The Influence of pH/Salt Concentrations on Tuning Lower Critical Solution Temperature of Poly(NIPAAm-co-DMAA-co-DTBAVA) Multi-Environmentally Terpolymer

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Abstract
New series of thermo-pH multi-responsive terpolymers were fabricated. Cationic acrylate monomer was synthesized and named by [2-((ditert-butylamino)methyl)-4-formyl-6-methoxyphenyl acrylate] and abbreviated as (DTBAVA). 1H NMR and 13C NMR investigated the new compounds and FT IR. The new terpolymers were fabricated by the free radical polymerization of N-isopropylacrylamide NIPAAm, 10 mol% N, N-dimethylacrylamide and 5, 10, and 20 mol% DTBAVA. The investigation process involved the chemical method such as 1H NMR and FT IR; physical methods for the solid terpolymers as glass temperature by DSC, polymer degradation by TGA, and polymer crystallinity via XRD. GPC was performed for molecular weights and dispersity; contact angles for identifying the hydrophilic or hydrophobic terpolymers solutions. The lower critical solution temperatures $T_{c,s}$ and cloud points $C_{p,s}$ of terpolymers were recorded considering the impact of pH solutions and the concentrations of different sodium salts of (SO$_4$$^{-2}$, Cl$^{-1}$, and SCN$^{-1}$) in the Hofmeister series; turbidity measurements were used via UV/vis spectroscopy and micro-DSC. In a new optimization study, we will use these terpolymers in the post-polymerization with biomolecules such as chitosan, protein, and amino acids via Schiff base.

Graphical Abstract

Keywords Thermal/pH-Salt concentrations environmentally terpolymer · N-isopropylacrylamide · N, N-dimethylacrylamide · Hofmeister anion · LCST/cloud point

Introduction
To define the environmental polymers, it is a material that can change their behavior according to the surrounding environment. In the last few decades, scientists have revealed
several kinds of environmental materials; they are defined with different meanings, such as responsive, intelligent, smart, and stimuli-responsive [1–6]. This material has been rapidly developed according to modern technology and its applications [7–9]. The sensitivity of polymers to temperature is known as thermo-responsive polymeric material [10–12]. According to the phase separation temperature of the polymer solution, there are two significant kinds; first is the most popular and has exhibited separation (two phases) after heating over its transition temperature, and is known as lower critical solution temperature or (UCST) [13–15]. On the other hand, the separation process occurs before its separation temperature, one phase after heating, while two phases before heating and is defined as upper critical solution temperature (UCST) [16, 17]. The main factor in both behaviors is the hydrogen bonding interaction between polymer chains and water molecules. Increasing the hydrogen bonding interaction raises the separation temperature to higher values and vice versa [13]. Massive studies have focused on preparing LCST copolymers using N-isopropylacrylamide (NIPAAm) [14–23]. The homo-polymerization of NIPAAm (PNIPAAm) shows the LCST at 32 °C [13, 15]; moreover, the copolymerization with different monomers with hydrophilic or hydrophobic groups will change LCST significantly to higher or lower value [24–27]. Other significant environmental polymers are pH-sensitive; they can change their behavior in response to the pH solution [28, 29]. They are polyelectrolytes with acidic or basic functional groups that can ionize in acidic or basic solutions [30, 31]; Carboxylic functional polymers such as poly(acrylic acid) PAA is a significant example of anionic polyelectrolyte [32]. Introducing of tertiary amine group into the monomer molecule is responsible for the formation of cationic polyelectrolyte, e.g., poly((2-dimethylamino) ethyl methacrylate) PDMAEMA [33]. The pH-responsive polymers have been widely used in many applications, essentially in bioseparation and drug delivery [34, 35]. Both thermo-responsive and pH-responsive monomers have been copolymerized to prepare dual-responsive thermo-pH responsive polymeric materials [36, 37]. In special interests, several scientific kinds of research have been studying the copolymerization of NIPAAm with cationic or anionic monomer to optimize the general characterization of polymeric material with the advantage to the lower critical solution temperature polymer solutions [1, 2, 19, 20]. Several research articles recently prepared vanillin-based monomers and its derivative due to their natural resource and nontoxic properties [38–43]. N, N-dimethylacrylamide (DMAA) is a hydrophilic monomer that has been copolymerized with N-isopropylacrylamide to enhance the hydrophilic efficiency of copolymer that is reflected in the change of LCST to a higher value [9, 42, 44, 45]. The Hofmeister series, also known as the lyotropic series, was unveiled by Franz Hofmeister [46]. They have discussed the influence of the anions and cations of salts on the solubility or coagulation of proteins [47]. Anions are the most familiar used than cations; they have two major types according to their arrangement in the Hofmeister series. Chaotropes anions are singly charged and have low charge density, e.g., Cl−, NO3−, SCN−; they weakly interact with water molecules and order-making exhibiting the formation of hydrogen bonds and the ability of solubility. On the other hand, kosmotropes anions are small with highly charged density, e.g., CO32−, SO42−, S2O32−; they strongly interact with water molecules than the self-interaction of water, forming breaking in the hydrogen bonds order-breaking [48–50]. Recently, several studies focused on Hofmeister salts’ effect on the LCST and the cloud point of PNIPAAm solutions and its copolymers [51, 52]. All studies unveiled the lower critical solution temperature lowered by the addition of kosmotropes; however, the effect has been weaker by using chaotropic [53, 54]. This work aims to prepare a series of thermo-pH-salt multi-responsive terpolymers by the copolymerization of NIPAAm, DMAA, and new tertiary pH monomer DTBAVA to optimize LCST of polymer solution as well as the formation of functional terpolymer. Next, this work will get many applications for the bioseparation of biological molecules by a one-pot reaction via Schiff’s base post-polymerization.

