Polymerization of Vinyl Chloride at Ambient Temperature using Macromolecular Design via the Interchange of Xanthate: Kinetic and Computational Studies

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Abstract

Reversible deactivation radical polymerization (RDRP) of vinyl chloride (VC) by methyl (ethoxycarbonothioyl)sulfanyl acetate (MEA)-mediated macromolecular design via the interchange of xanthate (MADIX) polymerization at ambient temperature is reported. The polymerization system was studied using two conventional radical initiators (having very distinct half-life times at room temperature). The system was optimized regarding the nature of the solvent, the monomer concentration, the polymerization temperature and the target molecular weight. The kinetic data showed linear first-order kinetics, linear evolution of molecular weights with conversion, and polymers with narrow molecular weight distributions ($Đ \sim$ 1.2-1.3), using low temperature (30 - 42 ºC) and cyclopentyl methyl ether (CPME) as "green" solvent. The resulting MEA-terminated PVC was fully characterized by ^{1}H nuclear magnetic resonance spectroscopy (^{1}H-NMR), that revealed the existence of a very small fraction of structural defects and the presence of chain-end functional groups. "One-pot" chain extension (with VC) and "one-pot" block copolymerizations (with vinyl acetate - VAc and *N*-vinylcaprolactam - NVCL) experiments confirmed the "livingness" of the MEA-terminated PVC chains, giving access to different PVC-based block copolymers. Computational studies confirm the results of the solvent screen and suggest that changes to the initial MADIX leaving or stabilizing groups could improve control. The computational data were further confirmed using methyl 2-(4-methoxyphenoxycarbonothioylthio)acetate. This work establishes a new green route to afford a wide range of new complex macrostructures including high value materials based on PVC segments.

1. Introduction

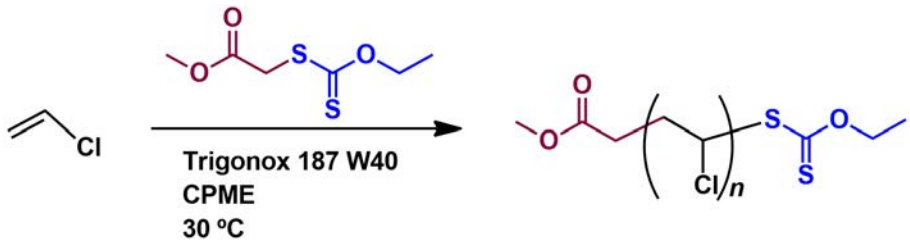
Poly(vinyl chloride) (PVC) is one of the most consumed polymers worldwide (more than 40 million tons per year) and is used to produce many items, namely healthcare devices.[1] The strong need for new polymers having different architectures, morphologies, controlled molecular weight, and functional chain-ends resulted in the unprecedented interest of the scientific community on reversible deactivation radical polymerization (RDRP).[2-5] RDRP offers a control over structure that is similar to ionic living polymerizations, but with all the advantages associated with radical based polymerizations.[6] Despite all the achievements, RDRP of nonactivated monomers, as VC, remains enormously challenging due to: low reactivity of the VC monomer and very high reactivity of the corresponding radical; an unusually high chain transfer constant to the monomer; and the insolubility of PVC in its monomer as well as in most common organic solvents.[7-9]

Different RDRP methods for VC (co)polymerizations have been reported, namely by single electron transfer living radical polymerization (SET-LRP),[10-12] single electron transfer degenerative chain transfer living radical polymerization (SET-DTLRP),[9, 13-14] cobalt-mediated radical polymerization (CMRP),[15-16] activators regenerated by electron transfer (ARGET) atom transfer radical polymerization (ATRP),[17] supplemental activator and reducing agent (SARA) ATRP,[18-20] reversible addition-fragmentation chain transfer polymerization (RAFT)[21-22] and nitroxide-mediated polymerization (NMP).[21, 23]

