

Study of the bactericidal-inhibitor properties of new reagents

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Abstract

It is well known that in oil-producing countries with advanced industrial development, one of the most pressing unresolved challenges is protecting the internal surfaces of equipment and facilities from the effects of aggressive corrosive environments, thereby extending their operational life. Based on this, the present article explores the results of numerous laboratory tests on the effects of the newly developed organic MARZA-4 reagent and a composition provisionally named HAK-2 against hydrogen sulfide, carbon dioxide, and sulfate-reducing bacteria, which are primary causes of internal surface corrosion in the oil industry. For the first time, the MARZA-4 reagent was studied for its effectiveness against sulfate-reducing bacteria in aggressive corrosive environments such as neutral, acidic, and alkaline media, as well as in the “Postgate-B” nutrient medium. It was determined that the MARZA-4 reagent possesses bactericidal-inhibitor properties at an optimal concentration of 20 mg/L. At this concentration, its corrosion protective effect in neutral, acidic, and alkaline environments was found to be 98%, 98%, and 94%, respectively. In the “Postgate-B” nutrient medium, the bactericidal effect against *Desulfovibrio desulfuricans* and *Desulfomicrobium* cells was 78% and 81%, respectively.

Keywords:

sulfate-reducing bacteria, inhibitor, hydrogen sulfide, carbon dioxide, aggressive environment

1. Introduction

Ensuring the reliability and long-term operation of field equipment and pipeline systems is one of the critical challenges in the development of oil and gas fields and the subsequent transportation of hydrocarbon resources. In this study, the term “aggressive environment” specifically refers to conditions that accelerate corrosion due to their chemical composition. These include acidic media (such as hydrochloric acid solutions), neutral chloride-containing media (such as 3.5% NaCl solution), alkaline media (sodium hydroxide solutions), and gas-rich environments containing hydrogen sulfide (H₂S), carbon dioxide (CO₂), or their combination—all of which are representative of actual conditions encountered in oil and gas production systems. While acidic and neutral media are commonly found in production and pipeline systems, alkaline conditions may arise in the oil industry during enhanced oil recovery (EOR) techniques – such as alkaline flooding – or during chemical treatments involving basic agents like sodium hydroxide. Furthermore, the presence of gases like H₂S,

CO₂, and O₂ in these environments significantly intensifies corrosion aggressiveness under operational conditions (Abdel-Gaber et al., 2011; Ansari et al., 2020). Additionally, condensation formed during the cooling of oil in pipelines presents a major corrosion risk, as it creates a biphasic system where corrosion processes primarily occur in the aqueous phase (Bao et al., 2012; Gurbanov and Gasimzade, 2023a).

The detrimental effects of corrosion extend beyond the degradation of metals. Particularly concerning is hydrogen sulfide-induced stress corrosion cracking. Furthermore, dispersed corrosion products (iron sulfides and oxides) clog and corrode pumping equipment, leading to reduced productivity of oil reservoirs. Iron sulfides and oxides extracted with well fluids act as stabilizers of oil emulsions, complicating demulsification and increasing the costs associated with crude oil preparation (Gurbanov et al., 2023b, Xu et al., 2016).

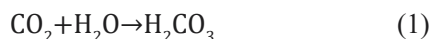
It should be noted that CO₂ gas reacts with water in the corrosive environment to form carbonic acid (H₂CO₃). It is specifically in the presence of carbonic acid that the corrosion of iron (Fe) occurs. The following reactions take place in the presence of CO₂ gas.

The dissolution of carbon dioxide in water and subsequent formation of carbonic acid occurs according to the following **Equation 1**:

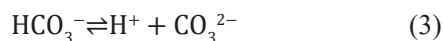
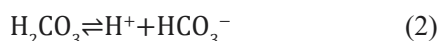
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The dissociation of carbonic acid occurs in two steps, as shown in the following **Equations**:



The ionization of iron as the anodic reaction can be represented by the following **Equation 4**:



The cathodic reaction, involving the reduction of hydrogen ions, proceeds according to the following **Equation 5**:



As a result, Fe^{2+} ions react with carbonate ions to form iron(II) carbonate (FeCO_3), which constitutes a passivating layer, as shown in the following **Equation 6**:

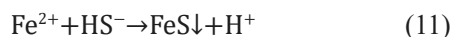


The resulting FeCO_3 layer can act as a protective barrier; however, in some cases, it is unstable, breaks down, and corrosion continues (**Matamoros-Veloza et al., 2020**).

H_2S gas creates a mildly acidic environment in water and leads to the formation of iron sulfide (FeS), which contributes to corrosion. The reactions can be represented by the following **Equations**:



Formation of iron sulfide through the reaction of Fe^{2+} ions with HS^- or S^{2-} ions can be expressed by the following **Equation 11**:



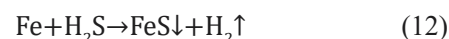
As a result, FeS is black in color and may sometimes act as a protective layer; however, it can also form a porous structure that allows corrosion to continue (**Wang et al., 2021**).

The corrosion of steel well equipment, as well as trunk and process pipelines, not only shortens their service life and increases repair costs, but also causes severe environmental damage. Equipment damage results in soil salinization by aggressive groundwater, as well as contamination of soil and natural water bodies with oil and oil products. Therefore, significant attention is being paid to extending the service life of technological well equipment in oil fields (**Kalinina et al., 2016**; **Kashkovskiy et al., 2012**).

One of the most effective methods to combat corrosion in oil production is the use of corrosion inhibitors. These inhibitors, which can be individual compounds or compositions of various substances, are designed to significantly reduce metal corrosion losses in harsh environments involving aggressive gases such as H_2S , CO_2 , and O_2 , as well as salts in technological media (**Kuznetsov et al., 2000**). Inhibitor-based protection is considered one of the most widely adopted and economically justified methods of corrosion protection for field equipment and pipelines. By varying the inhibitor dosage or using inhibitors with different anti-corrosion properties, it is possible to reduce corrosion rates to acceptable levels without significantly altering existing technological schemes (**Lecante et al., 2011**; **Lusk, 2008**).

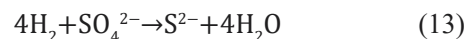
Sulfate-reducing bacteria (SRB), which cause severe corrosion, are microorganisms that live in anaerobic (oxygen-free) conditions and reduce sulfate (SO_4^{2-}) ions to produce hydrogen sulfide (H_2S).

As a result of SRB activity, the produced H_2S reacts with the metal surface to form iron sulfide (FeS) and other corrosion products, as shown in the following **Equation 12**:



It should be noted that the FeS layer is usually uneven and porous, and it does not fully protect the metal surface, resulting in the development of pitting corrosion. SRBs also accelerate corrosion through cathodic depolarization (**Wang et al., 2021**).

Normally, in metal corrosion, hydrogen ions (H^+) accept electrons to form molecular hydrogen (H_2). However, hydrogen molecules can accumulate on the metal surface, slowing down the corrosion process. Sulfate-reducing bacteria (SRBs) consume this hydrogen, preventing its accumulation and thereby increasing the rate of corrosion, as shown in **Figure 1** and represented by the following **Equation 13**:



The mechanism presented in **Figure 1** illustrates the microbiologically influenced corrosion (MIC) process initiated by sulfate-reducing bacteria (SRB). These anaerobic microorganisms utilize sulfate as a terminal electron acceptor, reducing it to hydrogen sulfide (H_2S), which subsequently reacts with metallic iron to form iron sulfide (FeS) corrosion products. This biogenic process not only deteriorates the protective oxide layer but also promotes localized corrosion through cathodic depolarization. The described mechanism is consistent with the model proposed by **Matamoros-Veloza et al. (2020)**.

Oil production companies impose high requirements on inhibitor compositions, demanding universal effects, including reducing hydrogen sulfide, carbon dioxide, and microbiological corrosion while mitigating hydrogenation of structural materials. Furthermore, it is ex-

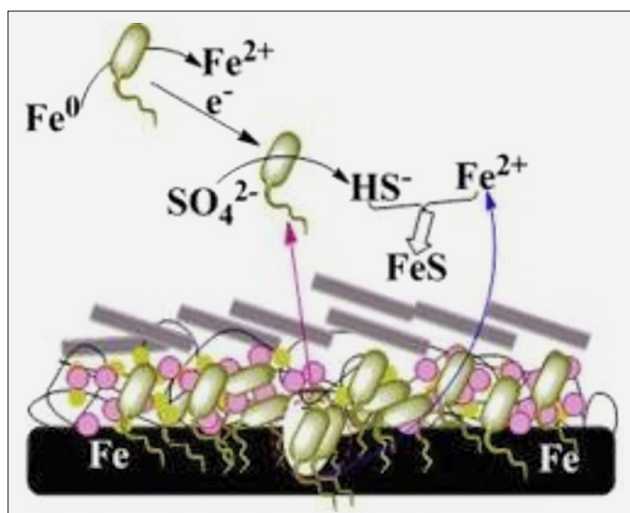


Figure 1. Mechanism of metal corrosion under the influence of sulfate-reducing bacteria (Matamoros-Veloza et al., 2020)

pected that their concentrations in operation environments should not exceed 100-200 mg/L. However, nearly all commercially produced corrosion inhibitors have narrow optimal application ranges (Martens and Berner 1974; Milovzorov et al., 2012).

