A Review on Fosfomycine and its Derivatives: New Scale Inhibitors for Oilfield Application

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Review Article

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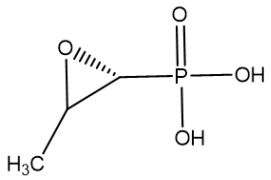
ABSTRACT

Amino methylene-phosphonate is an antibiotic medication use for urinary problems caused by bacterial infection. It works by interfering with bacterial cell wall synthesis. This is a widely use for studies based on scale inhibitors for various oilfield scales. Calcite and Gypsum new molecules are low toxic for test of fosfomycine. Fosfomycin trometamol synthesis from fosfomycin disodium salt and 1,2-dihydroxypropyl fosfonic acid prepare from fosfomycin disodium salt by hydrolysis method. Under the guideline of NACE, effectiveness comparison of commercial oilfield scale inhibitor HPAA and all these chemicals in inhibiting calcite and gypsum scales was assessed. Heidrun oilfield in Norway was used to evaluate the effectiveness of amino methylene-free phosphonate scale inhibitors (Product-1, Product-2, Product-3, and HPAA) in preventing calcite scale formation. This information suggests that the researchers were interested in understanding the performance of these inhibitors in a specific field environment, likely due to the prevalence of calcite scale issues in that region. The newly developed amino methylene-free phosphonate scale inhibitors demonstrated impressive resistance to calcium ions, effectively preventing the formation of both gypsum and calcite scale. All compounds derived from fosfomycin exhibited remarkable tolerance to high calcium concentrations, remaining stable at levels up to 1000 ppm for 24 hours, outperforming HPAA.

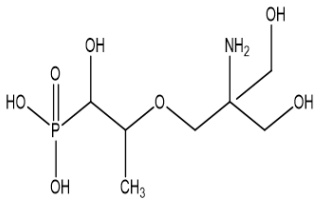
Keywords: Fosfomycine disodium salt; Fosfomycine Trometamol and 1,2-dihydroxy methylene phosphonic acid of oilfield scale inhibitions; Amino tris-methylene phosphonic acid; Ethylene diamine tetra ethylene phosphonic acid; Diethylene tri-amin penta methylene phosphonic acid

INTRODUCTION

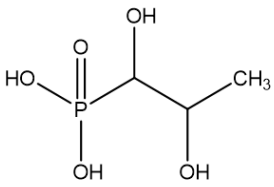
Amino methylene phosphonate scale inhibitors



Product-1

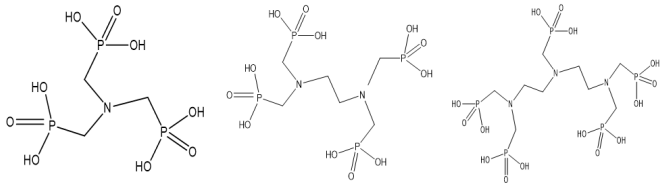


Product-2



Product-3

Scale inhibitors for amino methylene-free phosphonate



AMINOTRISMETHYLENE PHOSPHONIC ACID

ETHYLENEDIAMINE TETRAMETHYLENE PHOSPHONIC ACID

DIETHYLENETRIAMINE PENTAMETHYLENE PHOSPHONIC ACID

Severe flow restrictions in oil and gas production installations can be exacerbated by the formation of scale, even when various scale inhibitors are applied [1]. The deposition of inorganic solids due to excess mineral content in formation water is a critical aspect of the petroleum reservoir life cycle. Scale inhibition processes are essential to prevent these mineral buildups, which can significantly impact reservoir productivity and flow efficiency [2]. Over time, the accumulation of scale may impede the production process, setting off a cascade of issues that reduce oilfield productivity and risk economic losses, highlighting the imperative to prevent scale formation [3,4]. Calcite ($CaCO_3$), Barite ($BaSO_4$), Gypsum ($CaSO_4 \cdot 2H_2O$), and Celestite ($SrSO_4$) are the most prevalent divalent metal ion precipitates encountered in the oilfield industry. Among these, calcium carbonate calcite is the most common scale deposit and the most thermodynamically stable polymorph [5]. Moreover, seawater is laden with substantial concentrations of sulfate (SO_4^{-2}) ions. The variance in the ionic composition of seawater and formation water when combined during Enhanced Oil Recovery (EOR) results in scale precipitation. Sulfate scales tend to form more frequently when formation water mixes with injected seawater or when disparate waters combine in topside flow lines [6,7].