Xanthates are an important class of RAFT agents and they were first discovered and patented in 1998 by Rhodia.[24] Even though the mechanism of xanthates process and RAFT process are very similar, Macromolecular Design via the Interchange of Xanthate (MADIX)[25-26] is a terminology commonly used to describe the xanthate process and adopted by us in this work. Due to the lower reactivity of the C=S bond of xanthates, they are designed to polymerize less activated (or fast propagating) monomers (LAM), such

as vinyl acetate (VAc),[27-29] ethylene,[30-31] vinylidene fluoride (VDF)[32-33] and VC.[34-36] Nevertheless, they have also been used to polymerize more activated monomers (MAM), such as styrene,[37-38] acrylic acid,[39-40] acrylates[37, 41] and acrylamide,[41-42] with relative success. This demonstrates the versatility of these chain transfer agents (CTA), which has allowed access to the synthesis of controlled block copolymers using monomers with very disparate reactivities by simple sequential addition.[41, 43] However methyl methacrylate (MMA) polymerization is not controllable using xanthates and for them other RAFT agents such as fluorodithioformates[44-45] or switchable RAFT agents[46] are required to access such controlled block copolymers. Xanthates are inexpensive organic compounds which are easy to synthetize in comparison to dithioesters or dithiocarbamates. They are used in a variety of commercial processes, including the manufacture of Rayon®, cellulose films and textiles.[47] Recently, solution and aqueous miniemulsion polymerization of VC using a fluorinated xanthate ((3,3,4,4,5,5,6,6,7,7,8,8,8-tridecafluorooctyl-2-((ethoxycarbonothioyl)thio) propanoate)[35-36] and using 2-hydroxyethyl 2-(ethoxycarbonothioylthio) propanoate (HECP)[34] were reported. In these works, the temperature employed was 45 ºC or higher and 1,4 dioxane was used as solvent in solution polymerizations. Moreover, information regarding the kinetic studies or optimization of VC polymerization is limited.

In this context, in the present work we investigate the MADIX polymerization of VC (Scheme 1) mediated by methyl (ethoxycarbonothioyl)sulfanyl acetate (MEA) using ecofriendly conditions, ambient temperature and a “green” solvent as cyclopentyl methyl ether (CPME).[19, 21, 48-50] Also, computational studies were carried out to support and confirm the experimental data.



Scheme 1. General scheme and conditions for the MADIX of VC initiated by Trigonox 187 W40 and mediated by MEA.

2. Experimental section

2.1 Materials

VC (99.9%) was kindly supplied by CIRES Lda, Portugal. N-vinylcaprolactam (NVCL) (98%, Sigma-Aldrich) was purified by passing through a short alumina column and recrystallized in hexanes.VAc (99% stabilized; Acros) was passed over a basic alumina column before use to remove the radical inhibitors. Dichloromethane (DCM) (Fluka, HPLC grade), DMF (Sigma-Aldrich, +99.8%), DMSO (Acros, +99.8% extra pure), THF (Panreac, HPLC grade), were distilled before use. Azobisisobutyronitrile (AIBN) (Fluka, 98%) was recrystallized three times from ethanol before use. Trigonox 187-W40 (40% water and methanol emulsion of diisobutyryl peroxide – DIBPO) (AkzoNobel), deuterated tetrahydrofuran (d_8-THF) (Euriso-top, 99.5%), sulfolane (+99%; Acros), 1-butyl-3-methylimidazolium hexafluorophosphate (BMIM-PF_6, >98%; TCI (Tokyo Chemical Industry Co. LTD), CPME (Sigma-Aldrich, inhibitor-free, anhydrous, +99.9%), methanol (Labsolve, 99,5%), methyl bromoacetate (Aldrich, 97%), potassium ethyl xanthogenate (Aldrich, 96%), diethyl ether (Aldrich, 98%), 4-methoxy phenol (Aldrich, 99%), carbon disulfide (Aldrich, ≥ 99%), *N,N*-diisopropylethylamine (Aldrich, ≥ 99%) and polystyrene (PS) standards (Polymer Laboratories) were used as received.