The development, research, and application of locally produced similar inhibitors not only address the issue of import substitution but also solve the problem of reducing the dependency on foreign products in the domestic market. Thus, the development of universal inhibitors capable of reducing hydrogen sulfide, carbon dioxide, and microbiological corrosion, as well as mitigating hydrogenation of construction materials, remains one of the most pressing issues in the oil industry (Morris and Richard, 2002).

One promising approach to the search for such inhibitors is the creation of new multifunctional compositions from substances with individual inhibitory properties (Salasi et al., 2007). By jointly enhancing protective properties, these compositions aim to increase the effectiveness of corrosion protection (Starosvetsky et al., 2010; Talybov et al., 2020).

In conclusion, protecting the internal surfaces of equipment and pipelines in the oil industry from the effects of aggressive electrochemical corrosion environments with varying compositions necessitates the development of effective individual reagents and compositions. The study of their properties in laboratory conditions remains one of the most urgent tasks of our time (Taraneh et al., 2008; Zafari et al., 2020).

Objective of the Study: This research investigates the protective and bactericidal effects of the MARZA-4 reagent in neutral, acidic, alkaline environments, and in conditions where sulfate-reducing bacteria (SRB) are active. SRB activity results in the formation of FeS, Fe(OH)₂, and H₂S on metal surfaces, promoting pitting

corrosion. The release of H₂S, a highly toxic and hazardous gas, presents a serious risk to pipelines and oil-gas equipment. SRB-induced corrosion is a common problem in oil and gas production facilities, pipelines, and underground storage systems.

The primary objective of this study is to evaluate the corrosion protection performance of a newly developed reagent, HAK-2, and its composition under laboratory conditions. The research aims to compare the effectiveness of MARZA-4 and HAK-2 inhibitors, examine their chemical interaction mechanisms, and determine their overall impact on corrosion rates under different environmental conditions relevant to oil and gas operations.

2. Method

It is known that the equipment and installations used in the oil industry are primarily made from steel of grade Ct3. Therefore, in laboratory conditions, samples made of Ct3 steel were used to study the corrosion rate on metal specimens. The chemical composition of Ct3 steel is presented in Table 1.

Table 1. The elemental content of Ct3 steel (%)

Ct3	C	Mn	Si	P	S	Cr	Ni	Cu	Fe
	0.2	0.5	0.15	0.04	0.05	0.3	0.2	0.2	98.4

As seen in Table 1, Ct3 steel contains nine chemical elements in various percentages, with the main component being 98.36% iron. Specimens of Ct3 steel measuring 30x20x1 mm were used to conduct laboratory experiments. It should be noted that to determine the efficiency of the reagent's corrosion inhibition, the experiments were carried out under room conditions for a duration of six hours. The MARZA-4 reagent and a new composition, conditionally named HAK-2, consisting of MARZA-4 and chloroprene in a 1:1 ratio, were used as corrosion agents. MARZA-4 is an organic chemical compound, and its molecule comprises carbon, hydrogen, oxygen, halogen atoms, and a triple bond. MARZA-4 is a reagent produced in Azerbaijan, and its chemical formula is not disclosed by the manufacturers for commercial purposes (Pashayeva, 2022). In industry, this reagent is produced using methane gas, unsaturated monohydric alcohols, and halides as raw materials.

The experiments related to sulfate-reducing bacteria were carried out following the sequence outlined in RD-39-3-973-83. It should be noted that the laboratory tests were conducted in the "Postgate-B" medium, which provides an optimal environment for the growth of sulfate-reducing bacteria, at temperatures ranging from 28°C to 30°C (Zhang et al., 2009; Zhao et al., 2020).

The corrosion rate in an aggressive environment was determined using the gravimetric method outlined in RD-39-3-973-83. Metal coupons were exposed to the corrosive environment for a specified duration, after

Table 2. Composition of the “Postgate-B” nutrient medium, g/l

“Postgate-B”	NH ₄ Cl	K ₂ HPO ₄	MgSO ₄ ×7H ₂ O	CaSO ₄	lactate-Ca	Na ₂ S	Na ₂ SO ₃	FeSO ₄ (5% solution in 1% HCl)
	1,0	0,5	2,0	1,0	2,6	0,2	2,0	0,5

which they were cleaned and re-weighed to quantify the mass loss.

The protective effect of the MARZA-4 inhibitor was studied in acidic, neutral, and alkaline environments. The acidic environment was created using an HCl solution, resulting in a pH of 3. The alkaline environment was prepared with a NaOH solution, yielding a pH of 11. The neutral environment was created using a 3.5% NaCl solution, with a pH of 7. The pH values in the environments were measured and verified using a Hanna Instruments HI 2211 model pH meter. The metal sample surfaces were polished with #800 grit sandpaper, washed with distilled water, and dried. The effects of the MARZA-4 inhibitor at concentrations of 5, 10, 15, and 20 mg/L on corrosion environments were investigated. The corrosion rate K (g/m²·hour), retardation coefficient (γ), and protective efficiency (Z , %) were calculated.

Surface Preparation and Experimental Setup: before starting the experiments, the surfaces of the steel specimens were cleaned. Initially, the surfaces of the steel specimens were ground on a grinding machine. Then, the surfaces were wiped with acetone and alcohol, and their weights were determined using an analytical balance. Corrosion rate tests were conducted in two environments: the first being an aggressive corrosive environment, and the second being the same environment with the addition of an inhibitor.

After completing the laboratory experiments conducted at room temperature, the steel specimens were removed from the aggressive corrosion environment, and corrosion products were removed from their surfaces. Hydrochloric acid, 40% formalin, and cotton were used to clean the surfaces of the steel specimens. After chemical treatment, the specimens were rinsed with running water and then dried with acetone. The specimens were kept in a desiccator for two hours before and after the experiments. The purpose of storing the steel specimens in the desiccator was to bring them to a stable weight. After this process, the steel specimens were weighed again using an analytical balance to determine their final weights (Postgate, 1984).

The rate of corrosion in aggressive environments under laboratory conditions is calculated, as given in Equation 14, as follows (Pashayeva, 2022):

$$K = \frac{m_1 - m_2}{S \cdot \tau} \quad (14)$$

Where: m_1 – mass of the steel sample before the experiment, g; m_2 – mass of the steel sample after removing the corrosion products from its surface, g; S – surface area of the steel sample, m²; τ – duration of the experiment, hours.

The term “retardation coefficient” (γ) is also used in corrosion processes and is calculated as shown in Equation 15, as follows (Pashayeva 2022):

$$\gamma = \frac{K_0}{K_{inh}} \quad (15)$$

Where: K_0 – corrosion rate without reagents; K_{inh} – corrosion rate with the presence of the reagent (g/m²·hour). The retardation coefficient (γ) is a dimensionless quantity.

The protective effect of the reagents used in the experiment is calculated, as shown in Equation 16, as follows (Pashayeva, 2022):

$$Z = \frac{K_0 - K_{inh}}{K_0} 100\% \quad (16)$$

Where: K_0 – corrosion rate without reagents; K_{inh} – corrosion rate with the presence of the reagent (g/m²·hour).

One of the terms used in corrosion processes is the penetration factor (K_p), which is calculated as shown in Equation 17, as follows (Pashayeva 2022):

$$K_p = \frac{8760K_m}{\rho} \cdot 10^{-3} \text{ mm/year} \quad (17)$$

Where: K_m – corrosion rate, g/m²·hour; ρ – density of the metal being studied, g/cm³; 8760- a constant representing the number of hours in a year.

All chemicals used in the experiments (HCl, NaCl, NaOH, ethanol, acetone, chloroprene, etc.) were of analytical grade (AR) and were officially supplied to the Azerbaijani market by well-known manufacturers such as “Sigma-Aldrich” and “Merck.”

Corrosion tests based on mass loss were conducted using the gravimetric method, in accordance with the ASTM G31-21 and GOST 9.905-82 international standards.

Bactericidal Studies: the bactericidal properties of the reagents against sulfate-reducing bacteria were investigated in the “Postgate-B” nutrient medium (see Table 2).

In the laboratory, each experiment was repeated five times, and the standard deviation was calculated to ensure the reliability of the results. During the experiments, carbon dioxide (CO₂) was continuously introduced into the environment at a specific flow rate. Initially, the gases were introduced into the corrosive medium through controlled gas injection, simulating real-world conditions where gases interact with the metal surface (see Table 3).

The concentration of H₂S was set at 0.015 psi, representing typical field conditions where low levels of H₂S can significantly impact the corrosion rate. The CO₂ con-

centration was set at 10%, which is commonly found in pipeline systems. During the experiments, the pH of the solution was monitored, as the dissolution of CO₂ leads to the formation of carbonic acid, which lowers the pH. Initially, the pH was 6.5, and it decreased to approximately 5.2 in the presence of CO₂.

Corrosion rates were measured using both weight loss and potentiodynamic polarization methods. Both gases were maintained in the experimental environment for 24 hours. The simultaneous application of CO₂ and H₂S was performed to analyze their joint influence on corrosion, with flow rates carefully controlled during their introduction. These techniques provided real-time data on the influence of H₂S and CO₂ on corrosion behavior.

Finally, the impact of the inhibitors MARZA-4 and HAK-2 on H₂S and CO₂ environments was assessed. The results demonstrated that higher concentrations of these inhibitors significantly reduced corrosion rates.