Experimental

Materials and Instrumentation

Materials

Acryloyl chloride, 2-propenoyl chloride or acrylic acid chloride (AC) (97%, Sigma-Aldrich, (stabilized with phe-nothiazine) for synthesis, Germany), N-isopropylacryla-mide (NIPAAm) (97%, Sigma-Aldrich, Germany) was recrystallized from distilled n-hexane., 2,2′-Azobis(2-methylpropionitrile) (AIBN) (98%, Sigma-Aldrich, Germany) was recrystallized from methanol, vanillin, 4-Hydroxy-3-methoxybenzaldehyde, vanillic aldehyde (V) (97%, Sigma-Aldrich, Germany), N, N-dimethylacryla-mide (99%, Sigma-Aldrich, Germany) was recrystallized from methanol, vanillin, triethylamine (Grüssing), magnesium sulfate (Merck), tetrahydrofuran (THF), sodium chloride, sodium sulfate, and sodium thiocyanate (≥ 99%, Fluka-Fisher, Germany), chloroform, diethyl ether (Et2O) were distilled over potassium hydroxide. Other chemicals were used as purchased.
**Instrumentation**

Vertex 70 Fourier transform infrared instrument FT-IR. Bruker AV 500 spectrometer at 500 MHz and 125 MHz was used for recording $^1$H and $^{13}$C NMR, respectively, at 25 °C; samples were dissolved in CDCl$_3$ or DMSO-d$_6$. The dry sample was milled with KBr and then pressed into pellets for the measurement process.

Differential Scanning Calorimeter (DSC) Perkin Elmer Pyris 1; this technique is used to record the glass transition temperature ($T_g$) of solid polymers at a heat and cool rate of 5 °C/min. It was recorded at the onset value of the thermogram.

Thermogravimetric analysis (TGA); was used to investigate the thermal stability of the polymer sample related to its chemical decomposition by heating from 25 to 700 °C at and heating rate of 5 °C/min.

X-ray diffraction-(Bruker AXS D8 Advance); was used for recording the degree of crystallinity. The detector is Vantec-1; high precision microprocessor-controlled, Goe-bel mirror; two circle goniometer with independent stepper motors and optical encoders, reproducibility ± 0.0001°, smallest angular step 0.0001°, high-temperature MRI stage (RT-1400C), sample spinner, video camera, thin-film Reflectometry, sample plate fixed with 9-sample holders. The instrument was run as 2.2 kW Cu and Co, Running 40 kV, smallest angular step 0.0001°, high-temperature MRI stage, sample plate fixed with 9-sample holders. The instrument was run as 2.2 kW Cu and Co, Running 40 kV, 40 mA. The stability of power is better than 0.01%.