2.2 Techniques

400 MHz ^{1}H-NMR spectra of samples were recorded on a Bruker Avance III 400 MHz spectrometer, with a 5 mm TIX triple resonance detection probe, in d_8-THF with tetramethylsilane (TMS) as an internal standard. The chromatographic parameters of the samples were determined using a size exclusion chromatography set-up from Viscotek (Viscotek TDAmax) equipped with a differential viscometer (DV) and right-angle laser-light scattering (RALLS, Viscotek), low-angle laser-light scattering (LALLS, Viscotek) and refractive index (RI) detectors. The column set consisted of a PL 10 mm guard column (50 × 7.5 mm^2) followed by one Viscotek T2000 column (6 μm), one Viscotek T3000 column (6 μm) and one Viscotek LT4000L column (7 μm). A dual piston pump was set with a flow rate of 1 mL/min. The eluent (THF) was previously filtered through a 0.2 μm filter. The system was also equipped with an on-line degasser. The tests were done at 30 °C using an Elder CH-150 heater. Before the injection (100 μL), the samples were filtered through a polytetrafluoroethylene (PTFE) membrane with 0.2 μm pore. The system was calibrated with narrow PS standards. The *d*n/*d*c value was determined as 0.105 for PVC. Molecular weight (M_n^{SEC}) and dispersity ($Đ = M_w/M_n$) of synthesized polymers were determined by triple detection calibration using the OmniSEC software version: 4.6.1.354.

The Dynamic Mechanical Thermal Analysis (DMTA) of the samples was conducted in a Tritec2000DMA. The samples were placed in stainless steel material pockets and analyzed in single cantilever mode. The tests were carried out in a temperature range from -150ºC to 300ºC, with a heating rate of 2ºC.min-1, in multifrequency mode (1, 10 Hz). The Tg was determined from the peak of tan δ curve, at 1Hz.[51]

2.3 Procedures

MADIX of VC was carried out in a 50 mL glass high-pressure tube equipped with a magnetic stir bar. In the kinetic studies each point represents a single experiment.

Synthesis of methyl (ethoxycarbonothioyl)sulfanyl acetate (MEA).

MEA was obtained according to a previously described procedure.[31] In short, a suspension of potassium ethyl xanthogenate (23.2 g - 3 eq.) in diethyl ether (200 mL) was added portion wise to a solution of methyl bromoacetate (12 mL - 1 eq.) in diethyl ether (30 mL) at 0°C. The suspension was stirred overnight at room temperature. The solid was removed by filtration, more diethyl ether was added (200 mL) and the filtrate was washed with water (3x100 mL). The organic phase was dried over $MgSO_4$, filtered, and the solvent was removed *in vacuo* to afford a pale yellow oil (24 g - 85%). ^{1}H-NMR (400 MHz, acetone-d_6): δ (ppm) = 4.52 (q, 2H), 3.89 (s, 2H), 3.58 (s, 3H), 1.27 (t, 3H).

Synthesis of methyl 2-(4-methoxyphenoxycarbonothioylthio)acetate.

Methyl 2-(4-methoxyphenoxycarbonothioylthio)acetate was obtained according to a previously described procedure.[30] 4-Methoxy phenol (10 g, 81 mmol, 1 equiv) was dissolved in carbon disulfide (100 mL) at room temperature. *N,N*-Diisopropylethylamine (15 mL, 90 mmol, 1.1 equiv) was added and the yellow solution was stirred at 40 °C for 24 h. Methyl bromoacetate (4 mL, 41 mmol, 0.5 equiv) was added dropwise and the resulting orange suspension was stirred at 40 °C for an additional 24 h. The rest of the methyl bromoacetate (4 mL, 41 mmol, 0.5 equiv) was added and the mixture was again stirred at 40 °C for 24 h. The volatiles were removed *in vacuo* and the residue was dissolved in ethyl acetate (200 mL). A white precipitate was removed by filtration. The resulting clear orange solution was washed with H_2O (50 mL), 1M HCl (50 mL), 1M

NaOH (50 mL), H_2O (50 mL) and a saturated aqueous solution of NaCl (50 mL). The organic phase was dried over $MgSO_4$ and the solvent evaporated in vacuo. The resulting dark oilwas purified by flash chromatography on silica gel (toluene/petroleum ether 80:20 by volume) to yield the desired compound as a yellow oil (6.40 g, 23 mmol, 29%). R_f (toluene) = 0.2; ^{1}H-NMR (400 MHz, $CDCl_3$): δ (ppm) = 7.02 (m, 2H) 6.92 (m, 2H) 4.05 (s, 2H) 3.82 (s, 3H) 3.79 (s, 3H).

