A glutamic acid-based polymer keeping intact the integrity of all the three original functionalities of the amino acid

Zakariyah A. Jamiu, Hasan A. Al-Muallem and Shaikh A. Ali

Chemistry Department, King Fahd University of Petroleum & Minerals, Dhahran, Saudi Arabia

ABSTRACT

Dimethyl glutamate, on treatment with allyl bromide, afforded dimethyl N,N-diallyl glutamate which upon alkaline ester hydrolysis followed by acidification with aqueous HCl gave N,N-diallyl glutamic acid hydrochloride [(CH₂=CH–CH₂)₂NH⁺CH(CO₂H)(CH₂)₂CO₂H Cl⁻] I. Using Butler's cyclopolymerization protocol, new monomer I underwent ammonium persulfate-initiated polymerization to give pyrrolidine ring-embedded linear cycopolymer II i.e. −[−CH₃(C₆H₅)NH⁺{CH(CO₂H)(CH₂)₂CO₂H Cl⁻}CH₂−]ₙ, retaining the integrity of all the three functionalities of glutamic acid. Under the influence of pH, the repeating units of triprotic acid (+) in II were equilibrated to those of water-insoluble diprotic polyzwitterionic acid (±) III, water-soluble monoprotic poly(zwitterion-anion) (±−) IV, and its conjugate base polydianion (=) V. The critical salt concentration required to promote water solubility of (±) III has been determined to be 0.548 M NaCl, 0.271 M NaBr, 0.133 M NaI. The basicity constants of the carboxyl groups and trivalent nitrogen in (=) V have been determined. A 5 ppm and 20 ppm concentrations of III are effective in inhibiting the precipitation of CaSO₄ from its supersaturated solution with a ≈100% scale inhibition efficiency at 40 °C for a duration of over 3 and 16 h, respectively.

1. Introduction

Glutamic acid, one of the 20–23 proteinogenic amino acids, is a non-essential amino acid. Its salt, known as glutamate, one of the most abundant molecules in the brain, is an important neurotransmitter in neural activation.[1] Glutamate is involved in cognitive functions such as learning and memory in the brain [2] and a key compound in cellular metabolism.[3] Free glutamic acid, present in a wide variety of foods, is responsible for umami, one of the five basic tastes of the human sense of taste. Owing to its biodegradable, non-toxic, and non-immunogenic properties, poly (γ-glutamic acid) (γ-PGA) −[NHCH(CO₂H)CH₂CH₂CO]ₙ−, a biopolymer produced on the industrial scale by Bacillus subtilis, has unlimited potential for future application in foods, pharmaceuticals, healthcare, water treatment, and other fields.[4] PGA is widely used as a drug delivery system in cancer treatment.[5] A novel bio-based hydrogel, prepared by cross-linking microbial γ-PGA with glucose, has shown extremely high water absorption of 3000 g/g.[6] Many medical applications (especially drug delivery) have exploited poly (α-glutamic acid) (α-PGA) −[NHCH(CH₂CH₂CO₂H)CO]ₙ−, which is synthesized chemically as its microbial production is difficult.[7] For numerous biochemical reactions, enzymes work only in the presence of certain metal ions. In this context, the metal ion complexes of many amino acids including L-glutamic acid have been investigated.[8–10] Like aspartic acid-derived polymer, corresponding polymers from glutamic acid have the potential to act as polychelatogenes to scavenge toxic metal ions from contaminated water resources.[11]

Keeping in view the tremendous importance of glutamic acid and its abundant availability, we intend to synthesize a glutamic acid-based monomer that could lead to polymers keeping intact the unquenched valence of the nitrogen. Note that in proteins or PGA, the basic character of the nitrogen is lost in the peptide or amide bond. In the current endeavor, monomer 4, a pH-responsive triprotic acid with unquenched nitrogen valence would be subjected to walk through Butler’s cyclopolymerization protocol [12–16] to yield macromolecules bearing residues of glutamic acid (Figure 1). Interesting solution properties of the new polymer are anticipated, and its use as an antiscalant will be tested. It is worth mentioning in this context that the cyclopolymerization protocol has
2.2. Physical methods for structural characterization

