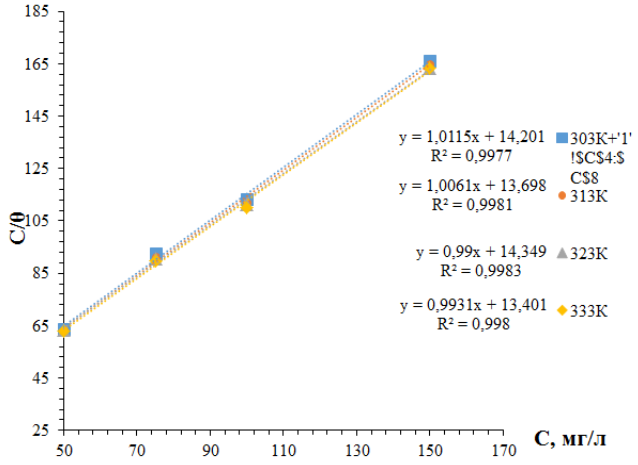

Figure 2. Langmuir isotherm of the PFAQ inhibitor in the working solution of 1 M HCl + 200 mg/L NaCl.

The Langmuir isotherm was plotted from the relationship between lgC$_{ing}$ning θ (Figure 3.22). Since the correlation coefficient of the PFAQ corrosion inhibitor is approximately equal to 1, it was confirmed that the inhibitor adsorption on the metal surface follows the monomolecular adsorption theory according to the Langmuir isotherm.

Table-2

Thermodynamic Functions of Adsorption of the PFAQ Corrosion Inhibitor in 1 M HCl + 200 mg/L NaCl Solution Based on the Langmuir Isotherm

T, K	Kads	R²	ΔGoads	ΔHoads kJ/mol	ΔSoads, J/mol
293	0,0704	0,9805	-10,36	15,397	0,0898
303	0,0730		-10,80		
313	0,0697		-11,04		
323	0,075		-11,58		

From Table 2, it can be seen that the Gibbs free energy values indicate that the process is spontaneous, since a negative Gibbs free energy value confirms that the reaction proceeds spontaneously.

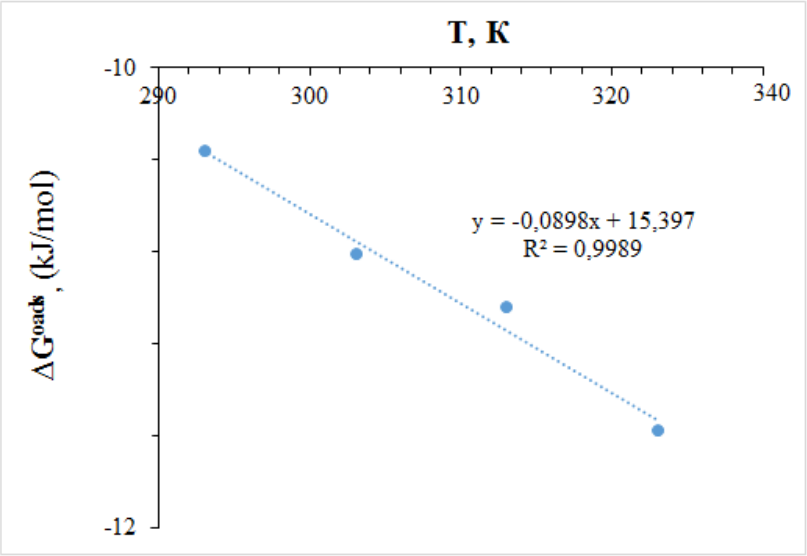

Figure 3. Temperature dependence of ΔG°ads in the working solution of 1 M HCl + 200 mg/L NaCl.

From the above relationship between C/θning, the Langmuir isotherm was obtained (Figure 3.23). The results derived from the Langmuir isotherm show that the correlation coefficient is close to unity, indicating that the adsorption process follows monomolecular adsorption. Using the value of K_{ads} determined from the relationship between C_{ing}/θ, the standard Gibbs free energy of adsorption K_{ads} was calculated in the temperature range of 303–333 K (Figure 3.23). The decrease in Gibbs free energy with increasing temperature indicates that the process occurs spontaneously. The inhibition efficiency of the corrosion inhibitor increases due to the enhanced rate of complex formation between the inhibitor molecules and the steel surface, which leads to an increase in disorder. As a result, the adsorption entropy is positive.