Typical procedure for the MADIX of VC in CPME at 30 °C with $[VC]_0/[MEA]_0/[Trigonox]_0$= 250/1/0.25

A 50-mL Ace Glass 8645#15 pressure tube, equipped with a bushing and a plunger valve, was charged with a mixture of MEA (57 mg, 0.29 mmol), Trigonox 187 W40 (32 mg, 0.073 mmol) and CPME (5.0 mL) (previously bubbled with nitrogen for 10 min). The precondensed VC (5 mL, 73 mmol) was added to the tube. The exact amount of VC was determined gravimetrically. The tube was sealed, submerged in liquid nitrogen and degassed through the plunger valve by applying reduced pressure and filling the tube with nitrogen about 20 times. The valve was closed and the tube reactor was placed in a water bath at 30 °C ± 0.5 °C under stirring (700 rpm). After 30 h, the reaction was stopped by plunging the tube into ice water. The tube was slowly opened, the excess VC was evaporated inside a fume hood, and the mixture was precipitated into methanol. The polymer was separated by filtration and dried in a vacuum oven until constant weight, yielding 2.35 g (51.7%) of PVC (M_n^{SEC} = 7.95 x 10^3, $Đ$ = 1.29).

Typical procedure for the "one-pot" chain extension experiment from xanthate-terminated PVC

A 50-mL Ace Glass 8645#15 pressure tube, equipped with a bushing and a plunger valve, was charged with a mixture of MEA (57 mg, 0.29 mmol), Trigonox 187 W40 (32 mg,

0.07 mmol) and CPME (2.5 mL) (previously bubbled with nitrogen for 10 min). The precondensed VC (2.5 mL, 36.4 mmol) was added to the tube. The exact amount of VC was determined gravimetrically. The tube was sealed, submerged in liquid nitrogen and degassed through the plunger valve by applying reduced pressure and filling the tube with nitrogen about 20 times. The valve was closed, and the tube reactor was placed in a water bath at 30 °C under stirring (700 rpm). After 16 h, the reaction was stopped by plunging the tube into ice water. The tube was slowly opened and the excess VC was evaporated inside a fume hood. The monomer conversion (conv.) were determined gravimetrically (48.8%), and the M_n^{SEC} = 4.30 x 10^3 and $Đ$ = 1.26 were determined by SEC. A mixture of Trigonox 187 W40 (27 mg, 0.06 mmol), CPME (17.0 mL) (previously bubbled with nitrogen for 10 min) and the precondensed VC (17.0 mL, 248 mmol) were added in the medium without any purification of the previously obtained xanthate-terminated PVC. The tube was sealed, submerged in liquid nitrogen and degassed through the plunger valve by applying reduced pressure and filling the tube with nitrogen about 20 times. The valve was closed, and the tube reactor was placed in a water bath at 30 °C under stirring (700 rpm). The reaction was stopped after 48 h by plunging the tube into ice water. The tube was slowly opened and the excess VC was evaporated inside a fume hood. The monomer conversion were determined gravimetrically (48.7%), and the M_n^{SEC} = 32.25 x 10^3 and $Đ$ = 1.36 of the resulting PVC-*b*-PVC diblock copolymer was determined by SEC.

Typical procedure for the "one-pot" synthesis of PVC-*b*-PVAc diblock copolymer by MADIX

A 50-mL Ace Glass 8645#15 pressure tube, equipped with a bushing and a plunger valve, was charged with a mixture of MEA (57 mg, 0.29 mmol), Trigonox 187 W40 (32 mg, 0.07 mmol) and CPME (2.5 mL) (previously bubbled with nitrogen for 10

min). The precondensed VC (2.5 mL, 36.4 mmol) was added to the tube. The exact amount of VC was determined gravimetrically. The tube was sealed, submerged in liquid nitrogen and degassed through the plunger valve by applying reduced pressure and filling the tube with nitrogen about 20 times. The valve was closed, and the tube reactor was placed in a water bath at 30 °C under stirring (700 rpm). After 16 h, the reaction was stopped by plunging the tube into ice water. The tube was slowly opened and the excess VC was evaporated inside a fume hood. The monomer conversion (conv.) were determined gravimetrically (48.8%), and the M_n^{SEC} = 4.30 x 10^3 and $Đ$ = 1.26 were determined by SEC. A mixture of AIBN (10 mg, 0.06 mmol), CPME (23.0 mL) (previously bubbled with nitrogen for 10 min) and VAc (11.5 mL, 125 mmol) were added in the medium without any purification of the previously obtained xanthate-terminated PVC. The tube was sealed, submerged in liquid nitrogen and degassed through the plunger valve by applying reduced pressure and filling the tube with nitrogen about 20 times. The valve was closed, and the tube reactor was placed in a water bath at 60 °C under stirring (700 rpm). The reaction was stopped after 48h and the mixture was analyzed by ^{1}H NMR spectroscopy to determine the VAc conversion (65%) and by SEC to determine the the macromolecular characteristics of the resulting PVC-*b*-PVAc diblock copolymer (M_n^{SEC} = 31.04 x 10^3 and $Đ$ = 1.31).