An elemental analyzer (Perkin Elmer Series II Model 2400) and a Fourier transform infrared (FTIR) spectrometer (Perkin Elmer 16F PC) were utilized for elemental analyses and IR spectroscopy, respectively. The nuclear magnetic resonance (NMR) spectra were recorded using a 500-MHz JEOL LA spectrometer. The 1H signal of tetramethylsilane (TMS) at $\delta = 0$ ppm in CDCl$_3$, TSP-deuterated at $\delta = 0$ ppm in D$_2$O, and the dioxane 13C peak at $\delta = 67.4$ ppm in D$_2$O were used as internal standards. Thermogravimetric analysis (TGA) was carried out using an SDT analyzer (Q600: TA Instruments, New Castle, DE, USA) in a nitrogen atmosphere. An Ubbelohde viscometer (viscometer constant = 0.005317 mm$^2$ s$^{-2}$) was utilized to measure viscosities using CO$_2$-free water under N$_2$. The pH of the solutions was measured using a Sartorius pH meter PB 11. The conductivity measurements were carried out using an Orion Versa Star benchtop meter (Thermoscientific, Beverly, MA, USA).
2.3. Synthesis of monomer and polymer

2.3.1. Dimethyl glutamate (2)

To a mixture of glutamic acid (1) (59 g, 0.4 mol) in methanol (500 mL) was added dry HCl (25 g, 0.68 mol) at 0 °C. The clear mixture was then stirred at room temperature for 3 days or until the esterification was complete as indicated by 1H MMR spectrum. High temperature was avoided to minimize the formation of cyclization product (lactam). After removal of the solvent at 25 °C, the hydrochloride salt of amine 2 was dissolved in water (100 mL) and carefully neutralized with K₂CO₃ at 0 °C; the aqueous mixture was then saturated with anhydrous K₂CO₃ and immediately extracted with CHCl₃ (5 × 100 mL). After drying and concentration, the residual amine 2 (61 g, 87%) was immediately used for the subsequent reaction with allyl bromide. Amine 2: δH (CDCl₃) 1.49 (2H, br s, NH₂), 1.85 (1H, m), 2.08 (1H, m), 2.48 (2H, t, J 7.3 Hz), 3.48 (1H, dd, J 5.2, 8.2 Hz), 3.68 (3H, s), 3.73 (3H, s).

2.3.2. Dimethyl N,N-diallylglutamate (3)

Allylbromide (85 g, 0.70 mol) was added dropwise to a stirred mixture of amine 2 (55 g, 0.314 mol) and anhydrous K₂CO₃ (87 g, 0.63 mol) in acetonitrile (300 mL) at 40–50 °C for a period of 30 min. The resultant mixture was then stirred at 60 °C for 18 h. After removal of the solvent, the residue was taken up in water (200 mL) and extracted with ether (3 × 100 mL). The organic layer was dried, concentrated, and distilled using a vigreux distillation column to obtain diallylamine derivative 3 as a colorless liquid (69 g, 86%); bp 0.2 mbar Hg 91 °C. (Found: C, 61.0; H, 8.1; N, 5.4%. C₁₁H₁₈ClNO₄ requires C, 61.16; H, 8.29; N, 5.49%); νmax (neat): 3078, 3002, 2974, 2844, 1738, 1642, 1437, 1364, 1258, 1201, 1164, 1120, 1074, 995, 923, and 793 cm⁻¹; δH (CDCl₃) 1.85–2.10 (2H, m), 2.42 (2H, m), 3.03 (2H, dd, J 7.8, 14.5 Hz), 3.32 (2H, dd, J 4.6, 14.5 Hz), 3.47 (1H, dd, J 5.8, 9.8 Hz), 3.67 (3H, s), 3.70 (3H, s), 5.15 (4H, m), 5.73 (2H, m); δC (CDCl₃) 24.45, 30.65, 51.08, 51.50, 53.29, 60.52, 117.18, 136.42, 173.13, 173.69 (TMS: 0.00 ppm).