CONCLUSION

The PFAQ corrosion inhibitor was successfully synthesized from p-phenylenediamine, formalin, and alpha amino succinate under an inert nitrogen atmosphere. Optimization of the synthesis conditions showed that the highest yield (≈86–88%) was obtained at a molar ratio of 1:2:2 and a temperature range of 40–65 °C. A significant

decrease in yield was observed at temperatures above 65 °C. FT-IR analysis confirmed the presence of characteristic functional groups such as –NH, –CH, –CH_2, and C=O, indicating successful polymer formation and the presence of active heteroatom centers. Thermodynamic analysis of the corrosion process revealed that the activation energy (Ea) increased with increasing inhibitor concentration, suggesting that the inhibitor primarily acts through physical adsorption on the metal surface. Adsorption isotherm studies showed that the adsorption behavior of PFAQ follows the Langmuir isotherm, indicating monomolecular adsorption on the steel surface. The negative values of ΔG°ads indicate the spontaneous nature of the adsorption process. The ΔG°ads values around −40 kJ/mol suggest that the adsorption mechanism involves a mixed mode of physical and chemical adsorption. Positive values of adsorption entropy (ΔS°ads) imply that the formation of complexes between inhibitor molecules and the steel surface increases disorder, enhancing inhibition efficiency.

Overall, the PFAQ inhibitor forms a stable protective film on the metal surface and effectively inhibits corrosion in aggressive environments, making it a promising candidate for steel protection.

REFERENCES

1. Sangtam, T., Longkumer, L., Venuh, V. *et al.* Eco-friendly corrosion inhibition: a review on the extraction and testing of plant-based inhibitors. *Chem. Pap.* **79**, 8253–8280 (2025). https://doi.org/10.1007/s11696-025-04361-5

2. Liu, X., Wu, S., Qin, Y. *et al.* In-depth research into the synergistic inhibition mechanism of amino acids and KI on the corrosion of carbon steel in acidic medium. *J Solid State Electrochem* **29**, 2871–2890 (2025). https://doi.org/10.1007/s10008-025-06194-4.

3. Li, C., Su, M., Hou, T. *et al.* Two new amino acid derivatives as green corrosion inhibitors against Q235 steel in HCl solution: Experimental and theoretical investigations. *Int J Miner Metall Mater* **32**, 1617–1627 (2025). https://doi.org/10.1007/s12613-024-3011-8.

4. Naundorf, T., Seddig, T., Ruf, E. *et al.* Alkali salts of amino acids as alkaline additives for neutralization of acidic corrosion inhibitors. *Amino Acids* **55**, 665–678 (2023). https://doi.org/10.1007/s00726-023-03260-x.

5. A. Nomozov, S. Khodjamkulov, Z. Misirov, S. Umurzakova, D. Buranova, Z. Nurova, S. Soatov. Antibacterial evaluation, and prediction of the ability of Salsola Oppositifolia extract. J. Chem. Lett., 6(3) (2025) 203–211. https://doi.org/10.22034/jchemlett.2025.546568.1348

6. Dahmani, K., Khattabi, M., Saber, I. *et al.* Study on the Corrosion Inhibition Properties of Quinoxaline Derivatives as Acidizing Corrosion Inhibitors for Mild Steel:

Synthesis, Experimental Analysis, and Theoretical Insights. *Chemistry Africa* **7**, 5461–5483 (2024). https://doi.org/10.1007/s42250-024-01135-6.

7. .K. Nomozov, Kh.S. Beknazarov, Y.A. Geldiev, B.E. Babamurodov, N.Sh. Muzaffarova, S.G. Yuldashova. Synthesis of PFG brand corrosion inhibitor and its quantum chemical calculation results. Chem. Probl., 2025, no. 3(23), 297–309. https://doi.org/10.32737/2221-8688-2025-3-297-309

8. Z.K. Misirov, K.S. Beknazarov. Synthesis and application of corrosion inhibitor for hydrogen sulfide corrosion of steel. Indian J. Chem. Technol., 32(3) (2023) 101–109. https://doi.org/10.56042/ijct.v32i3.7278

9. A. Nomozov, Kh.S. Beknazarov, B.A. Normurodov, Z.Kh. Misirov, S.G. Yuldashova, G.J. Mukimova, D.A. Nabiev, Z. Jumaeva. Inhibition potential of Salsola oppositifolia extract as a green corrosion inhibitor of mild steel in an acidic solution. Int. J. Corros. Scale Inhib., 14(3) (2025) 1103–1115. https://doi.org/10.17675/2305-6894-2025-14-3-5

10. M. Lagrenée, B. Mernari, M. Bouanis, M. Traisnel and F. Bentiss, Study of the mechanism and inhibiting efficiency of 3,5-bis(4-methylthiophenyl)-4H-1,2,4-triazole on mild steel corrosion in acidic media, *Corros. Sci.*, 2002, 44(3), 573–588. doi: 10.1016/S0010-938X(01)00075-0.

11. A.Z. El-Sonbati, M.A. Diab, M.I. Abou-Dobara, A.M. Eldesoky and H.R. Issa, Synthesis, characterization, electrochemical studies and antimicrobial activities of metal complexes, *J. Iran. Chem. Soc.*, 2021, 19(3), 979–1002. doi: 10.1007/s13738-021-02354-1.