Size exclusion chromatography (SEC) has been used for the determination of molecular weights ($M_n, M_w$) and dispersity ($D$) in THF as eluent contaminated with 0.1 vol% triethylamine and a flow rate of 0.75 ml/min at 30 °C. The sample was dissolved at 15 mg/ml; an automatic injection ran it. PSS-SDV Columns were used with 5 µm gel. The molecular weight $M_n$ of polystyrene (PS) was used as standard.

To measure the contact angle ($\Theta$): the sample was converted into a pellet and allowed a 4 µl drop of pH solution over the sample surface using a micropipette. The photographs were taken for each drop using a digital camera. The contact angles were detected from the photographs by using the software ImageJ.

**Measurements of the Phase Separation Temperature or Lower Critical Solution Temperature (LCST) ($T_c$) and Cloud Point for Terpolymer Solution**

(1) It was performed by UV–vis spectrometer (Perkin Elmer Lambda 45); it is known by the turbidity method. The process depends on the relation of transmittance and temperature of the polymer solution. The instrument has been built by metal covet stands with the water cycle and fixed using a thermostat and cooling system. The internal heat of the polymer solution was measured by a manual thermostat inside the solution at 2 °C/min over the range from 5 to 80 °C. The polymer solution concentration was at 1 wt% in water or pH solution.

(2) Another instrument was used for $T_c$ measurement of polymer solution; it is micro-DSC III from setaramto. The thermograms of the terpolymer solutions were recorded. The heating rate was at 5 °C/min; the concentration was 50 mg/ml in deionized water. The transition temperature $T_c$ was detected at the onset value.

**Preparation of [2-((di-tert-butylamino)methyl)-4-formyl-6-methoxyphenyl acrylate] (DTBAVA)**

It has been synthesized in two steps as described in our recent publication [41].

**Preparation of [3-((Di-Tert-Butylamino)methyl)-4-hydroxy-5-methoxy-benza-dyde] (DTBAVA)**

20 g (0.13 mol) of 4-hydroxy-3-methoxy benzaldehyde (vanillin), 20 g (0.66 mol) formaldehyde, and 20 g (0.15 mol) di-tert-butylamine in 150 ml EtOH, and 250 ml round flask. They were stirred and refluxed with a water trap in an oil bath at 130 °C for 6 h. The solution has converted to yellow suspension, and then the product has collected after solution evaporation; as a yellow solid, yielding 95%.

$^1$H NMR (500 MHz, CDCl$_3$): $\delta$ (ppm) = 1.22 (t, 1-18H, 6CH$_3$), 3.96(b, j, 5H, 2H, NCH$_2$ and 3H, -OCH$_3$) 5.18 (br, 1H, K-OH), 7.24 (d, 1H, f-Ar–CH), 7.36 (d, $^4$J = 1.7 Hz, 1H, h-Ar–CH), 9.76(s, 1H, i-CHO).

$^{13}$C NMR (125 MHz, CDCl$_3$): $\delta$ (ppm) = 30.83 (6C, a-6CH$_3$), 43.48 (1C, c-NCH2), 54.68(1-2C, b-C–), 58.86 (1C, k-OCH3), 118.77 (1C, g-Ar–CH), 123.59 (1C, i-Ar–CH), 127.67 (1C, d-Ar–C), 136.95 (1C, h-Ar–C), 151.94 (1C, f-Ar–C), 161.95 (1C, e-Ar–C), 190.65 (1C, j-CHO).

IR (KBr): $\nu$ (cm$^{-1}$) = 3240–3150(s) (OH), 2835–3105(s) (C–H), 1739–1723 (s) (C = O), 1615–1578 (s) (C = C), 886–836 (m) (Ar–CH).