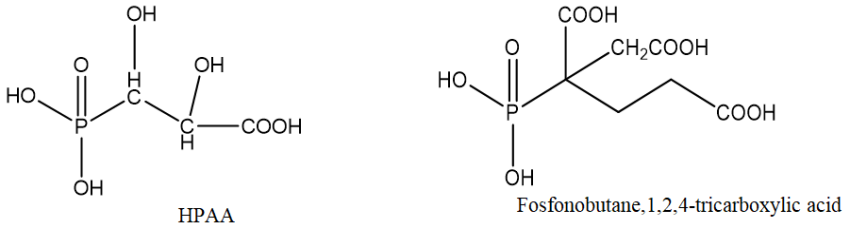
The application of scale prevention agents is one of the most common strategies for addressing scaling problems in various industries [8,9]. Scale inhibitors typically consist of water-loving substances that are used to prevent the formation of inorganic scales by inhibiting nucleation and crystallization [10,11]. Many existing scale inhibitors face a balance between inhibitory effectiveness and expenses. Nonetheless, they may fall short in other crucial attributes that necessitate careful evaluation before field application, such as calcium tolerance and biodegradability [12].

Amino methylene phosphonate compounds exhibit strong adherence to rock formations, resulting in extended squeeze treatment durations. However, their limited biodegradability in certain regions, such as the North Sea, restricts their use in offshore areas with stringent environmental regulations. Traditional scale inhibitors like ATMP, DTPMP, and EDTMP are often preferred in such cases (Figure 1). Moreover, a significant number of these types of scale inhibitors also exhibit poor tolerance characteristics when exposed to high-calcium brines, resulting in the formation and settling of a complex involving Ca^{+2} and scale inhibitors [13].

Amino methylene-free phosphonates are widely used as scale prevention agents in the upstream oil and gas industry. In a prior study, we assessed various amino methylene-free phosphonate compounds as scale prevention agents for various types of scale deposits found in the Heidrun oilfield in the Norwegian Sea [14]. The findings indicated that HPAA was highly effective in preventing calcite scale formation and showed satisfactory performance in reducing oilfield barite scaling under high-pressure dynamic flow conditions at 100 °C and 1200 psi (Figure 1) [15,16].

As environmental regulations tighten, novel production chemicals must meet specific criteria to qualify for usage in the petroleum sector. Consequently, there's a pressing necessity to develop chemicals that offer high efficacy in scale inhibition while also boasting an improved environmental profile to meet the expectations of diverse stakeholders. This study aims to create new amino methylene-free phosphonates derived from fosfomycin, a type of antibiotic used for urinary tract infections, and assess their ability to prevent scale formation in oilfield operations [17]. According to our knowledge and research, there is no publicly available information about using this chemical to prevent scale in oilfield operations. The choice to investigate fosfomycin as the starting compound is influenced by its low toxicity, stability at room temperature for 3 hours followed by refrigeration at 4 °C, high absorption rate, and the presence of chemical groups in its molecular structure that are known to improve scale prevention capabilities. These characteristics could potentially result in better scale prevention effectiveness and increased biodegradability compared to commercially available scale inhibitors. Furthermore, our research group has developed a range of low-toxicity bisphosphonates, typically used as bone-targeting drugs, as innovative scale prevention agents for carbonate and sulfate scales found in oilfields [18].

Figure 1. Schematic representation of chemical structures of series of scale inhibitors for amino methylene-free phosphonate (ATMP, EDTMP and DTPMP).



Reaction

Moreover, Product-1 will serve as the precursor for the synthesis of the bioavailable variant of fosfomycin, commonly recognized as fosfomycin trometamol (Product-2) (Figure 2) [19]. The molecular configuration includes an ether bond, which has been demonstrated to enhance biodegradation capabilities. Another non-polymeric phosphonate-based scale inhibitor was synthesized by hydrolyzing fosfomycin, resulting in the creation of 1,2-dihdroxypropyl phosphonic acid (Product-3) (Figure 3) [20,21].

Figure 2. Synthesis of fosfomycine trometamol from fosfomycine.