2.3.3. N,N-Diallylglutamic acid hydrochloride (4)

A heterogeneous mixture of 3 (54 g, 0.21 mol) in water (150 mL) containing NaOH (19.6 g, 0.49 mol, 2.33 equivalents) was stirred at room temperature for 24 h. Upon complete hydrolysis of the two ester groups, the reaction mixture was neutralized with concentrated HCl (80 g, 37 w/w%, 0.81 mol). The aqueous mixture was then freeze-dried; the residual mixture was triturated with acetone (300 mL), heated to boiling, and filtered to remove NaCl. The solid NaCl was washed with hot acetone (100 mL). The combined filtrate was concentrated, and the residual thick liquid was dissolved in boiling acetone and kept inside a freezer to obtain white crystals of 4 (49.8 g, 91%). A D₂O solution containing 4 (100.0 mg) and EtOH (20.0 mg) was subjected to 1H NMR analysis which helped us to determine the molar mass of the salt as 261.5 g mol⁻¹ as against the calculated molar mass of 263.72 g mol⁻¹ thereby confirming the structure of 4 as the hydrochloride salt as depicted in Figure 1. M.p. 103–105 °C (acetone). (Found: C, 49.8; H, 6.9; N, 5.2%. C₁₁H₁₉ClNO₄ requires C, 50.10; H, 6.88; N, 5.31%); νmax (KBr): 3410, 2954 (br) 1727, 1635, 1454, 1425, 1304, 1223, 1179, 1097, 996, 843, 796, and 619 cm⁻¹; δH (D₂O) 1.98 (1H, m), 2.09 (1H, m), 2.39 (1H, m), 2.47 (1H, m), 3.65 (1H, dd, J 7.3, 13.5 Hz), 3.74 (1H, dd, J 7.1, 13.5 Hz), 3.91 (1H, dd, J 3.5, 10.2 Hz), 5.41 (4H, m), 5.72 (2H, m) (HOD: 4.65); δC (D₂O) 21.56, 30.66, 54.91, 62.93, 126.33 (=CH), 127.84(=CH₂), 171.04, 176.66 (external dioxane: 67.40 ppm). DEPT 135 NMR analysis confirmed the 13C spectral assignments.

2.3.4. Cyclopolymerization of monomer 4

As described in Table 1, a solution of monomer 4 (7.90 g, 30 mmol) and water (2.63 g) was heated under N₂ to 85 °C in a 50-mL round bottom flask fitted with a condenser. Initiator APS (0.75 g) was added at 85 °C to the stirred solution in one portion. Exothermic polymerization ensued; after continued stirring at 85–90 °C for 15 min, the mixture was cooled to 20 °C. Resultant polymer cationic polyelectrolyte (CPe) 5 was transferred to a dialysis bag with the help of 4 M HCl (10 mL) and dialyzed against deionized water for 24 h. The homogeneous solution became cloudy during dialysis owing to the transformation of CPE 5 to polyzwitterionic acid (PZA) 6 and finally started to precipitate. The entire mixture was freeze-dried to obtain PZA 6 as a white powder (Found: C, 57.8; H, 7.7; N, 6.6%. C₁₁H₁₉NO₄ requires C, 58.14; H, 7.54; N, 6.16%); νmax (KBr) 3418 (br), 3028, 2942, 2688, 1720, 1620, 1454, 1399, 1214, 1064, 885, 810, 767 and 656 cm⁻¹.

2.4. Solubility measurements

The critical (minimum) salt concentration (CSC) values were determined by titrating a 1% w/w aqueous solution...
of PZA 6 containing salts or HCl at a higher concentration than their CSC values at 23 °C with deionized water. The average of the triplicate results of the CSCs were determined to be 0.548 M NaCl, 0.271 M NaBr, 0.133 M NaI, and 0.0104 M HCl with approximate accuracies of ±1–2%.