**Preparation of [2-((DiTert-Butylamino)methyl)-4-formyl-6-methoxyphenyl acrylate] (DTBAVA)**

A mixture of 16.0 g (0.054 mol) of II [3-((di-tert-buty lamino)-methyl)-4-hydroxy-5-methoxy-benzaldehyde-ye] (DTBAVA) and 5.6 g, (0.054 mol) triethylamine in 150 ml dry chloroform CHCl$_3$ were dissolved. They were stirred in a three-neck flask suitable for nitrogen balloon, water condenser, and dropping funnel. Then the reaction vessel was cold in an ice bath to 0–5 °C. An acryloyl chloride 4.88 g (0.054 mol) miscible in 30 ml dry CHCl$_3$ has been slowly dropped for 15 min. They continued stirring at low temperature for 1 h, followed by 7 h at room temperature. It was
filtered, and the solvent evaporated. Further, the crude product was purified by re-dissolved in chloroform, followed by washing in deionized water, 0.1 M Na2CO3, 0.1 M HCl, and finally in deionized water. The product was dried overnight over MgSO4. The solvent was evaporated. TLC purified it in a mixture of ethylacetate/n-hexane 2:1. Rf = 0.45. Yield 79%, orange solid. Figures 3, 4 1H and 13C NMR.

### General Procedure

The free radical polymerization was achieved by adding 10 mol% (0.26 g) of N, N-dimethylacrylamide DMAA, and 5, 10, and 20 mol% (0.45 g, 0.92 g, and 1.81 g) of TBAMVA initiated by 2, 2′-Azobis(2-methylpropionitrile) AIBN. All dissolved in absolute ethyl alcohol EtOH and 100 mL round flask. They were purged in nitrogen gas for 20 min.; stirred with heating at 75 °C for 8 h. The polymer solutions were precipitated in diethyl ether and then reprecipitated in diethyl ether. They are filtered off to collect pure polymers. The physical properties of all as solid were measured. The investigations of terpolymers have been performed by the same tools discussed lately. Both of the 1H and 13C NMR appeared to be identical. FTIR was used to confirm the chemical structure of the essential functional groups. The vibrations were observed for the essential functional groups. Compound II exhibited ν = 2645–2525, 1745–1733, and 1660–1658 cm−1 for –C–N, C=O carbonyl, and C–OH; however, compound III demonstrated the presence of vinyl group –C=C– group at ν = 1660–1658 cm−1.

### Results and Discussion

#### Monomer and Polymer Chemical Evaluations

The new monomer has been synthesized according to Scheme 1. The procedure was implemented in two steps. The cationic monomer from vanillin was first prepared via the reaction of vanillin, formaldehyde, and di-tert-butyramine producing compound II [3-(di-tert-butylamino) methyl]-4-hydroxy-5-methoxy-benzaldehyde (DTBAV). The evaluation has been done using the 1H, 13C NMR, and FT IR, showing the presence of successful protons and 13C at definite positions in charts, as shown in Figs. 1 and 2. Specific peaks of protons were exhibited in the tertiary amine group at δ = 1.22, and 3.96, (ppm) for 18 H of the methyl groups and 2 H methylene –NCH2; they have also been shown in 13C NMR at δ = 30.83, and 43.48 ppm; additionally, they keeping the aldehyde group at δ = 9.76 ppm, and 190.65 ppm for 1H and 13C. Through the next step and formation of the final product, compound II was reacted in an alkaline solution such as triethylamine in an inert atmosphere via purging nitrogen entailed the dropping of acid chloride (acryloyl chloride) for compound III (DTBAVA), all in equivalent molar concentrations. At first, the reaction appears exothermic and requires cooling; after that, the reaction proceeds at room temperature. The evaluation process was performed by the same tools discussed lately. Both of the 1H and 13C NMR appeared to be identical, and 13C demonstrated a successful reaction and achieved the chemical structure; the essential protons for the formation of the vinyl group were proofed at δ = 6.09, 6.39, and 6.63 ppm, and 13C at δ = 17.34 ppm. The FTIR infrared spectroscopy FT IR has been selected for detecting the functional groups. The vibrations were observed for the essential functional groups. Compound II exhibited ν = 2645–2525, 1745–1733, and 1660–1658 cm−1 for –C=O, C=O carbonyl, and C=O; however, compound III demonstrated the presence of vinyl group –C=C– group at ν = 1660–1658 cm−1, as shown in Fig. 6.