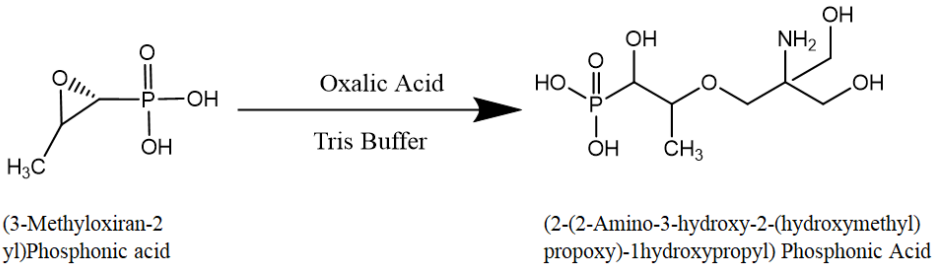
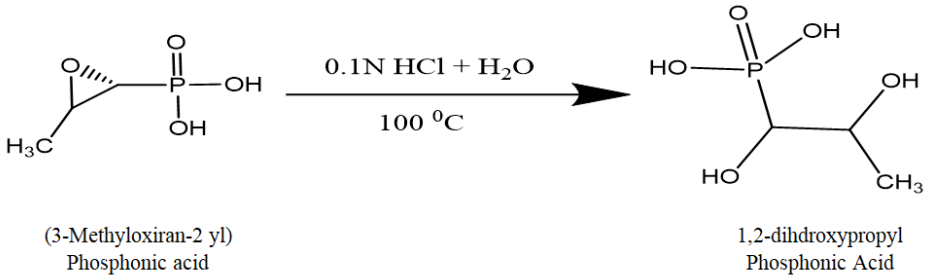


Figure 3. Synthesis of 1,2-dihdroxypropyl phosphonic acid from fosfomycine.



LITERATURE REVIEW

The necessary chemicals and Fosfomycin (API) were acquired from Tokyo Chemical Industry Co. ltd, Sigma-Aldrich, VWR Chemicals, and ACROS Organics. All solvents were purchased from ShanDong XinTai water Treatment Technology Co. ltd and used without additional purification. The structures of all derivatives were characterized using ^{1}H-NMR, ^{13}C-NMR, ^{31}P-NMR, and Fourier Transform Infrared (FTIR) spectroscopy with D_2O and a 400 MHz Bruker NMR spectrometer. All FTIR data was processed using Microlab PC software.

Fosfomycine

IUPAC name: (3-Methyloxiran-2-yl) phosphonic acid

IR (γmax cm^{-1}): 1089(PO_3).

^{1}H-NMR (δ ppm) D_2O 400 MHz: 3.20-3.13 (m,1H, -CH-CH_3), 2.75-2.69 (dd, 1H, -CH-PO_3H_2), 1.38-1.37 (d, 3H, -CH-CH_3).

^{31}P-NMR (δ ppm) D_2O 162.00 MHz: 10.00.

Synthesis of fosfomycine trometamol

Step 1: Dissolve 2.00 gm of fosfomycine disodium salt in 16 ml of methanol in a 100 ml two-necked flask equipped with a reflux condenser. Heat the mixture to 65°C with magnetic stirring.

Step 2: Dissolve 1.39 gm of oxalic acid dehydrate and 1.33 gm of tris-buffer in 9 ml of methanol in a 100 ml one-necked flask with a reflux condenser. Heat the mixture to 50°C with magnetic stirring. Slowly add the second solution to the first solution at the same temperature using a dropping funnel. After the reaction, allow the final solution to cool to room temperature for 3 hours, then refrigerate at 4°C overnight. The next day, filter the milky suspension under vacuum using a Buchner funnel and concentrate the solution using a rotary evaporator. Wash the product with a 1:1 mixture of acetone and ethanol with vigorous magnetic stirring at room temperature for 3 hours. Filter the resulting white crystal suspension under vacuum using a Buchner funnel. Wash the white crystal product with absolute ethanol and dry it, yielding Product-2 [22,23].

IUPAC name: (2-(2-Amino-3-hydroxy-2-(hydroxymethyl) propoxy)-1-hydroxypropyl) phosphonic acid

Yield: 85%

IR (γmax cm^{-1}): 3048(NH_2), 2945, 2822(OH), 1138(CO), 1035(PO_3).

^{1}H-NMR (δ ppm) D_2O 400 MHz: 3.60 (s, 6H, $(CH_2(OH))_2$-C(NH_2)-CH_2-), 3.27-3.20 (m,1H,-CH-CH_3), 2.87-2.80 (dd, 1H, -CH(OH) (PO_3H_2), 1.37-1.35 (d, 3H, -CH-CH_3).