2.5. Potentiometric titrations

The potentiometric titration used to determine protonation constants (K) is described elsewhere.[19,20] In each trial, a certain millimole (in terms of repeating unit (RU)) of PZA 6 (ZH₃⁺) in CO₂-free water (200 mL) was titrated by gradual addition of 0.05–0.15 mL of 0.0978 M NaOH or 0.1222 M HCl as described in Table 2. After each addition of the titrant, the recorded pH values were used to calculate log Kₙ at each pH value by the Henderson–Hasselbalch Equation (2) (Figure 1). The degree of protonation (α) of 8, 7, and 6 is calculated by [ZH₃⁺]/[ZH₂⁺]α, [ZH₂⁺]/[ZH⁺]α, and [ZH⁺]/ZH⁺, respectively, where [ZH₃⁺]/[ZH₂⁺], [ZH₂⁺]/[ZH⁺], and [ZH⁺]/ZH⁺ represent the corresponding concentrations at equilibrium of the protonated species 7, 6, and 5. [Z]₀ represents the initial polymer concentration in terms of RUs. Log Kₙ associated with the equilibrium 6 (ZH₃⁺) + H⁺ = (ZH₄⁺) 5 could not be determined in salt-free water.

Since PZA 6 is insoluble in salt-free water (200 mL), it was dissolved in 0.0978 M NaOH (8–11 mL) and then diluted to 200 mL using deionized water. The clear solution was then titrated with 0.1222 M HCl to determine the protonation constants. The log Kₙ, log Kₙ, and log Kₙ represent the protonation constants of the most basic center in polydianion (PDe) 8 (ZH⁻), polyzwitterion–anion (PZAN) 7 (ZH⁰⁻), and PZA 6 (ZH₂⁺), respectively. After each addition of 0.05–0.15 mL of the titrant, the recorded pH values were used to calculate the log Kₙ at each pH value by the Henderson–Hasselbalch Equation (2) (Figure 1). The degree of protonation (α) of 8, 7, and 6 is calculated by [ZH⁰⁻]/[ZH₀⁺]α, [ZH₀⁺]/[ZH⁺]α, and [ZH⁺]/ZH⁺, respectively, where [ZH⁰⁻]/[ZH₀⁺], [ZH₀⁺]/[ZH⁺], and [ZH⁺]/ZH⁺ represent the corresponding concentrations at equilibrium of the protonated species 7, 6, and 5. [Z]₀ represents the initial polymer concentration in terms of RUs. Log Kₙ associated with the equilibrium 6 (ZH₃⁺) + H⁺ = (ZH₄⁺) 5 could not be determined in salt-free water because of the insolubility of PZA 6. Note that log Kₙ was determined in 1 M NaCl which is higher than the CSC value for 6.

Because of the addition of 8–11 mL 0.0978 M NaOH, which is more than 2 equivalents of the RUs in 6 (ZH₂⁺),
the procedure described elsewhere.[21] The concentrations of the ions are three times the concentrations found in the reject brine of a Reverse Osmosis plant.[22] Induction time was assigned as the time when a rapid decrease in conductivity indicated the beginning of precipitation of CaSO₄ (Table 3). Visual inspections for any turbidity were performed.

3. Results and discussions

3.1. Synthesis and physical characterization of monomers and polymers

L-Glutamic acid (1) was esterified to dimethyl glutamate (2) which upon alkylation with allyl bromide afforded dimethyl N,N-diallylglutamate (3) in excellent yield (Figure 1). Alkaline hydrolysis of tertiary amine 3 followed by acidification gave new monomer N,N-diallylglutamic acid hydrochloride (4) in 91% yield. Note that the monomer retains the unquenched nitrogen valency as well as the two carboxyl groups of the glutamic acid. Monomer 4 underwent APS-initiated cyclopolymerization to give CPe 5 which upon depletion of HCl during dialysis was transformed to its water-insoluble zwitterionic form: PZA 6 in over 80% yields (Table 1).