Bactericidal Activity Calculation: For the growth and development of sulfate-reducing bacteria, the “Post-gate-B” nutrient medium is used, and the research is conducted based on the NACE standard methodology. The number of sulfate-reducing bacterial cells in 1 ml of the initial suspension which is calculated as shown in **Equation 18**, as follows (**Pashayeva 2022**):

$$M = \frac{1000an}{hs} \quad (18)$$

Where: M – the number of cells in 1 ml of the suspension; a – the average number of cells in the square grid; h – the depth of the chamber (in mm); S – the area of the square grid (in mm²); n – the dilution rate of the suspension; 1000 mm³ = 1 ml.

The growth rate of sulfate-reducing bacteria (N,%) with the involvement of the bactericide which is calculated as shown in **Equation 19**, as follows (**Pashayeva 2022**):

$$N, \% = \frac{100(n_0 - n_{inh})}{n_0} \quad (19)$$

Where: n₀ – the number of microorganisms in the reagent-free medium; n_{inh} – the number of microorganisms in the reagent-containing medium.

The bactericidal effect (S,%) of the reagent based on the amount of hydrogen sulfide which is calculated as shown in Equation 20, as follows (**Pashayeva 2022**):

$$S, \% = \frac{C_0 - C_{inh}}{C_{inh}} 100 \quad (20)$$

Where: C₀ – the concentration of biogenic hydrogen sulfide in the reagent-free medium; C_{inh} – the concentration of biogenic hydrogen sulfide in the reagent-containing medium.

The change in biogenic hydrogen sulfide concentration was measured using the methylene blue spectropho-

tometric method, a well-established technique for detecting H₂S in sulfate-reducing bacteria cultures. This method involves the reaction of H₂S with N,N-dimethyl-p-phenylenediamine and FeCl₃ under acidic conditions, forming methylene blue, which was quantified at 667 nm wavelength. The use of this method ensures high sensitivity and accuracy in detecting even minor changes in H₂S levels. The decrease in H₂S production directly correlates with the bactericidal efficiency of MARZA-4. The methodology aligns with similar studies on SRB inhibition (**Postgate, 1984; Muyzer and Stams, 2008**).

Scanning Electron Microscopy (SEM) Analysis: surface morphology and microstructural changes of the steel specimens before and after exposure to the corrosive medium were investigated using scanning electron microscopy (SEM). The SEM analysis was performed using a JEOL JSM-7001F field emission scanning electron microscope operating at an accelerating voltage of 15 kV under high vacuum conditions. Prior to imaging, all samples were cleaned with ethanol, air-dried, and then coated with a thin layer of gold (approx. 10 nm) using a sputter coater (Quorum Q150R ES) to enhance surface conductivity and imaging resolution.

The SEM investigation was carried out at various magnifications (ranging from ×500 to ×10,000) to assess surface degradation features such as pit formation, crack propagation, and corrosion product morphology.

All images were captured with a calibrated scale bar, and the micrographs were analyzed using ImageJ software to estimate the average pit diameter and surface coverage of corrosion products. Representative images were selected from at least three different areas on each specimen to ensure statistical reliability and reproducibility of the observations.

3. Results and discussions

Initially, the laboratory studies were conducted in three aggressive corrosion environments: neutral, acidic, and alkaline. It should be noted that the experiments for determining the corrosion rate were carried out in a U-shaped setup. The gravimetric method for determining the corrosion rate in a U-shaped setup was carried out in accordance with ASTM G31-72. It should be noted that the experiments for determining the corrosion rate were carried out in a U-shaped setup. The gravimetric method for determining the corrosion rate in the U-shaped setup was conducted in accordance with ASTM G31-72. During the experiments, there was no liquid flow in the system; however, to simulate real field conditions, a continuous flow of CO₂ and/or H₂S gases was introduced into the system at a controlled flow rate. The results of the numerous laboratory experiments lasting six hours are presented in **Table 3**.

The data presented in the table demonstrates the protective effectiveness of the MARZA-4 inhibitor under different environmental conditions: neutral, acidic, and

Table 3. The protective effectiveness of the MARZA-4 inhibitor in various aggressive environments

№	C _{inh} mg/L	K, g/m ² -hour		SD (±)	Retardation coefficient, γ	Protective effect, Z%
		Without inhibitor	With inhibitor			
a) Protective effectiveness of MARZA-4 inhibitor in a neutral environment (pH=7)						
1	0	0.6248	-	-	-	-
2	5.0		0.0749	±0.002	8.34	88
3	10.0		0.0562	±0.0018	11.11	91
4	15.0		0.0249	±0.0012	25.09	96
5	20.0		0.0124	±0.0008	50.38	98
b) Protective effect of MARZA-4 inhibitor in acidic environment (pH=3)						
1	0	1.2364	-	-	-	-
2	5.0		0.1730	±0.004	7.14	86
3	10.0		0.1236	±0.003	10.00	90
4	15.0		0.0618	±0.0025	20.00	95
5	20.0		0.0247	±0.0015	50.05	98
c) Protective effect of MARZA-4 inhibitor in alkaline environment (pH=11)						
1	0	1.012	-	-	-	-
2	5.0		0.2024	±0.004	5.00	80
3	10.0		0.1619	±0.0035	6.25	84
4	15.0		0.1416	±0.0032	7.14	86
5	20.0		0.0607	±0.0016	16.67	94

alkaline. As the concentration of MARZA-4 increases, there is a consistent improvement in corrosion protection across all environments. This indicates that the inhibitor is effective in mitigating corrosion as its concentration rises.

In the neutral environment, the protective efficiency of MARZA-4 increases steadily with the concentration of the inhibitor. Initially, the corrosion rate without the inhibitor is relatively high. However, as the inhibitor is introduced, a significant reduction in corrosion is observed, with the protection efficiency rising considerably. The highest inhibitory efficacy in the neutral environment was achieved at a concentration of 20 mg/L, with a protection efficiency of 98%.

Similarly, in the acidic environment, the inhibitor exhibits a similar trend of increasing protection efficiency with higher concentrations. Acidic conditions typically accelerate corrosion, but MARZA-4 effectively counteracts this by reducing the corrosion rate as its concentration increases. Even at lower concentrations, there is a noticeable reduction in the corrosion rate, which continues to improve with higher inhibitor concentrations. At 20 mg/L, the protection efficiency reached its maximum in acidic conditions, with a value of 98%.

In the alkaline environment, while the overall corrosion rates are lower than those in acidic conditions, the inhibitor still proves effective. The pattern of increased protection efficiency with higher concentrations remains consistent, although the degree of improvement is slightly less pronounced compared to the acidic environment. At 20 mg/L, the highest protection efficiency in the alkaline

environment was 94%. This suggests that the inhibitor performs better in acidic conditions but still provides significant protection in alkaline conditions.

Overall, the MARZA-4 inhibitor demonstrates strong protective properties across various environments, with higher concentrations offering more effective corrosion resistance. The results suggest that MARZA-4 is a versatile inhibitor capable of enhancing corrosion resistance in a range of pH conditions, with the highest efficacy observed at a concentration of 20 mg/L across all test environments.

It is known that the internal corrosion of oil pipelines is primarily due to formation water and sulfate-reducing bacteria present in the oil. It should be noted that corrosion caused by the activity of sulfate-reducing bacteria progresses rapidly, often resulting in leaks in pipelines within a short period. Therefore, the effect of MARZA-4 inhibitor on sulfate-reducing bacteria was also studied under laboratory conditions.

Figures 2–4 present the potentiodynamic polarization curves obtained for Ct3 steel in neutral, acidic, and alkaline environments with varying concentrations of the MARZA-4 inhibitor. The results clearly show that increasing the inhibitor concentration shifts the corrosion potential (E_{corr}) in a more positive direction and reduces the corrosion current density (I_{corr}), indicating a significant inhibition effect.

The inhibition performance of the MARZA-4 compound on Ct3 grade carbon steel was systematically evaluated using the potentiodynamic polarization method. Experiments were carried out in media of varying pH-neutral (pH = 7), acidic (pH = 3), and alkaline (pH =

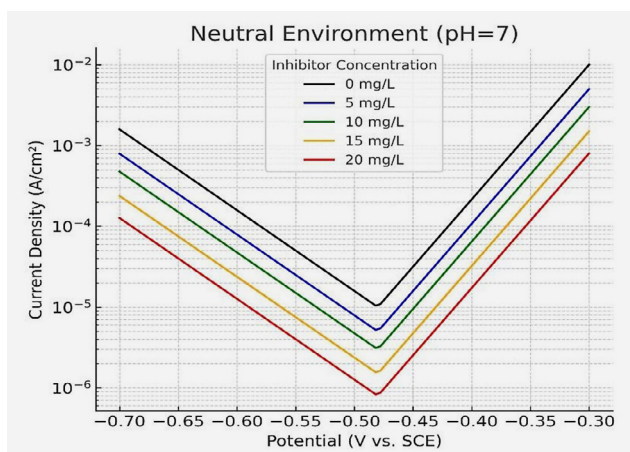


Figure 2. Potentiodynamic polarization curves of Ct3 steel in a neutral medium in the presence of the MARZA-4 inhibitor

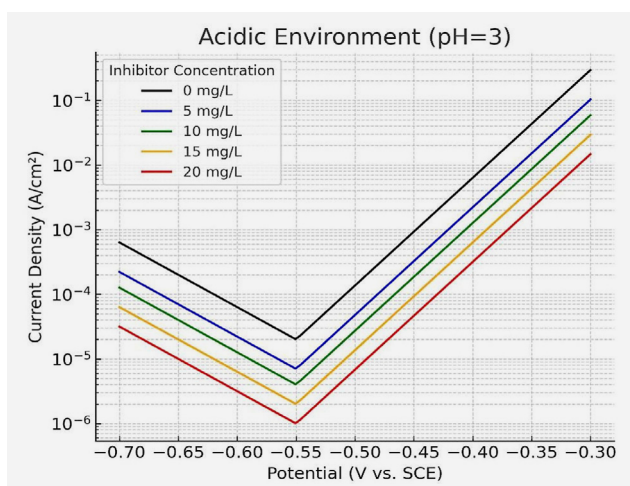


Figure 3. Potentiodynamic polarization curves of Ct3 steel in an acidic medium in the presence of the MARZA-4 inhibitor

11) – to assess the inhibitor's effectiveness under diverse corrosion environments. For each condition, polarization curves were constructed for inhibitor concentrations of 0, 5, 10, 15, and 20 mg/L (see **Figures 2–4**).