2.4 Computational Procedures

Standard ab initio molecular orbital theory and density functional theory calculations were carried out using Gaussian 09[52] and Molpro 2015.1.[53] Calculations were performed at a high level of theory that was based on our previous assessment studies for RAFT/MADIX reactions.[54-55] For all species, either full systematic conformational searches (at a resolution of 120°) or, for more complex systems, energy-direct tree

searches were carried out to ensure global, and not merely local minima were located.[56] These were performed at the M06-2X/6-31G(d) level of theory in a THF solution at 42 °C to mimic experimental conditions. The SMD continuum solvent model[57] was used to calculate the solvation energy at the same level of theory.

Having identified appropriate conformers, Gibbs free energies in solution for the various solvents were calculated via the thermocycle method. That is, for each species, accurate Gibbs free energies in the gas phase were added to Gibbs free energies of solvation in the various solvents as calculated via SMD, along with the term $RT(\ln V)$ to account for the change in standard state from 1atm to 1M.[58] To obtain the gas-phase Gibbs free energies, geometries of the solution-phase lowest Gibbs free energy conformers of all species were relaxed in the gas phase using M06-2X/6-31G(d); this level was also used to perform frequency calculations, which were scaled by the recommended scale factors.[59] Gas phase entropies and thermal corrections at 42 °C were calculated using standard textbook formulae[60] for the statistical thermodynamics of an ideal gas under the harmonic oscillator approximation in conjunction with the optimized geometries and scaled frequencies. These were then added to accurate gas phase electronic energies, which were calculated using G3(MP2)-RAD method based on the M06-2X/6-31G(d) optimized geometries.[61] Where G3(MP2)-RAD was impractical due to system size, an ONIOM approximation[62-63] to G3(MP2)-RAD was utilized, in which G3(MP2)-RAD was applied to the core and R(O)MP2/GTMP2Large//M062X/6-31G(d) was used for the full system (see the Supporting Information).

3. Results and discussion

3.1. Effect of the conventional initiator and its concentration

In this work, the controlling ability of the MEA was investigated for the polymerization of VC. The results obtained in previous publications from our group for RAFT polymerization using cyanomethyl methyl(phenyl)carbamodithioate (CMPCD) as RAFT agent[21-22] led us to use similar conditions for preliminary experiments for MADIX of VC.

Here, two radical initiators having very distinct half-life times, AIBN (with $t_{1/2}$ = 1 h at 82 °C)[64] and Trigonox 187-W40 (with $t_{1/2}$ = 1 h at 39 °C),[64] were investigated as a free radical source during the polymerization. The influence of the molar ratio $[initiator]_0/[MEA]_0$ in the control of the MADIX polymerization of VC is presented in Table 1. Results of the MADIX polymerization of VC using THF as solvent at 42 ºC, suggest that the Trigonox 187-W40 and $[initiator]_0/[MEA]_0$ ratio equal to 0.25/1 are the most successful conditions in providing fast and well-controlled polymerization. These results may be explained by the fact that isopropyl radical (formed from diisobutyryl peroxide: $(CH_3)_2CH{-}C(O){-}O{-}O{-}C(O){-}CH(CH_3)_2$) should add much faster to the VC and MEA when compared to the cyanoisopropyl radicals (formed by AIBN thermal decomposition).

Table 1. Conversion and Polymer Characteristics Obtained for the MADIX of VC in THF Using Different Conventional Initiators and Its Concentration at 42 °C after 22 h.