The polymer is converted to its dianionic form 8 (Z⁻) by neutralization with 2 equivalents of NaOH. By considering the excess NaOH as added OH⁻, the concentration of the protonated species 7 [ZH⁺] during the first step of titration of 8 (Z⁻) with HCl to determine log $K_1$ was given by $[ZH⁺]_{eq} = C_{H⁺}^- - C_{OH}^- - [H⁺]$ + $[OH^-]$, where $C_{OH}^-$ represents the concentration of the added ‘excess NaOH’. The equilibrium [H⁺] and [OH⁻] values were determined from the pH values, whereas $C_{H⁺}^-$ represents the concentration of added HCl during titrations. Continuing the titration, log $K_2$ and log $K_3$ were calculated using titrant volume after subtracting one-equivalent and two-equivalent volume, respectively, from the total volume. In few instances, 0.1222 M HCl (8 mL) was added to 6 (ZH₂±) to convert it to 5 (ZH₃⁺) to attain a suitable value of $\alpha$ (See Table 2, footnote). The solution was then titrated with 0.0978 M NaOH to determine log $K_3$ using equation: $[ZH₃⁺]_{eq} = [Z]₀ + C_{H⁺}^− - C_{OH}^- - [H⁺]$ + $[OH^-]$, where $C_{H⁺}^−$ represents the concentration of added ‘excess HCl’, and $C_{OH}^-$ represents the concentration of added NaOH during titrations. Note that 1 equivalent of HCl is required to transform 6 (ZH₂±) to 5 (ZH₃⁺); as such the added excess $C_{H⁺}^-$ was calculated after subtracting 1 equivalent from the total added HCl.

2.6. Evaluation of antiscalant behavior

The precipitation and inhibition of calcium sulfate (gypsum) scale formation were evaluated at 40 ± 1 °C in a supersaturated solution of CaSO₄ containing 2598 mg L⁻¹ of Ca²⁺ and 6300 mg L⁻¹ of SO₄²⁻ in the presence of newly synthesized antiscalant 6 (x ppm) (Table 1, entry 2) using Table 3. Percent inhibition against precipitation at various times in the presence of various concentrations of the synthesized polymer 6 in a supersaturated CaSO₄ solution at 40 °C.

| Entry | Sample (ppm) | 200 | 300 | 500 | 1000 | 2000 | 3000 | Induction time (min) |
|-------|--------------|-----|-----|-----|------|------|------|---------------------|
| 1     | 5            | 99  | 97  | 87  | 9.6  | –    | –    | 500                 |
| 2     | 10           | 100 | 100 | 100 | 90   | 11   | –    | 1200                |
| 3     | 20           | 100 | 100 | 100 | 100  | 98   | 96   | –a                  |

*No induction observed on the studied time range.

Figure 2. TGA curve of PZA 6.
polymers containing amine and carboxy motifs has been reported.[23]

### 3.2. IR and NMR spectra

The symmetric and antisymmetric stretching of COO− in the dipolar form (±) 6 appeared at respective 1399 cm⁻¹ and 1620 cm⁻¹ similar to those observed for simple amino acids,[30] while the absorption for the C=O stretch of COOH appeared at 1720 cm⁻¹.

As evident from the NMR spectra of monomer 4, polymers 6 and 8 (Figures 3 and 4), the absence of the protons or carbons of the alkene motifs in the polymers’ spectra suggests the chain termination to occur via coupling process.[24] The low molar masses as reflected by the lower intrinsic viscosities also point toward chain termination process by abstraction of an allylic proton of the monomer to give stable non-propagating allyl radicals.[25] Integration of the relevant carbon signals [26,27] revealed a 70:30 cis/trans ratio of the ring substituents at C_{b,b} (Figure 1; Figure 4c).

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**Figure 3.** $^1$H NMR spectrum using trimethylsilylpropionate-2,2,3,3-d$_4$ (TsP) as internal standard of (a) 4, (b) 6 (+NaCl), (c) 8 in D$_2$O.