The electrochemical measurements were supported by gravimetric data, which provided estimated corrosion current densities (I_{corr}). These values were used to quantify the inhibitor's impact on the corrosion kinetics. Test parameters, including a metal surface area of 0.0013 m², density of 7850 kg/m³, and 6-hour immersion time, were maintained consistently across all systems to ensure comparability.

As observed from **Figures 2 to 4**, increasing the concentration of MARZA-4 led to:

- A progressive shift in corrosion potential (E_{corr}) toward more positive values, suggesting enhanced surface passivation,
- A substantial reduction in corrosion current density (I_{corr}), indicating effective suppres-

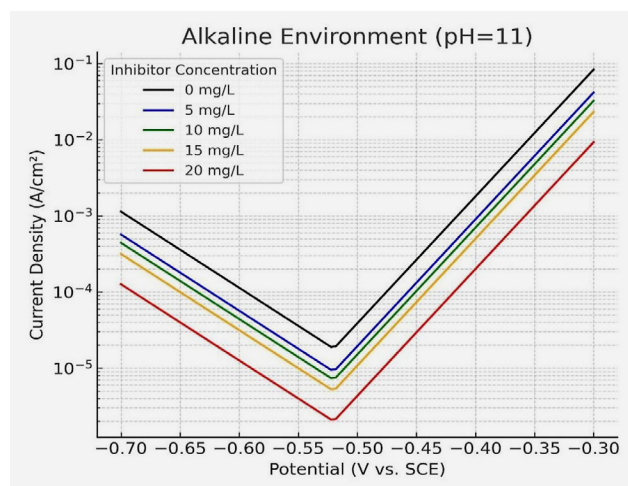


Figure 4. Potentiodynamic polarization curves of Ct3 steel in an alkaline medium in the presence of the MARZA-4 inhibitor

sion of electrochemical activity at the metal–electrolyte interface.

These trends confirm that MARZA-4 functions as a mixed-type inhibitor, affecting both anodic metal dissolution and cathodic hydrogen evolution or oxygen reduction reactions. This dual-mode inhibition likely arises from the formation of a protective adsorbed film on the steel surface, which acts as a physical and electrochemical barrier to charge and mass transfer.

The highest inhibition efficiency was observed in the acidic medium (pH = 3), where a reduction in I_{corr} of approximately 90–95% was recorded at 20 mg/L. This superior performance may be attributed to the enhanced adsorption of MARZA-4 molecules in acidic conditions, where protonation of functional groups can facilitate electrostatic interactions with the positively charged metal surface. The agreement between the electrochemical and gravimetric protection efficiencies ($Z\%$) supports this interpretation.

In both neutral and alkaline environments, a similar concentration-dependent inhibition trend was observed, although the magnitude of protection was slightly lower. This suggests that MARZA-4 remains active across a broad pH spectrum, a critical feature for practical applications in variable oil and gas pipeline environments where pH conditions may fluctuate due to processing fluids or environmental ingress.

Collectively, the data demonstrate that MARZA-4 exhibits:

- Strong inhibition across all tested media,
- Enhanced activity in acidic environments,
- A mechanism consistent with adsorption-controlled inhibition,
- The characteristics of a passivating, mixed-type inhibitor capable of forming a stable barrier layer on steel surfaces.

These findings place MARZA-4 among the most promising candidates for corrosion control in oilfield environments, particularly where aggressive acid media are encountered. Compared to literature-reported inhibitors with similar structures and mechanisms (Enning and Garrelfs, 2014; Gu et al., 2019), MARZA-4 provides competitive or superior protection, affirming its potential for industrial-scale deployment.

The effect of MARZA-4 inhibitor on the growth of sulfate-reducing bacteria was examined over seven days. Figure 5 presents the impact of the inhibitor on *Desulfovibrio desulfuricans* bacterial cells, while Figure 6 shows its effect on *Desulfomicrobium* bacterial cells.

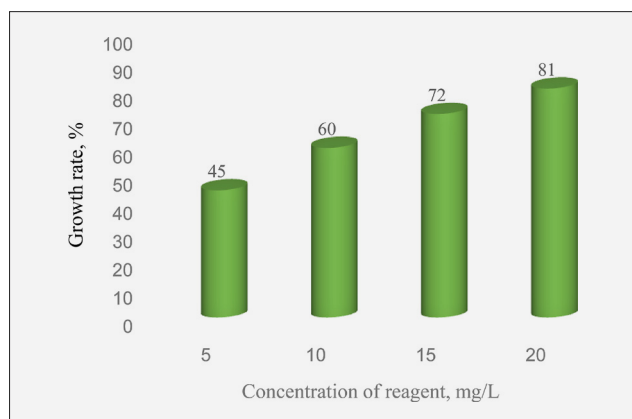


Figure 5. Effect of MARZA-4 reagent on the growth coefficient of *Desulfovibrio desulfuricans* bacterial cells (over 7 days)

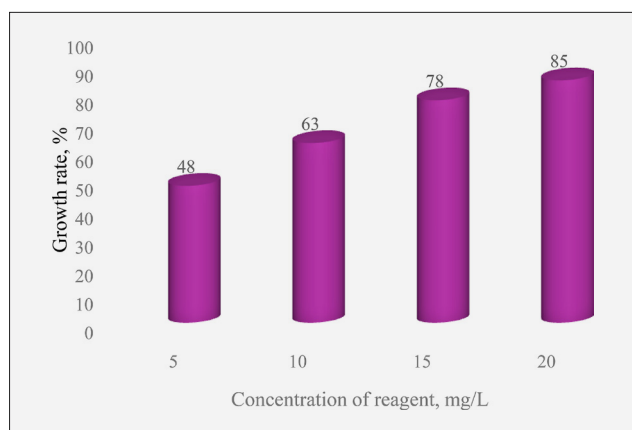


Figure 6. Effect of MARZA-4 reagent on the growth coefficient of *Desulfomicrobium* bacterial cells (over 7 days)

From the figures, it is evident that as the concentration of the MARZA-4 inhibitor increases in the nutrient medium, its inhibitory effect on the growth coefficient of bacterial cells also rises. Specifically, at concentrations of 5, 10, 15, and 20 mg/L, the inhibitory effect on the growth coefficient of *Desulfovibrio desulfuricans* bacterial cells is 45%, 60%, 72%, and 81%, respectively. For *Desulfomicrobium* bacterial cells, the corresponding inhibitory effects are 48%, 63%, 78%, and 85%. Thus, a concentration

of 20 mg/L was found to be the most effective in suppressing bacterial growth in both strains tested.

In the “Postgate-B” nutrient medium, the bactericidal effect of the MARZA-4 inhibitor against *Desulfovibrio desulfuricans* and *Desulfomicrobium* cells was calculated based on changes in the concentration of biogenic hydrogen sulfide. The results for various concentrations of the MARZA-4 inhibitor are shown in Figure 7 and Figure 8, respectively.

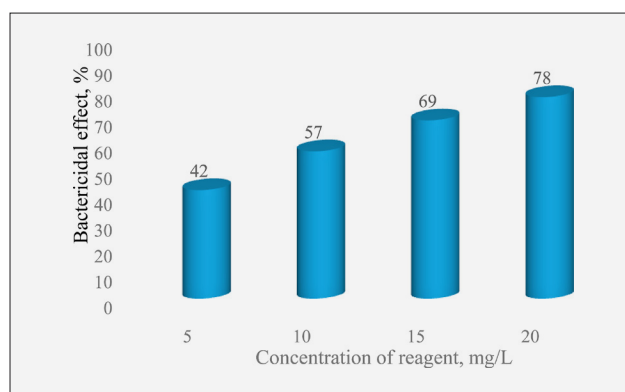


Figure 7. Bactericidal effect of the MARZA-4 reagent in a medium containing *Desulfovibrio desulfuricans* bacterial cells (over 7 days)

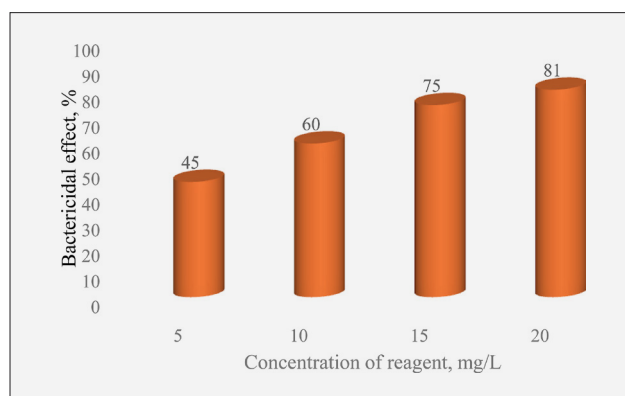


Figure 8. The bactericidal effect of MARZA-4 reagent in a medium containing *Desulfomicrobium* bacteria cells (over 7 days)

The experimental results presented in the figures provide insight into the bactericidal effects of the MARZA-4 inhibitor on *Desulfovibrio desulfuricans* and *Desulfomicrobium* bacterial cells in the “Postgate-B” nutrient medium. The data shows a clear trend in the increase of bactericidal activity with higher concentrations of MARZA-4.