Eventually, the work has been accomplished by fabricating thermo-pH environmentally terpolymers via the free radical polymerization of N-isopropylacrylamide and N, N-dimethylacrylamide, and three different molar concentrations of (DTBAVA) (5, 10, and 20 mol%) in solution and initiated by AIBN. One notable was taken in the yield percentage of polymer; they decreased with increasing the molar concentration of DTBAVA in the polymer chain. The investigations of terpolymers have been performed via 1H NMR and FT IR. Figure 5 illustrates the
The Glass Transition Temperature \( T_g \) Via Differential Scanning Calorimetry (DSC)

The glass transition temperature \( T_g \) of polymer is a specific character like the figure print and has been influenced by other characterizations of the polymeric material. Differential scanning calorimetry DSC was used to record the glass temperature \( T_g \) at a heating rate of 5 °C/min. All terpolymers were quenching from melting to liquid nitrogen temperature. The diffractogram was calibrated with standards; the glass temperature \( T_g \) was measured at the inflected point. Figure 7 shows the diffractogram curves of terpolymer samples indicating the glass transition temperatures at 141, 135, and 119 °C for VIa, VIb, and VIc, respectively, as mentioned in Table 1. The regular decrease of the \( T_g \) inflected the effect of the molar concentration of DTBAVA in the polymer main chain; the reason is the addition of aromatic monomer, which restricts the flexible rotation of repeating unit in the polymer chain [55].
Thermal Stability Via Thermogravimetric Analysis TGA

Thermogravimetric analysis has performed the thermal degradation of terpolymers at 10 °C/min from 25 to 600 °C. Figure 8A, B illustrates the thermal decompositions and their 1st derivatives of synthetic terpolymers. The significant degradation of terpolymer VIa with 5 mol% of DTBAVA has occurred in three steps the first from 200 to 250 °C for evaporator materials water and ammonia, the principle degradation was detected from 390 to

Fig. 1 ¹H NMR (CDCl₃) [3-((di-tert-butylamino)methyl)-4-hydroxy-5-methoxy-benzaldehyde] (DTBAV) (II)

Fig. 2 ¹³C NMR (CDCl₃) [3-((di-tert-butylamino)methyl)-4-hydroxy-5-methoxy-benzaldehyde] (DTBAV) (II)
415 °C, this is due to the decomposition of repeating unit in the polymer chain, eventually full decomposing from 495 to 550 °C for hydrocarbon. For terpolymer VIb 10 mol% DTBAVA has also exhibited three main degradable stages; the first has occurred from 130 to 170 °C, the next one from 365 to 385 °C, refereeing to the principal decomposition of the polymer chain, and finally 520–555 °C. The higher molar concentration of 20 mol% of DTBAVA VIc demonstrated the first degradation from 135 to 180 °C; however, the principle degradation of polymer chains showed different features; it exhibited two distinct degradations as shown in Fig. 8B, from 325 to 360
°C, and from 365 to 390 °C, this might be attributed to the decomposition of the polymer chain in two stages at the lowest temperature for DTBAVA repeating unit, while the highest to NPAAm and DMAA. The complete decompose has been detected from the range like lately of VIb terpolymer.

Degree of Crystallinity Via X‑Ray Diffraction XRD

The crystallization process and the degree of crystallinity differentiate among the state of the material is crystalline, semi-crystalline, or amorphous. Figure 9 illustrates the crystallographic analysis of XRD of new synthetic terpolymers VIa-c. Diffraction peaks at 2θ = 25° to 37° and 38° to 47° are attributed to the enhancement of the crystallization. The crystallinity percent has been calculated for each terpolymer via the crystallographic by (area of crystalline peaks/area of all peaks × 100) [56]. They demonstrated crystallinity% of 53.4, 48.3, and 42% for VIa, VIb, and VIc, respectively. The essential feature of the crystallographic is the absence of the sharpest peak indicating the semi-crystalline state. One other note is that the correlation of crystallinity on the molar concentration of DTBAVA demonstrated a reversible process, increasing steric hindrance and restricted rotation sparked by increasing DTBAVA.