**Figure 4.** $^{13}$C NMR spectrum using trimethylsilylpropionate-2,2,3,3-d$_4$ (TsP) as internal standard of (a) 4, (b) 6 (+NaCl), (c) 8 in D$_2$O.
the backbone composition of repeat units of (±−)/(±−)$^7$ solution of (=) metric titrations that the addition of HCl to an aqueous becomes less than 10 : 90. Thus, increasing the zwitterionic water solubility. It has been revealed during potentio-
overcomes the zwitterionic interactions so as to impart $^7$ as expected of any polyelectrolyte; anionic portion in (±−)$^7$ are water soluble insolubility vanishes. PZAN $^8$ and PDe $^9$ right where the zwitterionic interactions required for water 
shifting the mobile equilibrium: (±)$^6$ was found to be soluble in 0.0104 M HCl as a result of 
and interchain attractive interactions.[14] Zwitterionic (±)$^6$ was water insoluble like the 
6 $^+$ was determined to be soluble in 0.0104 M NaCl, and (ix) $^6$ in 1.0 M NaCl, (vii) $^6$ in 0.1 M NaCl, (vi) ◊ (±−)$^6$ in salt-free water, (ii) □ in salt-free water, (i) (=) (±−)$^7$ in 0.1 M NaCl, (iv) Δ in 1.0 M NaCl, (v)$^*$ (±−)$^7$ in 0.1 M NaCl, (vi) ◊ (±−)$^6$ in 1.5 M NaCl, (vii) ○ (±)$^6$ in 1.0 M NaCl, and (ix) ♠ (±)$^6$ in 0.75 M NaCl.

3.3. Solubility behavior

The electroneutral (±)$^6$ was water insoluble like the majority of known polyzwitterions [28–30] but soluble in the presence of various salts of small molar masses. For various salts, the CSCs at 23 °C were determined to be 0.548 M NaCl, 0.271 M NaBr, 0.133 M NaI. Iodide ions, being the most polarizable (soft), effectively neutralizes the ionic cross-links so as to disrupt the intragroup, intra- 
and interchain attractive interactions.[14] Zwitterionic (±)$^6$ was found to be soluble in 0.0104 M HCl as a result of shifting the mobile equilibrium: (±)$^6$ + H$^+$ ⇌ (+)$^5$ toward right where the zwitterionic interactions required for water insolubility vanishes. PZAN $^7$ and PDE $^8$ are water soluble as expected of any polyelectrolyte; anionic portion in (±−)$^7$ overcomes the zwitterionic interactions so as to impart water solubility. It has been revealed during potentiometric titrations that the addition of HCl to an aqueous solution of (±)$^8$ led to its insolubility at a point where the backbone composition of repeat units of (±−)$^7$/(±)$^6$ becomes less than 10:90. Thus, increasing the zwitterionic portion to more than 90% leads to the polymer’s insolubility in salt-free water.

3.4. Viscosity measurements

Viscosity data for (±)$^6$, (±−)$^7$, and (=)$^8$ (entry 2, Table 1) are given in Figure 5. The viscosity plots for (±−)$^7$ and (=)$^8$ in salt-free water were concave upward like any polyelectrolytes (Figure 5i, ii); whereas, the plots become linear in the presence of NaCl in the concentration range 1–0.25 g dL$^{-1}$ (Figure 5iii–vi). At lower concentrations, the linearity cannot be maintained; the viscosity falls off as a result of movement of the mobile equilibrium: (=)$^8$ or (±−)$^7$ + H$^+$ ⇌ (±−)$^7$ or (±)$^6$ toward right. As per general rule of hydrolysis, the degree of transformation of $^8$ to $^7$ (or $^7$ to $^6$) increases with decreasing concentration; overall decrease in the charge imbalance on the polymer chains decreases, thereby leading to lesser electrostatic repulsions, hence lesser viscosity values. Only the linear portion of the plots is extrapolated to obtain the intrinsic viscosities. Note that by virtue of having larger negative charge density, (=)$^8$ has higher viscosity values both in salt-free water as well as in NaCl-added solutions. As expected, the viscosity values are lower in 1.0 M NaCl than in 0.1 N NaCl as a result of greater shielding of the backbone and pendant charges in the former medium. Antipolyelectrolyte behavior of (±)$^6$ is confirmed by the increase in [η] with increase in the concentration of NaCl (cf. Figure 5vii–ix). The zwitterionic dipole has an overall excess negative charge by virtue of more effective binding of the N$^+$ by Cl$^-$ than the binding of CO$_2^-$ by Na$^+$. The repulsion among the dipole centers with excess negative charges leads to increasing viscosity with increasing NaCl concentration.[29,31,32]