In the case of *Desulfovibrio desulfuricans*, the inhibitor demonstrates a notable bactericidal effect, which intensifies as the concentration of MARZA-4 increases. The highest level of bactericidal activity is observed at a concentration of 20 mg/L.

For *Desulfomicrobium* bacterial cells, a similar pattern is observed, with increasing bactericidal effects cor-

responding to higher concentrations of MARZA-4. The results also indicate that the inhibitor's efficiency is higher against *Desulfomicrobium* than *Desulfovibrio desulfuricans*, as reflected in the overall percentages of bacterial inhibition at each concentration level.

These trends highlight the effectiveness of MARZA-4 as a bactericidal agent, with its efficacy improving at higher concentrations, and demonstrate the compound's potential in inhibiting the growth of sulfate-reducing bacteria in relevant industrial contexts. During the research process, a new composition, conditionally named HAK-2, was prepared under laboratory conditions using a 1:1 ratio of MARZA-4 inhibitor and chloroprene reagent, and its properties were studied. Laboratory tests were initially conducted in aggressive corrosion environments containing hydrogen sulfide, carbon dioxide, and both gases together.

Reagents based on chloroprene (2-chloro-1,3-butadiene), particularly compositions containing polychloroprene, are widely used as effective corrosion inhibitors in industrial applications. Their high anti-corrosion efficiency is attributed to the chemical structure of chloroprene and the functional groups facilitating adsorption onto the metal surface (Zhang et al., 2021).

The mechanism of action of chloroprene-based inhibitors, such as those found in the MARZA-4 reagent, can primarily be explained by the following factors:

Formation of an adsorption barrier: the unsaturated C=C bonds and the electronegative chlorine atom in the chloroprene structure strongly interact with the metal surface, promoting chemisorption. This leads to the formation of a uniformly distributed, dense adsorption layer, which acts as a physical barrier between the metal and the electrolyte, thereby limiting the ingress of oxygen and water molecules to the metal surface. MARZA-4 enhances this mechanism by including organic surfactants and polar functional groups (e.g. carboxylic and amine groups), which further increase adsorption density and stability on the steel surface (Oginni et al., 2018; Gurbanov et al., 2022).

Electrochemical passivation: due to the electron-withdrawing effect of the chlorine atom in chloroprene, the electron density on the metal surface is reduced, thereby suppressing anodic dissolution reactions (e.g. $\text{Fe} \rightarrow \text{Fe}^{2+} + 2\text{e}^-$). MARZA-4 contains halogenated organic compounds and stabilizers that complement this effect by forming complexation zones at anodic sites, contributing to decreased corrosion currents and reduced metal ion solubility (Akinmoladun et al., 2018; Gurbanov et al., 2022).

Jointly enhancing protective properties within the composition: the combination of chloroprene-based inhibitors with ionic and non-ionic surfactants in MARZA-4 improves the destabilization of oil-water emulsions, which is critical in corrosion-prone environments. Our experiments showed that the MARZA-4 mixture accelerated phase separation and enhanced the homoge-

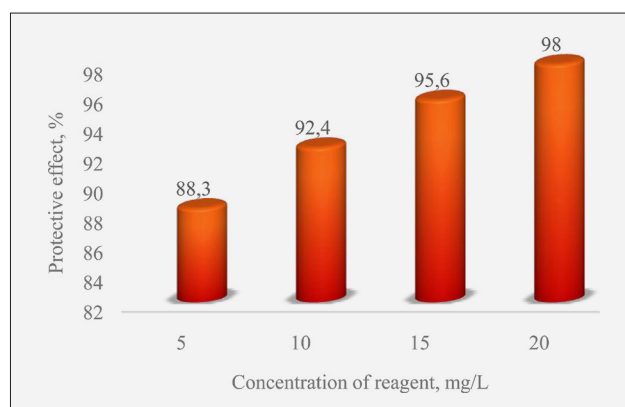


Figure 9. Dependence of the reagent concentration on the protective effect in an H_2S environment ($t = 24$ hours) for the HAK-2 composition

neity of the adsorption film. This is attributed to its formulation, which includes emulsifiers and dispersants that increase surface coverage and minimize interfacial tension (Xu et al., 2018; Gurbanov et al., 2022).

Prevention of microbiologically influenced corrosion: chloroprene-based compounds have been shown to suppress the metabolic activity of sulfate-reducing bacteria (SRB), a common source of MIC. MARZA-4 further improves this function through the incorporation of organic biocides and quaternary ammonium salts, which exhibit strong antimicrobial effects against SRB and acid-producing bacteria. This dual inhibition mechanism effectively mitigates both electrochemical and biological corrosion (Popoola et al., 2017; Akinmoladun et al., 2018; Gurbanov et al., 2022).

Analysis of our experimental results demonstrated that the application of the chloroprene-based composition significantly reduced the quantity of corrosion products on the metal surface. Moreover, the inhibitor efficiency, expressed as a percentage, was observed to be 10–15% higher compared to previously tested variants. These findings confirm that chloroprene provides a comprehensive protective effect through both physical barrier formation and chemical passivation mechanisms.

The corrosion rate was calculated using the gravimetric method. Subsequently, the composition's corrosion protective effect and penetration factor were determined. For durations of 24 and 240 hours, the dependency of the composition's concentration on its protective effect in the hydrogen sulfide environment is presented in Figures 9 and 10. The dependency of the composition's concentration on its protective effect in the carbon dioxide environment is shown in Figures 11 and 12, and in environments containing both hydrogen sulfide and carbon dioxide, this relationship is shown in Figures 13 and 14.

As seen in Figure 9, in the hydrogen sulfide environment, the protective effect of the HAK-2 composition at concentrations of 5, 10, 15, and 20 mg/L is 83.3%, 92.4%, 95.6%, and 98%, respectively, over a 24-hour period.

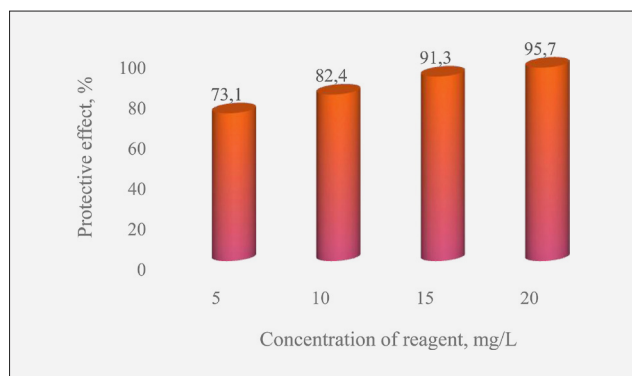


Figure 10. Dependence of the reagent concentration on the protective effect in an H_2S environment ($t = 240$ hours) for the HAK-2 composition

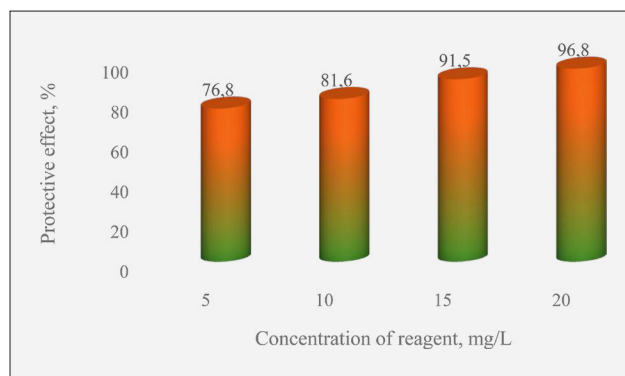


Figure 13. Dependence of reagent concentration on the protective effect in an $H_2S + CO_2$ environment ($t = 24$ hours) for the HAK-2 composition

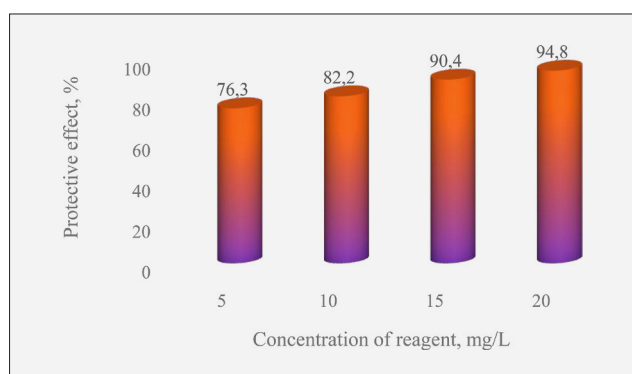


Figure 11. Dependence of the reagent concentration on the protective effect in a CO_2 environment ($t = 24$ hours) for the HAK-2 composition