^{31}P-NMR (δ ppm) D_2O 162.00 MHz: 12.29.

Synthesis of 1,2-dihdroxypropyl phosphonic acid

Dissolve 2.00 gm of fosfomycine disodium salt in 6 ml of deionized water adjusted to pH 2.89 with 0.1 M HCl. Stir the mixture overnight at 100°C. Cool the solution to room temperature and remove excess water using a rotary evaporator. Finally, wash the product with absolute ethanol using vigorous magnetic stirring for 4 hours at room temperature and dry it, resulting in Product-3.

IUPAC name: 1,2-dihdroxypropyl phosphonic acid

Yield: 76%

IR (γmax cm^{-1}): 3249(OH), 1041(PO_3).

^{1}H-NMR (δ ppm) D_2O 400 MHz: 3.99-3.92 (m, 1H, (-CH(OH)-CH_3), 3.46-3.42 (dd, 1H, -CH(OH) (PO_3H_2), 1.22-1.20 (d, 3H, -CH-CH_3).

^{31}P-NMR (δ ppm) D_2O 162.00 MHz: 17.33.

Static bottle test protocol

In Table 1 gypsum brines were prepared.

Table 1. As per NASE procedure water chemical composition for the gypsum scale

Ion	Na^+	Ca^{+2}	SO_4^{-2}
ppm	5900	3028	7209
Chemical	NaCl	$CaCl_2$. $2H_2O$	Na_2SO_4
Brine-1 (g/L)[a]	7.5	11.1	0
Brine-2 (g/L)[b]	7.5	0	10.66
Note: Brine-1 pH[a] is 5.5 and Brine-2 pH[b] is 5.5			

In Table 2 Calcite brines were prepared.

Table 2. As per NASE procedure water chemical composition for the calcite scale.

Ion	Na^+	Ca^{+2}	Mg^{+2}	HCO_3^{-1}
ppm	25,964	3314	440	5346
Chemical	NaCl	$CaCl_2$. $2H_2O$	$MgCl_2$. $6H_2O$	$NaHCO_3$
Brine-1 (g/L)[a]	33	12.15	3.68	0
Brine-2 (g/L)[b]	33	0	0	7.36
Note: Brine-1 pH[a] is 5.5 and Brine-2 pH[b] is 7.1				

Further, these chemicals were screened against Heidrum calcite scale system, Norway. This water composition of Heidrum brines prepared by 1:1 volume mixture of Seawater and Formation water (Table 3).

Table 3. As per NASE procedure water chemical composition of the Heidrum calcite oilfield scale.

Ion	Na^{+}	Ca^{+2}	Mg^{+2}	HCO_3^{-1}	Sr^{+2}	K^{+}	Ba^{+2}
ppm	39020	2040	530	1000	290	1090	570
Chemical	NaCl	$CaCl_2.2H_2O$	$MgCl_2.6H_2O$	$NaHCO_3$	$SrCl_2.6H_2O$	KCl	$BaCl_2.2H_2O$
Brine-1 (g/L)[a]	49.59	7.48	4.43	0	0.882	2.078	1.014
Brine-2 (g/L)[b]	49.59	0	0	2.76	0	0	0
Note: Brine-1 pH[a] is 5.5 and Brine-2 pH[b] is 7.1							

The proposed stock solution for all products, prepared at a concentration of 100 ppm, was made by dissolving the appropriate amount of product in 500 ml of distilled water. The pH of the resulting mixture was then adjusted to a range of 4.0 to 6.0 for all reservoir pH values. Finally, each static bottle was screened in triplicate, and the standard deviation of the results was found to be between 1 and 3% [24].

Calcium compatibility test

Organophosphorus compounds are commonly used as scale inhibitors in squeeze treatment processes. Nevertheless, most of these chemicals are incompatible with production water, which contains Ca^{+2} ions, resulting in the formation of a calcium-scale inhibitor precipitate. Consequently, it is essential to evaluate the compatibility of the proposed scale inhibitors with Ca^{+2} ions to ensure their effectiveness. A series of compatibility tests were conducted using varying concentrations of Scale Inhibitors 100, 1000, 10,000, and 50,000 ppm and different Ca^{+2} ion concentrations 100, 1000, and 10,000 ppm in the presence of 30,000 ppm NaCl (3% of weight) dissolved in 20 ml of distilled water. The pH of the solution mixtures was adjusted to a range of 4 to 6. Subsequently, all prepared containers were placed in an 80°C oven for 24 hours.