3.5. Basicity constants

The linear regression of pH vs. log [(1 – α)/α] led us to determine the ’$n_i$ and log $K_i^\alpha$ as the slope and intercept, respectively, using Equation (2) (Figure 6). The apparent basicity constants of anionic centers are described by Equation 3, where log $K_i^{\alpha} = pH$ at $\alpha = 0.5$ and $n_i = 1$ in the case of sharp basicity constants. In salt-free water, basicity constants log $K_i$ of the amine group in (±)$^8$, which is the pK$^\alpha$ of its conjugate acid (±−)$^7$, and log $K_j$ of the terminal CO$_2^−$ in (±−)$^7$ (i.e. pK$^\alpha$ of its conjugate acid in (±)$^6$) were determined to be 10.94 and 5.25, respectively, in salt-free water (Table 2) and 9.94 and 4.56 in 1 M NaCl. In salt-free water, log $K_i$ (i.e. pK$^\alpha$) involving the equilibrium: $^6$ (ZH$^2^+$) + H$^+$ ⇌ (ZH$^1^+$)$^5$ cannot be determined owing to the solubility problem associated with zwitterionic (±)$^6$ (vide supra). In 1.0 M NaCl, which is higher than the CSC value for the polyzwitterion, log $K_j$ was determined to be 2.56 (Table 2).
For log $K_1$ and log $K_2$, the $n_1$ values, which are a measure of polyelectrolyte effect, are found to be greater than 1. The $n_1$ values of 2.19 and 1.36 in salt-free water and 1.0 M NaCl, respectively, and the corresponding $n_2$ values of 1.80 and 1.34 reflect the greater polyelectrolyte effect in the former medium. In salt-free water, charge centers in polymer (+=) 8 or (−) 7 are expected to be more hydrated than in 1.0 M NaCl where greater numbers of water molecules are busy to fill up the hydration shells of $\text{Na}^+$ and $\text{Cl}^-$ ions. The average number of hydrated water molecules per RU in salt-free water is, therefore, greater than in 1.0 M NaCl. The higher log $K_1$, log $K_2$, $n_1$, and $n_2$ values in salt-free water are the consequences of the entropy-driven [33] protonation step; during which it releases more water of hydration in salt-free water than in 1 M NaCl. The variations of log $K_i$ with $\alpha$, shown in Figure 6 reflect their ‘apparent’ [34] nature since instead of remaining constant, they either decrease or increase with the increase in $\alpha$. An increase in $\alpha$ in the polymer chains decreases the overall negative charges that induces protonation thereby resulting in a decrease in log $K_i$ and log $K_2$. In both cases of protonation in salt-free water and in 1 M NaCl, the exothermic enthalpy changes ($\Delta H^o$s) remain constant with increasing $\alpha$, and the $\Delta G^o$s become less negative as a result of progressive decrease in the $\alpha$, and associated with an $\alpha$ value of 0.52. An $n$ value of less than 1 is considered as diagnostic of a compact conformation. Polyzwitterion (±) 6, being the most compacted and least hydrated as confirmed by the viscosity data (Figure 5), continuously expands during the progressive increase in $\alpha$; thus making an easier access of the incoming protons to the more exposed COO$^-$ groups. With each protonation of the COO$^-$ in (ZH$_3$)$^+$ 6, the charge imbalance in favor of the positive charges on the polymer chain increases, hence the number of water molecules to be released in the next protonation from the hydration shell of each unit also increases. This behavior seems to be general in all cases in which the basic COO$^-$ group is in the $\alpha$ position to the nitrogen.[35,36]