Entry[a]	$[VC]_0/[MEA]_0/[Initiator]_0$	Conv. (%)	M_n^{th} x 10^{-3}	M_n^{SEC} x 10^{-3}	$Đ$
1	250/1/0.25 (AIBN)	55.9	8.92	6.07	1.52
2	250/1/0.25 (Trigonox)	58.5	9.33	8.76	1.40
3	250/1/0.50 (Trigonox)	62.3	9.93	6.04	1.53
4	250/1/0.10 (Trigonox)	38.3	6.18	5.41	1.41

[a]Reaction conditions: $[VC]_0/[THF]$ = 1/1 (v/v).

3.2. Effect of the solvent

After establishing the initiator and its initial concentration ($[Trigonox]_0/[MEA]_0$ = 0.25/1), the study was focused on the influence of the solvent over the polymerization. Since PVC is not soluble in its monomer, the MADIX polymerization was conducted in the presence of different solvents and solvent mixtures that dissolve both VC and PVC (Table 2). THF, DCM, DMF, sulfolane and DMSO were the most obvious organic solvents tested. From these, CPME has emerged as a green alternative due to its high hydrophobicity, relative stability under both acidic and basic conditions, and low formation of peroxides as by products.[50] Moreover, CPME reveals negative skin sensitization,[48] presents no genotoxicity and no mutagenicity,[49] and it is approved by the Toxic Substances Control Act (TSCA) and the European List of Notified Chemical Substances (ELINCS).[19, 21, 50]

Results showed that the MEA was able to significantly improve the control of the polymerization of VC by MADIX compared to early attempts by producing PVC, with $Đ$<1.4. The MADIX of VC was effective in a wide range of solvents which demonstrates the versatility of the reaction system. The best results concerning molecular weight distribution were obtained in THF (Table 2, entry 1), sulfolane (Table 2, entry 4) and especially in CPME for which $Đ$ = 1.35 (Table 2, entry 7). DCM, DMF and DMSO appeared less adequate solvents since $Đ$ values ranged from 1.65 to 1.56 (Table 2, entries 2, 3 and 5). Nevertheless, in all cases a good agreement between the theoretical and experimental molecular weights was observed, which suggested good control over the PVC structure. Regarding polymerization rate, the higher conversions of VC after 22 h of reaction were obtained in THF (Table 2, entry 1) and in CPME (Table 2, entry 7).

Table 2. Conversion and Macromolecular Characteristics Obtained for the MADIX of VC Using Different Solvents at 42 °C after 22 h.

Entry[a]	Solvent	Conv. (%)	M_n^{th} x 10^{-3}	M_n^{SEC} x 10^{-3}	$Đ$
1	THF	58.5	9.33	8.76	1.40
2	DCM	30.4	4.94	4.22	1.62
3	DMF	30.0	4.88	3.53	1.65
4	Sulfolane	29.6	4.82	5.17	1.36
5	DMSO	22.6	3.72	4.90	1.56
6	BMIM-PF_6/DMSO = 50/50 (v/v)	9.6	1.69	2.35	1.61
7	CPME	56.7	9.06	9.17	1.35

[a]Reaction conditions: $[VC]_0/[MEA]_0/[Trigonox]_0$ = 250/1/0.25; $[VC]_0$/[solvent] = 1/1 (v/v).

Taking into account the results obtained from Table 2 and the "green" characteristics, CPME was selected as the solvent for a further comprehensive kinetic study of the MEA-mediated MADIX of VC. After 22 h, a relatively high VC conversion was obtained (~57%). Also, a constant concentration of growing radicals during the polymerization was observed, suggesting a first-order kinetics process (Figure 1a). This fact is in accordance to the typical linear dependency of $\ln[M]_0/[M]$ *vs.* time plots which was observed in the polymerization of VC by both NMP,[21, 23] SARA ATRP[18-20] and ARGET ATRP[17] methods, but is in strong contrast with SET-DTLRP[9, 14] and RAFT[21-22] methods which present two linear dependencies. MADIX of VC was well-controlled as shown by the decrease of the $Đ$ values during the polymerization (reached values around 1.35), as well as by perfect agreement between experimental and theoretical molecular weight values (Figure 1 (b)). Lastly, SEC chromatograms of PVC samples obtained at different polymerization times showed substantial shifts towards higher molecular weights and unimodal distributions with no visible sign of accumulation of dead polymer chains (Figure 1 (c)).