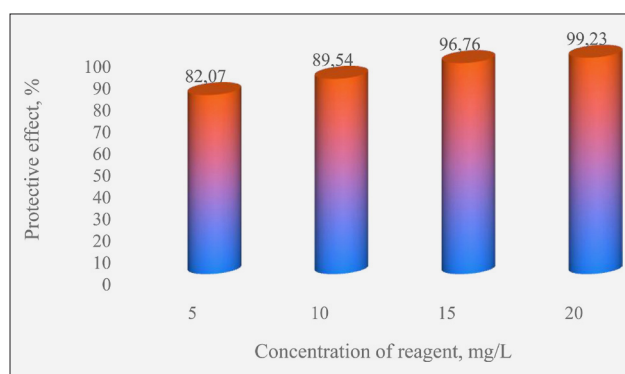


Figure 14. Dependence of reagent concentration on the protective effect in an $H_2S + CO_2$ environment ($t = 24$ hours) for the HAK-2 composition

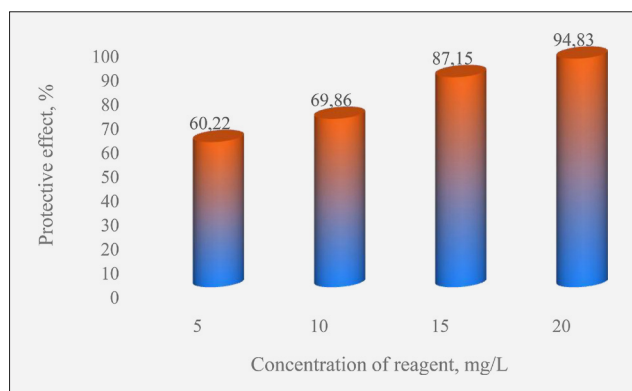


Figure 12. Dependence of the reagent concentration on the protective effect in a CO_2 environment ($t = 240$ hours) for the HAK-2 composition

As seen in **Figure 10**, in the hydrogen sulfide environment, the protective effect of the HAK-2 composition at concentrations of 5, 10, 15, and 20 mg/L is 73.1%, 82.4%, 91.3%, and 95.7%, respectively, over a 240-hour period.

As seen in **Figure 11**, in the carbon dioxide environment, the protective effect of the HAK-2 composition at concentrations of 5, 10, 15, and 20 mg/L is 76.3%, 82.2%, 90.4%, and 94.8%, respectively, over a 24-hour period.

As seen in **Figure 12**, in the carbon dioxide environment, the protective effect of the HAK-2 composition at concentrations of 5, 10, 15, and 20 mg/L is 60.22%, 69.86%, 87.15%, and 94.83%, respectively, over a 240-hour period.

As seen in **Figure 13**, in the $H_2S + CO_2$ environment, the protective effect of the HAK-2 composition at concentrations of 5, 10, 15, and 20 mg/L is 76.8%, 81.6%, 91.5%, and 96.8%, respectively, over a 24-hour period.

As seen in **Figure 14**, in the $H_2S + CO_2$ environment, the protective effect of the HAK-2 composition at concentrations of 5, 10, 15, and 20 mg/L is 82.07%, 89.54%, 96.76%, and 99.23%, respectively, over a 240-hour period.

The data from **Figures 6–11** clearly demonstrate that the corrosion protection efficiency of the HAK-2 composition increases proportionally with concentration across all test environments and time intervals. The most notable observation is that the highest corrosion inhibition in each environment was achieved at a concentration of 20 mg/L, validating this dosage as the most effective within the experimental range.

In the hydrogen sulfide environment (see **Figures 9 and 10**), the HAK-2 composition shows a consistently high level of protection. This may be due to the inhibitor's strong chemisorption onto the metal surface, form-

ing a dense protective film that resists the penetration of corrosive H₂S molecules. Over extended exposure (240 hours), although the protection slightly decreases compared to the 24-hour results, it still remains highly effective (up to 95.7%).

In carbon dioxide environments (see **Figures 11** and **12**), the efficiency is slightly lower, especially over the longer duration. This could be attributed to CO₂'s ability to form carbonic acid in aqueous environments, which might partially compromise the integrity of the inhibitor layer. However, the inhibitor still achieves 94.83% protection at 20 mg/L after 240 hours, highlighting its resilience.

In mixed H₂S+CO₂ environments (see **Figures 13** and **14**), the inhibitor's performance is particularly impressive. Despite the aggressive nature of this combined corrosive environment, the HAK-2 composition delivers superior protection – up to 99.23% at 20 mg/L over 240 hours. This suggests a synergistic protective mechanism, where the inhibitor forms a dual-function barrier that limits both sulfide and acid gas attack.

The increasing efficiency with concentration can be explained by enhanced surface coverage and adsorption of the active components, which block corrosion-prone sites more effectively. Furthermore, the time-dependent data show that the protective layer formed by the inhibitor remains relatively stable over prolonged exposure, especially at the highest concentration.

These results confirm that 20 mg/L is the optimal concentration for the HAK-2 composition, ensuring robust corrosion resistance in acidic, CO₂-rich, and combined environments commonly encountered in the oil and gas industry.

Figure 15 shows the effect of the composition on the growth rate of *Desulfovibrio desulfuricans* bacterial cells, while **Figure 16** shows the effect on the growth rate of *Desulfomicrobium* bacterial cells.

As seen from the figures, as the concentration of the HAK-2 composition in the nutrient medium increases, the effect on the growth rate of bacterial cells also increases. Specifically, at concentrations of 5, 10, 15, and 20 mg/L, the effect of the composition on the growth rate of *Desulfovibrio desulfuricans* bacterial cells is 52%, 68%, 82%, and 89%, respectively, while the effect on the growth rate of *Desulfomicrobium* bacterial cells is 55%, 72%, 85%, and 94%, respectively.

These results clearly demonstrate that the HAK-2 composition exhibits strong bacteriostatic activity, particularly against sulfate-reducing bacteria, which are known to significantly accelerate microbiologically influenced corrosion (MIC) in oil and gas infrastructure. The data indicate a dose-dependent inhibitory effect: as the concentration of the composition increases, the ability of bacterial cells to proliferate diminishes substantially. This is likely due to the disruption of bacterial cell membranes and metabolic processes by the active components in the HAK-2 formulation.

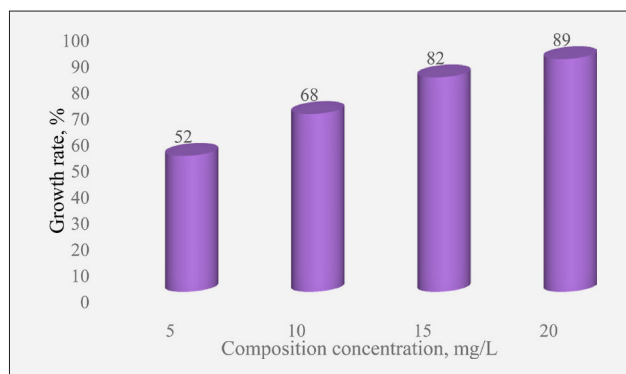


Figure 15. Effect of the HAK-2 composition on the growth rate of *Desulfovibrio desulfuricans* bacterial cells (over 7 days)

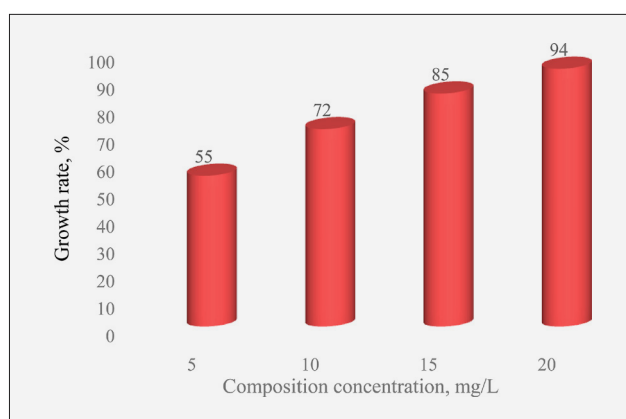


Figure 16. Effect of the HAK-2 composition on the growth rate of *Desulfomicrobium* bacterial cells (over 7 days)

At a concentration of 20 mg/L, the highest level of inhibition was achieved for both bacterial strains, with growth suppression reaching 89% for *Desulfovibrio desulfuricans* and 94% for *Desulfomicrobium*. These findings suggest that 20 mg/L is the optimal concentration for effectively controlling bacterial activity and preventing microbiological corrosion in operational environments. This bactericidal effect complements the corrosion protection function of the HAK-2 composition, making it a dual-purpose reagent suitable for use in oil and gas systems vulnerable to both chemical and biological corrosion mechanisms.

In the “Postgate-B” nutrient medium, based on the change in the concentration of biogenic hydrogen sulfide, the bactericidal effect of the HAK-2 composition on *Desulfovibrio desulfuricans* and *Desulfomicrobium* cells was calculated for different concentrations. The obtained results are shown in **Figure 17** and **Figure 18**, respectively.