RESULTS AND DISCUSSION

Chemistry of products: All three products which were amino methylene free phosphonate studied as anti-scaling agent for calcite and gypsum scales. First of all, we purchased commercial and natural product antibiotic fosfomycine of oilfield under scale Inhibitors. Secondly we prepared fosfomycine trometamol. Fosfomycine disodium salt react with tris buffer and oxalic acid in presence of acidic media. Finally Product-3 was form by hydrolysis of fosfomycine disodium salt in presence of acidic media with pH 2.89 adjust with acid in reflux condenser at high temperature [25].

The all structures were characterized by NMR, FTIR spectroscopic techniques.

Product-1: In FTIR spectroscopic spectra give a sharp absorption peak was shown at 1089 cm^{-1}, In IR spectra CO was identify as epoxide. Moreover, in structure C=O band at 1650-1800 cm^{-1} and O-H band at 3200-3700 cm^{-1}. ^{1}H NMR fosfomycine disodium shown multiple peak with D_2O in range of 3.20-3.13 which indicates that -CH-CH_3. Double doublet peak observed which was represent that CH-PO_3H_2 at 2.75 ppm value. Also we observed sharp doublet peak of methyl group (CH-CH_3) at 1.38 and 1.37.

Product-2: Fosfomycine trometamol structure characterized in FTIR broad spectra at 3048 cm^{-1}, also present NH stretching vibration and OH stretching band at 2945 and 2822 cm^{-1}. Phosphonate group was presence at 1035 cm^{-1}. A sharp singlet peak was observed at 3.60 ppm which indicate that methyl group (CH_2-$(OH)_2$-$C(NH_2)$-CH_2-).

Product-3: 1,2-dihdroxypropyl phosphonic acid was characterized by FTIR broad spectra of OH at 3249 cm^{-1} and sharp spectra absorption peak at 1041 cm^{-1} was identified that phosphonate was present in 1,2-dihdroxypropyl phosphonic acid. Moreover, 1,2-dihdroxypropyl phosphonic acid was shown chemical shift from fosfomycine to 1,2-dihdroxypropyl phosphonic acid.

When fosfomycine shown singlet signal at 10.00ppm in ^{31}P-NMR while 1,2-dihdroxypropyl phosphonic acid was shifted that 17.33 ppm and fosfomycine trometamol shafted to 12.29 ppm.

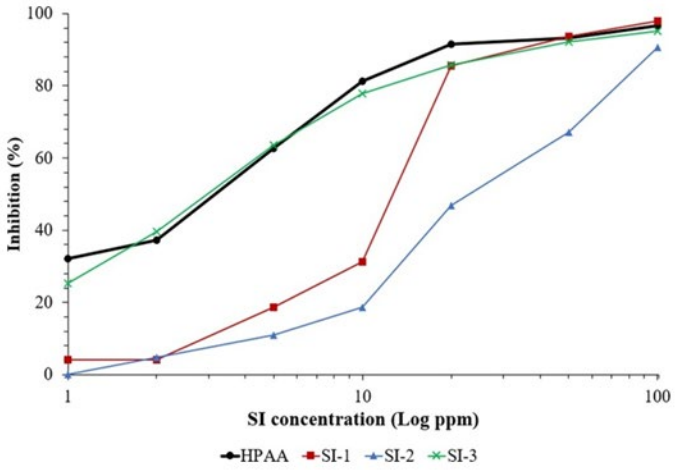
Scale inhibition performance all products scale inhibitors product concertation was 100 50, 20, 10, 5, 2 and 1 ppm were evaluated using static bottles at 80°C for 5 hours. Also scale inhibitors products HPAA was tested their performance comparison under same condition.

Gypsum scale: Table 4 and Figure 3 demonstrate the scale inhibition effectiveness of the commercial scale inhibitor HPAA and three novel amino methylene-free phosphonates (Product-1, Product-2, and Product-3) against gypsum scale formation in static bottle tests. All amino methylene-free phosphonate scale inhibitors evaluated showed excellent performance in preventing gypsum scale formation. The commercial scale inhibitor HPAA exhibited superior inhibition efficiency at higher scale inhibitor concentrations (100-20 parts per million) and moderate inhibitory activity at lower scale inhibitor levels (10-1 parts per million).