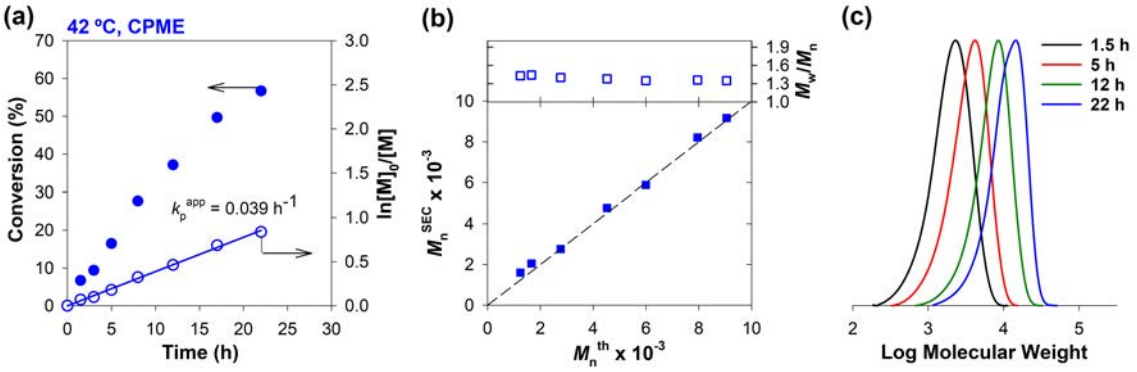


Figure 1. MADIX of VC in CPME at 42 °C initiated by Trigonox 187 W40 and mediated by MEA. (a) Conversion and $\ln[M]_0/[M]$ *vs.* time. (b) Number-average molecular weight (M_n^{SEC}) and dispersity (M_w/M_n) *vs.* theoretical number-average molecular weight (M_n^{th}). (c) Evolution of the SEC traces during the polymerization. Reaction conditions: $[VC]_0/[MEA]_0/[Trigonox]_0 = 250/1/0.25$; $[VC]_0/[CPME] = 1/1$ (v/v).

3.3. Effect of the monomer concentration

The initial monomer-to-solvent ratio (which also corresponds to the monomer concentration) may strongly affect the polymerization rate and may also sometimes jeopardize the quality of control.[7-8, 22-23] Thus, three different monomer-to-solvent ratios (2/1, 1/1 and 1/2) were investigated for the MEA-mediated MADIX of VC in CPME at 42 ºC (Table 3). At first sight, the results showed no general tendency regarding the effect of the initial concentration of VC. The rate of polymerization increased with the initial concentration of the monomer (Table 3, entries 1–2), as higher VC conversion was achieved for the same reaction time (22 h). But, for the highest VC concentration studied ($[VC]_0/[CPME] = 2/1$) there was an apparent decrease on the polymerization rate, as judged by the lower VC conversion obtained for the more diluted polymerization medium (Table 3, entries 2–3). This might be correlated to the poor solubility of the growing PVC

in the VC, which can cause diffusional limitations during the reaction and limit VC conversion.

Table 3. Conversion and Polymer Characteristics Obtained for the MADIX of VC in CPME at 42 °C after 22 h. Using different solvent/monomer ratios.

Entry[a]	$[VC]_0/[CPME]$ (v/v)	Conv. (%)	M_n^{th} x 10^{-3}	M_n^{SEC} x 10^{-3}	$Đ$
1	1/2	39.8	6.41	6.15	1.48
2	1/1	56.7	9.06	9.17	1.35
3	2/1	43.3	6.96	7.34	1.35

[a]Reaction Conditions: $[VC]_0/[MEA]_0/[Trigonox]_0 = 250/1/0.25$.

3.4. Effect of polymerization temperature

An important parameter to consider when optimizing RDRP systems is the polymerization temperature. Temperature is particularly crucial for polymerization of VC because high temperatures can contribute to the appearance of structural defects in the polymeric structure.[9, 65] MADIX of VC was evaluated in the range of 30–60 ºC (Table 4). The results showed that MADIX of VC can proceed successfully at near room temperature (T = 30 °C) with improved effect on the control of PVC compared to the same experiment carried out at 42 °C (Table 4, entries 1–2). On the other hand, when the temperature used was 60 ºC (Table 4, entry 3), even the final monomer conversion increased for the same reaction time, a significant increase of the $Đ$ was observed as well as the difference between M_n^{th} and M_n^{SEC}, suggesting the occurrence of side and/or irreversible termination reactions during the polymerization.