Terpolymer Solution

Molecular Weight/Dispersity

Gel permeation chromatography measures the molecular weight (weight average molecular weight $M_w$ and number average molecular weight $M_n$) and dispersity $M_w/M_n$, $D$ for all polymeric samples dissolving in THF and using PS as standard. The chromatogram analysis has shown a good responsibility of the detector with the retention time. It has also demonstrated an essential feature as the formation of one peak for each sample, indicating monomers' disappearance [1, 2]. Figure 10 illustrated log [M] distributions against $M_n$, $M_w$. From data summarized in Table 1, the number average molecular weight $M_n$ and dispersion $D$ for all terpolymers; was observed an opposite relationship of $M_n$ and dispersion $D$ with a polymer content of DTBAVA monomer in the chain that attributed to the aromaticity steric hindrances caused a reduction in the flexibility of polymer solution [5] (Table 2).
The effect of incorporating hydrophilic and hydrophobic groups in the terpolymers has been studied by measuring the contact angles, which is the key to recognizing the tendency of polymeric material to hydrophilicity or hydrophobicity [57]. A recent study has been interpreted the difference among hydrophilic, hydrophobic, and superhydrophobic polymeric material via the determination of their contact angles; it has shown that hydrophilic polymers should be at $\theta < 90^\circ$ and hydrophobic at $\theta > 90^\circ$; however, superhydrophobic always measured at $\theta \geq 145^\circ$ [57]. The measurements of the contact angles of terpolymers VIa-05, VIb-10, and VIc-20 with 5, 10, and 20 mol% of DTBAVA showed the influence of the contact angles

| Polymer | Yield % | Composition (%) | pH | $M^\alpha$ (g/mol)$^{10^3}$ | $M^\gamma$ (g/mol)$^{10^3}$ | $D^\alpha$ | $T_g^\alpha$ (°C) DSC | $T_g^\gamma$ (°C) DSC | $C_{p}\%^\gamma$ (%) | $C_{\alpha}\%^\gamma$ (%) | $T_c$ (°C) DSC | $T_c$ (°C) UV |
|---------|---------|----------------|----|-----------------------------|-----------------------------|----------|------------------------|------------------------|----------------|----------------|----------------|----------------|
| VIa-05  | 86      | 9.3            | 2.3| 3.3                         | 3.3                         | 2.3      | 141                    | 53.4                    | 48.3           | 42.3           | 49/50.4        | 24/25.4       |
| VIb-10  | 83      | 9.0            | 2.2| 3.4                         | 3.4                         | 2.2      | 135                    | 48.3                    | 43/44.6        | 42/43.7        | 29/30.9        | 24/25.4       |
| VIc-20  | 74      | 8.6            | 2.3| 3.4                         | 3.4                         | 2.3      | 119                    | 42                      | 31/32.3        | 30/31.5        | 22/23.6        | 23/24.4       |

Fig. 6 FT IR spectra of monomer II, III, and terpolymers VIa, VIb, and VIc

Fig. 7 $T_g$ measurements from DSC diffractogram for terpolymers VIa, VIb, and VIc

**Terpolymers Contact Angles**
of terpolymers on the DTBAVA content in the terpolymer main chain in various pH solutions. Table 3 cleared all data of contact angles. For terpolymer VIa-05 exhibited a lower value of contact angles in a strong acidic solution that slowly increased in the neutral solution and spikier in the alkaline solution and demonstrated 83.5°, 86.5°, 84.6°, and 96.4° in pH 1.68, pH 4, pH 7, and pH 10.4, respectively; the hydrophilicity decreased by increasing the pH from strong acidic solution to strong alkaline solution. Increasing the molar concentration of DTBAVA in the polymer chain VIb-10; showed the hydrophilic property in strong acid at pH 1.68 and lower contact angle Θ ~ 82° than VIa-05 attributed to the effect of ionization of tertiary amine group in acidic solution. It is increased regularly in higher pH solutions. The highest hydrophilicity was detected for terpolymer VIc-20 at the strongest acidic solution pH 1.68 and the lowest contact angle at Θ  ~ 80.8°; the reason has been interpreted as the highly charged DTBAVA in the polymer chain reflected the highly hydrophilic character of the polymer solution. These changes in the contact angle measurements proved the influence of DTBAVA via pH solution producing hydrophilic or hydrophobic chains.