Table 4. All three product and commercial SI (HPAA) with gypsum inhibition efficiency.

	% Inhibition						
Concentration (ppm)	100	50	20	10	5	2	1
HPAA	97	93	91	81	63	37	32
Product-1	98	94	85	31	19	4	4
Product-2	91	67	47	19	11	5	0
Product-3	95	92	86	78	63	40	25

Figure 3. All three product and commercial SI (HPAA) with gypsum inhibition efficiency diagram.



For instance, HPAA exhibited a 97% inhibition efficiency at 100 ppm, as indicated in Table 4. Comparatively, the newly evaluated scale inhibition-based fosfomycin analog, Product-1, demonstrated only a marginal 1% improvement over HPAA at 100 and 50 ppm. Additionally, Product-1 demonstrated a respectable inhibition efficiency of 85% at 20 parts per million, but this efficiency decreased to 31% at 10 parts per million. Moreover, Product-1 exhibited weaker inhibition performance at lower scale inhibitor concentrations compared to HPAA. Product-2, a modified fosfomycin containing one phosphonate group and three hydroxyl moieties, displayed moderate gypsum inhibition performance relative to HPAA. For example, Product-2 showcased a calcium inhibition activity of 91% at 100 parts per million. Furthermore, it was observed that the inhibition activity of Product-2 gradually declined throughout the test, eventually reaching less than 10% inhibition at 2 and 1 parts per million (Table 4). In conclusion, Product-3 exhibited exceptional inhibition efficacy at elevated scale inhibitor concentrations, comparable to the performance of the commercial scale inhibitor HPAA, as shown in Table 4. Static scale efficiency trials indicated a 95% inhibition performance at 100 ppm for Product-3. Even at lower concentrations, Product-3 demonstrated significant inhibition, reaching 63% at 5 ppm SI. Moreover, Product-3 exhibited a 25% inhibition at 1 part per million, slightly lower than HPAA's 32% inhibition. Overall, HPAA consistently displayed the highest inhibition activity against gypsum scale among the scale inhibitors tested. Both Product-1 and Product-2 demonstrated commendable performance only at the highest concentrations of the scale inhibitor. In contrast, Product-3 exhibited effective performance across all tested scale inhibitor concentrations. The slight difference in performance between HPAA and Product-3 can be attributed to the carboxyl moiety present in the structural backbone of HPAA. This functional group facilitates interactions between the scale inhibitor and ions in the solution, thereby enhancing inhibition performance.

Simplified calcite scale: Table 5 presents the inhibition performance of all products against calcite scale. HPAA exhibited 71% inhibition at a concentration of 100 ppm and 57% inhibition at a concentration of 50 ppm. At 100 ppm, Product-1

showed 43% inhibition, Product-2 showed 48% inhibition, and Product-3 showed 62% inhibition. However, Product-1 exhibited a decrease in inhibition to 22% at 50 ppm and further to 17% at 20 ppm, while Product-2 immediately dropped to 18% at 50 ppm. Both Product-1 and Product-2 demonstrated inhibition below 10% from 10 and 20 ppm, respectively. As for Product 3, it displayed a decent inhibition performance of 62% at 100 ppm, decreasing to 42% and 17% at 50 and 20 ppm, respectively. Similarly observed with the gypsum scale, Product-3 exhibited enhanced inhibition performance in comparison to Product-1.

Table 5. All three product and commercial SI (HPAA) with calcite inhibition efficiency.

	% Inhibition						
Concentration (ppm)	100	50	20	10	5	2	1
HPAA	71	57	34	29	18	3	1
Product-1	43	22	17	8	6	4	1
Product-2	48	18	6	1	0	0	0
Product-3	62	42	17	12	9	6	1

This improvement could be due to the linear structure of SI-3, which includes a hydroxyl group that may provide additional binding sites compared to the epoxide ring present in Product-1. As previously mentioned, Product-3 has a chemical structure similar to HPAA, except for the absence of the carboxyl group. This structural difference leads to HPAA achieving inhibition levels greater than 10% at concentrations up to 5 parts per million, a feature not shared by Product-1 or Product-3.