The results presented in **Figures 17** and **18** demonstrate the bactericidal effectiveness of the HAK-2 composition in the “Postgate-B” nutrient medium against *Desulfovibrio desulfuricans* and *Desulfomicrobium* bacterial cells. As the concentration of HAK-2 increases, a

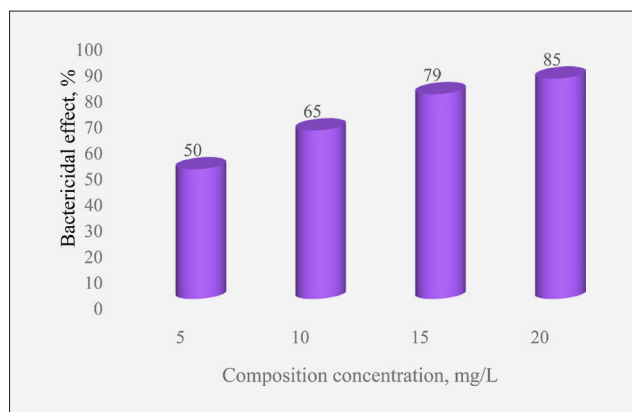


Figure 17. Bactericidal effect of the HAK-2 composition in a *Desulfovibrio desulfuricans* bacterial cell medium (over 7 days)

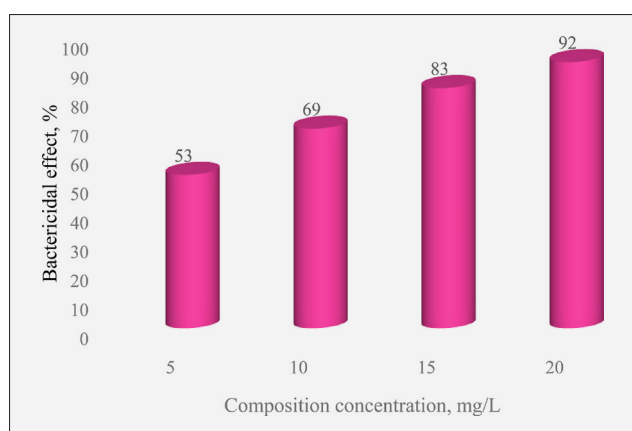


Figure 18. Bactericidal effect of the HAK-2 composition in a *Desulfomicrobium* bacterial cell medium (over 7 days)

significant enhancement in bactericidal activity is observed for both bacterial strains.

For *Desulfovibrio desulfuricans*, the bactericidal effect increases progressively with higher concentrations of the HAK-2 composition. The highest bactericidal efficiency is observed at the 20 mg/L concentration, indicating the composition's potential to effectively reduce bacterial growth.

Similarly, for *Desulfomicrobium*, the bactericidal effect follows the same trend, with higher concentrations resulting in greater bacterial inhibition. The inhibitor demonstrates more pronounced effectiveness against *Desulfomicrobium* than *Desulfovibrio desulfuricans*, as indicated by the greater inhibition at corresponding concentrations.

These findings highlight the potential of HAK-2 as a potent bactericidal agent, with its effectiveness improving as the concentration increases. The results suggest that HAK-2 can be an effective tool for controlling sulfate-reducing bacteria in industrial environments.

Thus, for the first time, the corrosion protective effect of the organic-origin MARZA-4 reagent, which can be produced from local raw materials, in neutral, acidic,

and alkaline environments, as well as the new HAK-2 composition in aggressive corrosion environments with hydrogen sulfide, carbon dioxide, and both gases together, has been investigated. Their optimal consumption rates have been determined. Additionally, the effect of both reagents on sulfate-reducing bacteria in the "Post-gate-B" nutrient medium has been studied. It has been established that, compared to the MARZA-4 reagent, the HAK-2 composition exhibits higher bactericidal-inhibitor properties. Therefore, it is proposed to use the HAK-2 composition as a widely applicable bactericidal-inhibitor reagent in the oil industry, especially in field conditions.

The observed bactericidal effectiveness of HAK-2 can be attributed to its ability to interfere with the metabolic processes and membrane integrity of sulfate-reducing bacteria. This inhibition is particularly important in mitigating microbiologically influenced corrosion (MIC), which poses a severe threat in oilfield operations. The consistent increase in bactericidal activity with concentration suggests a dose-dependent response, with 20 mg/L emerging as the most effective dose. The superior performance against *Desulfomicrobium* may be due to structural or physiological differences between the two bacterial species.

These findings highlight the potential of HAK-2 as a potent bactericidal agent. Its dual function as both a corrosion inhibitor and a biocide makes it highly valuable for industrial application in environments prone to both chemical and microbial corrosion.

Thus, for the first time, the corrosion protective effect of the organic-origin MARZA-4 reagent, which can be produced from local raw materials, in neutral, acidic, and alkaline environments, as well as the new HAK-2 composition in aggressive corrosion environments with hydrogen sulfide, carbon dioxide, and both gases together, has been investigated. Their optimal consumption rates have been determined. Additionally, the effect of both reagents on sulfate-reducing bacteria in the "Post-gate-B" nutrient medium has been studied. It has been established that, compared to the MARZA-4 reagent, the HAK-2 composition exhibits higher bactericidal-inhibitor properties. Therefore, it is proposed to use the HAK-2 composition as a widely applicable bactericidal-inhibitor reagent in the oil industry, especially under field conditions.

As shown in **Figure 19**, the surface morphology of the Ct3 steel coupons significantly differs depending on the presence of the HAK-2 composite reagent and sulfate-reducing bacteria.

Figure 19a–d presents SEM images of steel surfaces after 360 hours of exposure to environments containing sulfate-reducing bacteria (SRB), specifically *Desulfomicrobium* and *Desulfovibrio desulfuricans*, both in the absence and presence of the HAK-2 composite reagent at its optimal concentration.

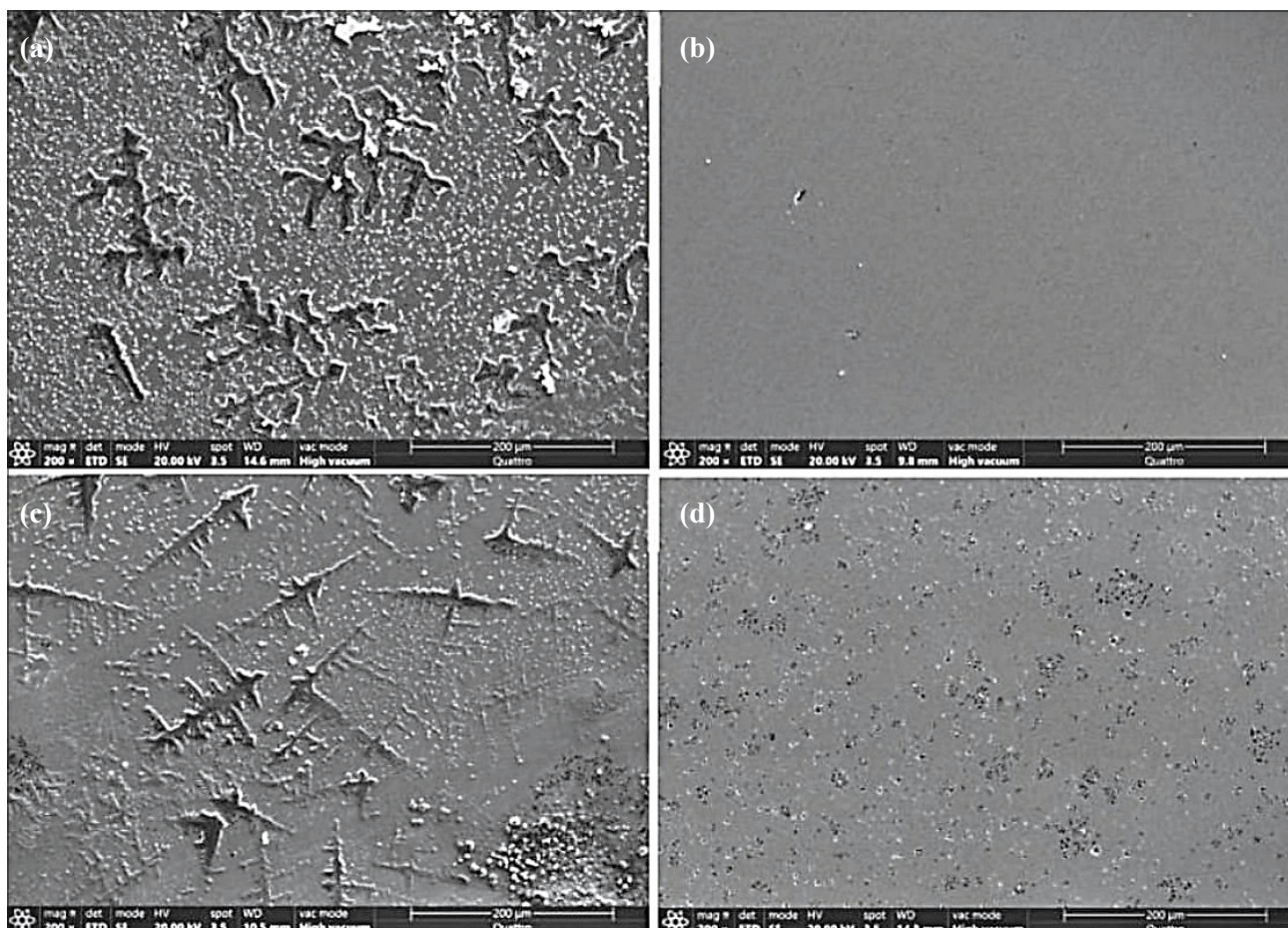


Figure 19. SEM images of corrosion on Ct3 grade steel coupons under the influence of sulfate-reducing bacteria and with the application of the HAK-2 composite reagent: a) Corrosion of steel in the presence of *Desulfomicrobium* species without any reagent applied; b) Corrosion of steel in the presence of *Desulfomicrobium* species with the addition of the HAK-2 composite reagent at its optimal concentration ($C_{\text{comp}}=20$ mg/L); c) Corrosion of steel in the presence of *Desulfovibrio desulfuricans* species without any reagent applied; d) Corrosion of steel in the presence of *Desulfovibrio desulfuricans* species with the addition of the HAK-2 composite reagent at its optimal concentration ($C_{\text{comp}}=20$ mg/L).