12. T. Du, J. Chen and D. Cao, N,N-Dipropynoxy methyl amine trimethyl phosphonate as corrosion inhibitor for iron in sulfuric acid, *J. Mater. Sci.*, 2001, 36(16), 3903–3907. doi: 10.1023/A:1017909919388.

13. M.E. Palomar, C.O. Olivares-Xometl, N.V. Likhanova and J.-B. Pérez-Navarrete, Imidazolium, pyridinium and dimethyl-ethylbenzyl ammonium derived compounds as mixed corrosion inhibitors in acidic medium, *J. Surfactants Deterg.*, 2010, 14(2), 211–220. doi: 10.1007/s11743-010-1236-1.

14. K. Prajapati, P.S. Desai, R.T. Vashi, et al., Investigating the corrosion inhibition of aluminium by diamine derivatives in hydrochloric acid: a multi-technique approach, *Chem. Pap.,* 2024, 78, 7999–8018. doi: 10.1007/s11696-024-03651-8.

15. C. Shen, J. Yan, Z. Ai, et al., Insights into the newly synthesized bi-Mannich base for carbon steel corrosion inhibition in H_2S and HCl solution, *Sci. Rep.,* 2024, 14, 19869. doi: 10.1038/s41598-024-70905-6.

16. M.M. Sayed, S.M. Ahmed, M. Abdel-Hakim, et al., Design and thermal imidization of new 1,3-thiazine-based polyimides and copolyimides for high-performance corrosion inhibition, *Sci. Rep.,* 2025, 15, 37354. doi: 10.1038/s41598-025-22235-4.

17. A.K. Nomozov, S.Ch. Eshkaraev, Z.E. Jumaeva, J.N. Todjiev, S.S. Eshkoraev and F.A. Umirqulova, Experimental and theoretical studies of *Salsola oppositifolia* extract as a novel eco-friendly corrosion inhibitor for carbon steel in 3% NaCl, Int. J. Eng. Trends Technol., 2024, 72(9), 312–320. doi: 10.14445/22315381/IJETT-V72I9P126.

18. S.B. Mammadli, F.A. Amirov, A.V. Alamdarly, U.B. Orucaliyeva and D.R. Nurullayeva, Synthesis of an optically transparent copolymer on the basis of N-vinyl carbazole and styrene, Chem. Probl., 2022, 20(4), 374–380. doi: 10.32737/2221-8688-2022-3-374-380.

19. A.K. Nomozov, Kh.S. Beknazarov, N.B. Chorieva, Kh.Ch. Mirzakulov, K.S. Arifdjanova, A.S. Mukimov, A.A. Pardaev and N.D. Ashurova, Recent developments in polymer-based composite anticorrosion coatings: materials, mechanisms and applications, Int. J. Corros. Scale Inhib., 2025, 14(3), 1362–1390. doi: 10.17675/2305-6894-2025-14-3-190.

20. Z.Kh. Misirov, Kh.S. Beknazarov, U.Ch. Akhmedov, A.K. Nomozov and B.E. Babamuratov, Synthesis and application of corrosion inhibitor for hydrogen sulfide corrosion of steel, Indian J. Chem. Technol., 2025, 54(May), 407–417. doi: 10.56042/ijct.v32i3.7278.

21. A.K. Nomozov, Kh.S. Beknazarov, Y.A. Geldiev, B.E. Babamurodov, N.Sh. Muzaffarova and S.G. Yuldashova, Synthesis of PFG brand corrosion inhibitor and its quantum chemical calculation results, Chem. Probl., 2025, 23(3), 297–309. doi: 10.32737/2221-8688-2025-3-297-309.

22. A.K. Nomozov, Kh.S. Beknazarov, B.A. Normurodov, Z.Kh. Misirov, S.G. Yuldashova, G.J. Mukimova, D.A. Nabiev and Z. Jumaeva, Inhibition potential of *Salsola oppositifolia* extract as a green corrosion inhibitor of mild steel in an acidic solution, Int. J. Corros. Scale Inhib., 2025, 14(3), 1103–1115. doi: 10.17675/2305-6894-2025-14-3-5.

23. N.Sh. Muzaffarova, F.N. Nurkulov, Z.N. Khaydarova, A. Abdirazokov, M.I. Bozorova and I.I. Abdimalikov, Synthesis of fire retardant with phosphorus and metal for preservation and reduction of flammability of textile materials, Chem. Probl., 2024, 22(3), 290–302. doi: 10.32737/2221-8688-2024-3-290-302.

24. F.N. Nurkulov, U. Ziyamukhamedova, E. Rakhmatov and J. Nafasov, Slowing down the corrosion of metal structures using polymeric materials, E3S Web Conf., 2021, 264, 02055. doi: 10.1051/e3sconf/202126402055.