Heidrum calcite scale: In this study, the scale inhibition effectiveness of all examined amino methylene-free phosphonates was evaluated against Heidrun calcite scale using the NACE Standard. The inhibition efficiencies of Heidrun calcite for amino methylene-free phosphonates (Products) and the commercial scale inhibitor (HPAA) are presented in Table 6. The results obtained indicated satisfactory inhibition performance for all tested Scale Inhibitors (SIs) at higher concentrations. Concerning the commercial Scale Inhibitor (SI), HPAA maintained an inhibition efficiency exceeding 90% up to 5 ppm. However, it was observed that the inhibition performances of HPAA decreased to 36% and 13% at concentrations of 2 and 1 ppm, respectively. Regarding the new amino methylene-free phosphonate scale inhibitors, fosfomycin Product-1 (which is based on an epoxide ring) demonstrated 92% inhibition at 100 ppm. However, this inhibition decreased to 71% at 50 ppm. Additionally, Product-1 exhibited weak inhibition at low inhibitor doses against Heidrun calcite scale. As for the modified fosfomycin, Product-2 displayed moderate inhibition performances, achieving 68% and 55% inhibition at 100 and 50 ppm, respectively. Notably, inhibition performance consistently decreased at lower concentrations, resulting in poor efficiency. Furthermore, the new linear amino methylene-free phosphonate Product-3 exhibited excellent inhibition efficiency against calcite scale at high SI concentrations (100-10 ppm). For instance, Product-3 achieved 97% inhibition at 100 ppm. However, Product-3 demonstrated inferior inhibition performances at lower inhibitor concentrations compared to other new amino methylene-free phosphonates (Product-1 and Product-2) and the commercial SI HPAA, as illustrated in Table 6.

Table 6. All three product and commercial SI (HPAA) with Heidrum calcite inhibition efficiency.

	% Inhibition						
Concentration (ppm)	100	50	20	10	5	2	1
HPAA	100	98	97	95	95	36	13
Product-1	92	71	49	38	32	24	24
Product-2	68	55	34	24	18	15	13
Product-3	97	73	61	42	15	10	7

Evidently, the new amino methylene-free phosphonate scale inhibitors exhibit moderate inhibition capabilities for both calcite and gypsum oilfield scales. The presence of a limited number of functional inhibition groups (such as PO_3H_2, COOH, and SO_3H) within the inhibitor's structural framework led to reduced inhibition performance, particularly at lower SI concentrations. Additionally, it is likely that the testing conditions of the Heidrun calcite water system significantly influenced the scale inhibitor's effectiveness compared to standard calcite. In the case of standard calcite, the mixed brine contains a Ca^{+2} ions concentration of 1657 ppm and Mg^{+2} concentration of 220 ppm. Conversely, for Heidrun calcite, the calcium ion concentration is 1020 ppm, and the magnesium ion concentration is 265 ppm. Although the magnesium ion concentration

is slightly higher under Heidrun conditions compared to the NACE Standard recommendation, it did not seem to negatively affect the inhibition performance of the tested scale inhibitors. This could be due to the lower calcium ion concentration in Heidrun water chemistry, as the detrimental effect of magnesium ions on inhibition efficiency tends to be more pronounced at higher calcium ion concentrations.

CONCLUSION

Three novel non-toxic fosfomycin compounds based on amino methylene-free phosphonates have been developed as scale inhibitors in the petroleum industry. These new amino methylene-free phosphonates, specifically fosfomycin disodium salt Product-1, fosfomycin trometamol Product-2, and 1,2-dihydroxypropyl phosphonic acid Product-3, were compared and screened alongside the commercial scale inhibitor Hydroxyl Phosphono Acetic Acid (HPAA) using a static bottle test and calcium compatibility assessment. Regarding gypsum scale, only Product-1 and Product-2 exhibited significant performance, but only at the highest concentrations of the scale inhibitor. However, Product-3 demonstrated consistent and commendable performance across all concentrations of scale inhibitors tested. Furthermore, HPAA displayed exceptional scale inhibition efficiency. The slight difference in performance between HPAA and Product-3 can be attributed to the presence of the carboxyl group within the structure of HPAA. Concerning calcite scale, the inhibition efficiency of all examined scale inhibitors appeared relatively moderate for simplified calcium carbonate, as per the NACE Standard. However, these substances exhibited satisfactory inhibition activity against the Heidrun calcite scale in Norway. We hypothesize that the main reason for the reduced inhibition of these scale inhibitor classes could be due to the limited number of functional inhibition groups (such as PO_3H_2, COOH, and SO_3H) within the inhibitor's structural framework.

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