Figure 19a–d presents SEM images of steel surfaces after 360 hours of exposure to microbiologically active environments containing either *Desulfomicrobium* or *Desulfovibrio desulfuricans* species, with and without the addition of the HAK-2 composite reagent.

In the absence of any inhibitor (see **Figures 19a** and **19c**), severe corrosion damage is evident, with more aggressive surface degradation observed in the environment containing *Desulfovibrio desulfuricans* (**19c**).

In contrast, the addition of HAK-2 at its optimal concentration significantly reduces corrosion effects in both environments (see **Figures 19b** and **19d**). The surface exposed to *Desulfomicrobium* in the presence of HAK-2 (**25b**) appears smoother and more uniform, indicating strong inhibitory performance. However, in the case of *Desulfovibrio desulfuricans* (**19d**), although corrosion is mitigated, localized pitting remains visible – suggesting reduced effectiveness against this more aggressive SRB strain.

Overall, the HAK-2 composite demonstrates superior corrosion protection compared to individual reagents across both microbial environments, and the observed

SEM results are in full agreement with the quantitative laboratory findings.

The SEM observations support the quantitative results obtained from corrosion rate measurements and bacteriological tests. The surface morphology clearly reveals that the 20 mg/L concentration of HAK-2 provides the most effective protection, minimizing corrosion damage and bacterial colonization. The significant decrease in pitting and corrosion product deposition confirms that HAK-2 disrupts both the microbial corrosion pathway and the electrochemical processes underlying steel degradation.

The optimal performance at 20 mg/L can be attributed to a saturation effect, where the active components of HAK-2 sufficiently adsorb onto the metal surface, forming a protective barrier while simultaneously neutralizing the metabolic byproducts of SRB. This dual mechanism ensures both inhibition of bacterial proliferation and stabilization of the metal surface.

These findings reinforce the earlier experimental data, showing that the HAK-2 composition exhibits superior

performance compared to MARZA-4, particularly in aggressive environments and in the presence of SRB. The clear reduction in corrosion damage at 20 mg/L suggests this dosage as the optimal operational concentration for field applications where MIC is prevalent.

This study investigates the corrosion protective and bactericidal-inhibitor properties of the organic-origin MARZA-4 reagent and the novel HAK-2 composition in various environmental conditions. The reagents were tested in neutral, acidic, and alkaline environments, as well as in aggressive environments containing hydrogen sulfide (H₂S), carbon dioxide (CO₂), and a combination of both gases. Furthermore, their effects on sulfate-reducing bacteria in the "Postgate-B" nutrient medium were evaluated.

The explanation can be expanded with more scientific details to better clarify why the 20 mg/L concentration of HAK-2 exhibits optimal performance. Below is the rationale based on scientific principles.

Saturation effect: the saturation effect occurs when the concentration of the inhibitor HAK-2 reaches a level at which the active components in the composition fully interact with the metal surface. When the concentration of HAK-2 is increased to 20 mg/L, a sufficient amount of inhibitor molecules adsorb to the steel surface, forming a stable and protective layer. This layer reduces the direct interaction between corrosive agents (such as hydrogen sulfide, carbon dioxide, or sulfate-reducing bacteria) and the metal, thereby preventing corrosion.

Adsorption mechanism: the adsorption of HAK-2 molecules onto the metal surface is an important process in corrosion inhibition. Inhibitors like HAK-2 typically contain functional groups that can bond with the steel surface, creating a physical barrier that prevents further oxidation or chemical degradation. At 20 mg/L, there is enough of the active ingredient to form a dense, continuous film on the steel surface, offering maximum protection.

Bactericidal action on SRB: the sulfate-reducing bacteria (SRB), such as *Desulfovibrio desulfuricans* and *Desulfomicrobium*, are known to produce hydrogen sulfide (H₂S) and other corrosive metabolites, which accelerate the corrosion process. At lower concentrations of HAK-2, the number of bacteria is not sufficiently controlled, allowing them to continue their metabolic activity. However, at 20 mg/L, the bactericidal properties of HAK-2 become more effective, leading to a noticeable reduction in SRB proliferation. This not only reduces the bacterial-induced corrosion but also prevents the generation of aggressive metabolic byproducts like H₂S, further mitigating corrosion.

Dual protective mechanism: the dual mechanism of HAK-2 is particularly important. First, it inhibits the microbial activity of SRB, which prevents them from producing corrosive metabolites. Second, the inhibitor provides electrochemical protection by forming a barrier that reduces the interaction of corrosive species with the

steel surface. This combined action leads to the significant reduction of both microbial-induced corrosion (MIC) and electrochemical corrosion.

Optimal concentration: the 20 mg/L concentration represents a threshold concentration where the beneficial effects of HAK-2 are maximized. Concentrations above this level may lead to diminishing returns in terms of additional protective effects, as the surface may become saturated, and any excess inhibitor might not further enhance performance. Conversely, concentrations below 20 mg/L might not fully protect the metal surface or control bacterial activity, leading to reduced effectiveness.

Field applications: in field conditions, especially in environments prone to microbiologically influenced corrosion (MIC), 20 mg/L of HAK-2 is the optimal dosage that balances cost and performance. Higher concentrations might be wasteful, while lower concentrations may fail to prevent the harmful effects of SRB and corrosion. Therefore, 20 mg/L is recommended for industrial applications in environments where corrosion and bacterial degradation are significant concerns, ensuring both long-term protection and efficient use of the inhibitor.

This scientific reasoning ties together the experimental observations (SEM images, corrosion rates, and bacterial growth inhibition) and explains why the 20 mg/L concentration of HAK-2 offers the best balance between bactericidal activity, corrosion inhibition, and efficiency.

In conclusion, this study demonstrates that HAK-2 not only provides superior corrosion protection, but also offers more potent bactericidal-inhibitor effects compared to MARZA-4. These findings support the potential application of HAK-2 in mitigating both corrosion and microbial activity in the oil and gas industry, particularly under challenging operational conditions.

4. Conclusions

1. For the first time, the corrosion protective effect of the organic-origin MARZA-4 reagent in neutral, acidic, and alkaline environments, as well as the new HAK-2 composition in aggressive environments with hydrogen sulfide, carbon dioxide, and both gases together, has been investigated. Additionally, their effect on sulfate-reducing bacteria in the "Postgate-B" nutrient medium has been studied. It has been determined that both reagents, at an optimal concentration of 20 mg/L, possess bactericidal-inhibitor properties.
2. It has been established that the bactericidal-inhibitor MARZA-4 reagent, at concentrations of 5, 10, 15, and 20 mg/L in neutral, acidic, and alkaline environments, provides corrosion protective effects of 88%, 91%, 96%, 98%, 86%, 90%, 95%, 98%, and 80%, 84%, 86%, 94%, respectively. In the "Postgate-B" nutrient medium, the bactericidal effect against *Desulfovibrio desulfuricans* and

Desulfomicrobium cells is 42%, 57%, 69%, 78%, and 45%, 60%, 75%, 81%, respectively.

- The corrosion protective effect of the HAK-2 composition in hydrogen sulfide, carbon dioxide, and both gases together in aggressive corrosion environments, as well as its effect on sulfate-reducing bacteria in the "Postgate-B" nutrient medium, has been studied. It has been determined that, compared to the MARZA-4 reagent, the HAK-2 composition exhibits higher bactericidal-inhibitor properties. Therefore, the HAK-2 composition is proposed for widespread use as a bactericidal-inhibitor reagent in the oil industry, particularly in field conditions.

Acknowledgement

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SAŽETAK

Istraživanje inhibitorskih svojstava novih reagensa na djelovanje bakterija

Opće je poznato da je u industrijski razvijenim zemljama proizvođačima nafte jedan od najvećih neriješenih izazova, kojim se ujedno produljuje radni vijek opreme i postrojenja, zaštita unutarnjih površina opreme i postrojenja od korozije. S obzirom na navedeno, ovaj rad analizira rezultate brojnih laboratorijskih ispitivanja učinaka novorazvijenoga organskog reagensa MARZA-4 i sastava privremeno nazvanoga HAK-2 na bakterije koje reduciraju sumporovodik, ugljikov dioksid i sulfate, koji su primarni uzroci korozije unutarnjih površina u naftnoj industriji. Prvi put istraživana je učinkovitost djelovanja reagensa MARZA-4 protiv bakterija koje reduciraju sulfate u agresivnim korozivnim okruženjima kao što su neutralni, kiseli i alkalni mediji te u hranjivome mediju „Postgate-B”. Utvrđeno je da reagens MARZA-4 posjeduje inhibitorska svojstva pri optimalnoj koncentraciji od 20 mg/L. Pri toj koncentraciji njegov zaštitni učinak od korozije u neutralnim, kiselim i alkalnim okruženjima utvrđen je na 98 %, 98 % i 94 %. U hranjivoj podlozi „Postgate-B” bakteriциден učinak protiv stanica *Desulfovibrio desulfuricans* i *Desulfomicrobium* bio je 78% odnosno 81%.

Ključne riječi:

bakterije koje reduciraju sulfate, inhibitor, sumporovodik, ugljikov dioksid, agresivno korozivno okruženje

Author's contribution

Guseyn R. Gurbanov (Professor, Doctor of Science in Chemistry): methodology development and validation. **Aysel Gasimzade** (PhD, Associate Professor): conceptualization, investigation and software. All authors have read and agreed to the published version of the manuscript.