3.6. Scale inhibition properties of the synthesized polymers

In reverse osmosis (RO) process, scaling of inorganic salts like CaSO$_4$ and CaCO$_3$ damages the smooth functioning of membranes. The scaling occurs when the concentration of the relevant ions in the inlet stream of feed water is supersaturated in the reject brine after producing the product water in the outlet stream. The percent inhibition (PI) of scaling is calculated using the following Equation 4:

$$\%\text{Scale Inhibition} = \frac{[\text{Ca}^{2+}]_{\text{inhibited}}(t) - [\text{Ca}^{2+}]_{\text{blank}}(t)}{[\text{Ca}^{2+}]_{\text{inhibited}}(t) - [\text{Ca}^{2+}]_{\text{inhibited}}(0)} \times 100$$  

(4)

where $[\text{Ca}^{2+}]_{\text{inhibited}}(t)$ is the initial concentration at time zero, $[\text{Ca}^{2+}]_{\text{inhibited}}(t)$ and $[\text{Ca}^{2+}]_{\text{blank}}(t)$ are the concentrations in the inhibited and blank solution (without antiscalant) at time $t$, respectively.

In the current work, a supersaturated solution of CaSO$_4$ containing 2598 ppm of Ca$^{2+}$ and 6300 ppm of SO$_4^{2-}$ in
the presence of various concentration of the synthesized antiscalant was investigated by following the conductivity of the solutions. Percent inhibition (PI) of 6 at concentrations of 5, 10, and 20 ppm is given in Table 3. A sudden drop in conductivity in the absence of antiscalant indicates the precipitation of CaSO₄ (Figure 7iv: Blank). To our great satisfaction, the presence of 20 ppm of 6 imparted a 100% scale inhibition for about 1000 min, while it was 98 and 96% at the time of 2000 and 3000 min, respectively, as calculated using Equation 1. Note that the presence of a meager 5 ppm of the antiscalant was able to register a 99% scale inhibition at a time of 200 min. This is efficient enough since a usual residence time of ≈30 min is required for the feed water to stay in the osmosis chamber. An induction period is observed before the onset of quick precipitation; a sharp drop in conductivity happens at a time of 500 and 1200 min in the presence of 5 and 10 ppm of the antiscalant, respectively. Note that at the time scale of 3000 min, no induction period was observed for the antiscalant concentration of 20 ppm; it still imparted 96% inhibition. The new antiscalant has thus demonstrated its efficacy to scavenge metal ions and disrupt the nucleation and crystallization processes [37,38]; hence, it could be used as a potential antiscalant to minimize the fouling of membranes by CaSO₄ scale.

4. Conclusions

A new monomer 4 containing glutamic acid residue has been synthesized and polymerized in excellent yields using Butler’s cyclopolymerization protocol to a pH-responsive polymer 5 which represents the first example of cyclopolymer-containing residues of glutamic acid (an amino acid) as pendants. The solution properties of the pH-responsive polymers 5–8 having backbone charges (+), (±), (±−), and (=), respectively, along with the CSC required to promote water solubility of zwitterionic (±) 6 have been studied. The basicity constants for the nitrogen and the anionic centers in (=) 8 have been determined; the data would be of great value to utilize and understand its ability to act as a scavenger of toxic metal ions and inhibitor of metal corrosion. PZA 6 has demonstrated remarkable efficiency as a potential antiscalant additive in RO plants; it has been found to be an effective antiscalant even at a meager concentration of 5 ppm. Polymeric aminomethylphosphonic acids, prepared using Butler’s cyclopolymerization protocol, have been utilized as chelating agents for separation of transition metal ions [39,40]; the current work involving the corresponding polymer of aminoolidcarboxylic acid also holds similar prospects for utilization as polychelatogens. Glutamic acid has three \( pK_a \) values of 2.1, 4.07, and 9.47, while the corresponding values for an RU in 5 were determined to be 10.94, 5.25, and \( ≈2.5 \). The conjugate bases being more stronger in the RU would make it a better chelating ligand. Work is currently underway in our laboratory to utilize the current monomer to synthesize cross-linked polymers retaining all three functionalities (i.e. amine and two carboxyl groups) which would act as chelating adsorbents for the removal of toxic materials.[41]

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Disclosure statement

No potential conflict of interest was reported by the authors.

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