Fig. 8 A B TGA degradation steps of terpolymers and their 1st derivatives

Fig. 9 XRD of terpolymers VIa, VIb, and VIc and their crystallinity percent

Fig. 10 The molecular weights of terpolymer via GPC
Table 2: Transition temperatures and cloud points affected by different concentrations of salt ions in deionized water

| Polymer | Tc°C (°C) | Cp°C (°C) | Na2SO4 | NaCl | NaSCN |
|---------|-----------|-----------|--------|------|-------|
| VIa-05  | 30/31.3   | 28.7/29   | 35/35.7| 30.3/31| 37/37.8|
| VIb-10  | 27.4/28   | 26/27.5   | 26/27.5| 30.3/31| 24.3/25.3|
| VIc-20  | 24.3/25   | 22/23.3   | 22/23.3| 20.4/21| 18/18.5 |

Figures 11 and 12 describe the relationship between the contact angles of all terpolymers with the pH change.

The Impact of pH Solutions on the Phase Separation Temperature and the Cloud Points

Two methods were used to identify and measure the lower critical solution temperature and the cloud point. The first method via turbidity test was UV/vis spectroscopy; the relation between transmittance percent to temperature, as shown in Fig. 13 A-D, represents the transition temperature $T_c$ at the inflected point and the cloud point $C_p$ at the mid transmittance to temperature (50%). The hydrophilic/hydrophobic balance in the terpolymers inflected the presence of hydrophilic groups besides the hydrophobic in NIPAAm, DMAA,
Fig. 13 A–D the turbidity tests of terpolymer VIa, VIb, and VIc in various pH solutions via the relationship of transmittance with the temperature change; A in pH 1.68, B in pH 4, C in pH 7, and D in pH 10.4

and DTBAVA monomers; moreover, the sensitivity of these terpolymers towards the pH solution. All have been affected by the fluctuations of both the transition temperatures and the cloud point of the terpolymer solution. The terpolymers solution in pH 1.68 demonstrated the highest \( T_{c,s} \) and \( C_{p,s} \) for terpolymers under investigation. They exhibited 40.5, 43.7, and 51.5 °C for \( T_{c,s} \), corresponding to \( C_{p,s} \), at 41.3, 44.6, and 52.3 °C for VIa, VIb, and VIc, as shown in Fig. 13A. The regular raising in both \( T_{c,s} \) and \( C_{p,s} \) was detected by increasing the molar concentrations of DTBAVA due to the domination of the hydrophilic chains acting in the cationic tertiary amine that increase the hydrogen bonding in the terpolymer solutions. Figure 13B has recorded the \( T_{c,s} \) and \( C_{p,s} \) in the pH 4 for all terpolymers. By going from the strongest acidic solution to the weaker one; the obtained \( T_{c,s} \) and \( C_{p,s} \) have demonstrated lower values, 39, 42, 49 °C, and 37.5, 32, and 25.4 °C \( C_{p,s} \), Fig. 13C. The last test was achieved in a strong alkaline pH 10.4 solution. The resulted \( T_{c,s} \) and \( C_{p,s} \) are 34.6, 29.8, 22.3, and 34.4, 30.9, 23.5 °C, respectively. They exhibited the same behavior as in the previous test, as shown in Fig. 13D. Both cases showed the domination of the hydrophobic groups and the weakness of hydrogen bonding [13, 15]. The Confirmation of the last tests, a micro-DSC for terpolymers in pH 7 has been performed. They exhibited the \( T_{c,s} \) as the onset point of the diffractogram at 35.5, 29.6, and 23.5 °C for VIa, VIb, and VIc, respectively. A slight difference in the \( T_{c,s} \) values recorded by micro-DSC to values obtained by the turbidity test interpreted to the different methods used to determine \( T_{c,s} \) such as inflected point or onset point, as shown in Fig. 14 [5, 13].
The Impact of Salt Concentrations of Hofmeister Anions on the LCST/Cp

The effects of Hofmeister anions and salt concentrations on the lower critical solution temperature and the cloud point have been urged in this study. The turbidity test measured both \( T_c \) and \( C_p \) by the UV–Vis spectrophotometer at 500 nm wavelength. Different weight percent concentrations (0.1–0.5 wt.%) sodium sulfate (Na\(_2\)SO\(_4\)) acting kosmotropes anion, sodium chloride (NaCl), and sodium thiocyanate (NaSCN) as chaotropic anions; they were dissolved in aqueous solutions. The transmittances versus the temperatures were used to detect the \( T_c \) and \( C_p \), as shown in Fig. 15.

The transmittance vs. temperatures of terpolymers VIa-05, VIa-10, VIa-20 dissolved in aqueous solutions 0.1–0.5 wt.% Na\(_2\)SO\(_4\) were measured as illustrated in Fig. 15A; the transition temperatures \( T_c \) and \( C_p \) exhibited the highest value for 0.1 wt.% Na\(_2\)SO\(_4\) (VIa-05) at 30/31.3 °C \( T_c/Cp \), the lowest value was recorded for 0.5 wt.% NaCl (VIc-20); the interpretation of results has been discussed lately. Conversely, the solubility of terpolymers in sodium thiocyanate solutions has been seen in Fig. 15C. The strongest spiky for the \( T_c/Cp \) was detected at 52/53 °C for 0.5 wt.% NaSCN (VIc-20). The much higher hydrophilic groups based on the interaction of the thiocyanates anions with the amide group (NIPAAm) as well as the aldehyde group (DTBAVA), producing structure-making and increased the solubility of terpolymers and therefore slowing the phase separation process to higher temperature [55, 57]. All data has been summarized in Table 2. Figure 15D illustrated the relationship between the LCST (\( T_c \)) and weight percent concentrations of terpolymer solutions with Na\(_2\)SO\(_4\), NaCl, and NaSCN showing the highest \( T_c/Cp \) for terpolymer VIc-20 dissolved in 0.5 wt.% NaSCN, while the lowest one for terpolymer VIc-20 dissolved in 0.5 wt.% Na\(_2\)SO\(_4\).

Conclusion

A new monomer DTBAVA was prepared from vanillin in two facile methods; the chemical structure was confirmed by suitable instruments that achieved good results. Three thermo-pH responsive terpolymers were designed from NIPAAm, DMAAm, and DTBAVA. The terpolymerization process was made by free radical polymerization using different molar concentrations of DTBAVA 5, 10, and 20 mol%. The general physical characterizations were implemented; the glass transition temperature \( T_g \), molecular weight, and dispersity demonstrated their reversible relation with the content of DTBAVA in the polymer chain. Furthermore, the crystallinity by XRD has also represented a lower crystallinity percent with increasing DTBAVA. The degradation steps have illustrated two steps with VIa-05, VIb-10, and three steps with VIc-20. The lowest contact angle and the highest hydrophilic were also seen for VIc-20 at pH 1.68. The phase separation temperature of terpolymers was tested in various pH solutions and different Hofmeister salt via UV/vis spectroscopy. They have been demonstrated the highest \( T_c \) in pH 1.68 for VIc-20; however, the lowest value has also been seen at pH 10.4 for the same terpolymer. The salt effect was tested using three solutions of salts from kosmotropic as Na\(_2\)SO\(_4\), chaotropic NaCl, and NaSCN. The study illustrated the structure-breaking of Na\(_2\)SO\(_4\) terpolymer solution by recording the lowest transition temperature with the highest concentration of salt. Otherwise, the lowest \( T_c \) value has
been detected for terpolymer in chaotropic NaSCN solution with the highest salt concentration and the highest DTBAVA molar concentration. Future research will be interested in applying these terpolymers in the separation process of biological molecules.

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Declarations

Conflict of interest The authors declare that there are no conflict of interest regarding the publication of this paper.

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![Fig. 15 A-D (A-C) the LCST via transmittances vs. temperatures of terpolymers Vla-0.5, Vlb-10, and Vlc-20 in 0.1–0.5 wt.% of Na2SO4 (A), NaCl (B), and NaSCN (C). D summarized the Tcs of all terpolymers with variations of salt concentrations](image-url)
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