Table 4. Conversion and Macromolecular Characteristics Obtained for the MADIX of VC in CPME at Different Temperatures After 22 h.

Entry[a]	T (° C)	Conv. (%)	M_n^{th} x 10^{-3}	M_n^{SEC} x 10^{-3}	$Đ$
1	30	40.5	6.52	6.48	1.30
2	42	56.7	9.06	9.17	1.35
3	60	72.6	11.54	6.24	1.52

[a]Reaction conditions: $[VC]_0/[MEA]_0/[Trigonox]_0$ = 250/1/0.25; $[VC]_0/[CPME]$ = 1/1 (v/v).

Based on these results (Table 4) and the strong need for new successful ambient temperature RDRP systems, especially for VC polymerization,[7-8] 30 ºC was selected as the optimal temperature for a comprehensive kinetic study of the low temperature MEA-mediated MADIX of VC (Figure 2). As expected a slight decrease of the polymerization rate when compared with 42 ºC (Figure 1), k_p^{app}(30 ºC)=0.025h^{-1}< k_p^{app}(42 ºC)=0.039h^{-1} was observed. The first-order kinetics (Figure 2a) suggests a constant concentration of growing radicals during the polymerization. Ambient temperature MADIX of VC (T=30 ºC) was even more controlled as shown by the decrease of the $Đ$ values during the reaction. It reached values around 1.30, maintaining the perfect agreement between experimental and theoretical molecular weight values (Figure 2 (b)).

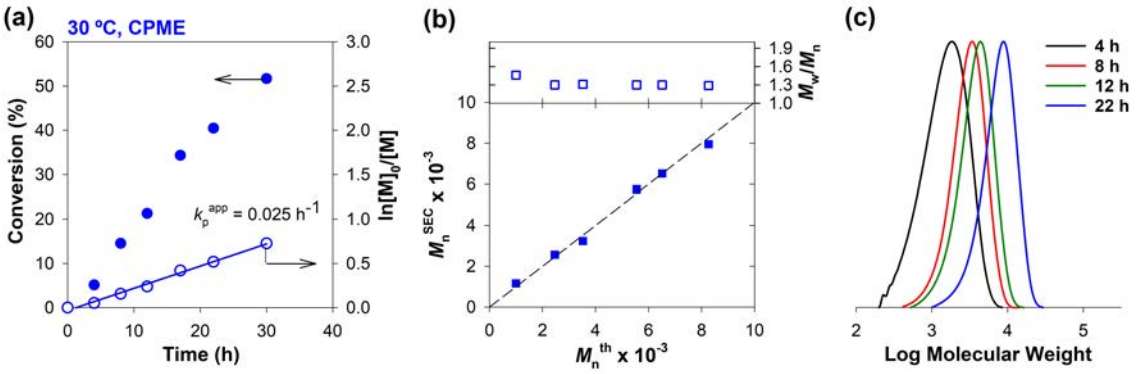


Figure 2. MADIX of VC in CPME at 30 °C initiated by Trigonox 187 W40 and mediated by MEA. (a) Conversion and $\ln[M]_0/[M]$ *vs.* time. (b) M_n^{SEC} and M_w/M_n *vs.* M_n^{th}. (c) Evolution of the SEC traces during the polymerization. Reaction conditions: $[VC]_0/[MEA]_0/[Trigonox]_0$ = 250/1/0.25; $[VC]_0/[CPME]$ = 1/1 (v/v).

3.5. Effect of the degree of polymerization

The ability to control the growth of polymer chains for different targeted molecular weights is one of different criteria to be evaluated in a RDRP system. Figure 3 shows the kinetics of the MADIX of VC for a targeted number-average degree of polymerization (DP_n) (which also corresponds to $[VC]_0/[MEA]_0$ ratio) of 1000. The polymerization proceeded in a controlled manner, with perfect agreement between the predicted and experimental values, as well as maintaining $Đ$ values throughout the reaction around 1.4 (Figure 3b) even for high molecular weight (M_n~40 x 10^3). As with the previous experiments performed with DP_n = 250 (Figure 1), the SEC chromatograms of PVC samples obtained at different reaction times showed constant shifts towards higher molecular weights and unimodal distributions with no visible sign of accumulation of dead polymer chains (Figure 3c).

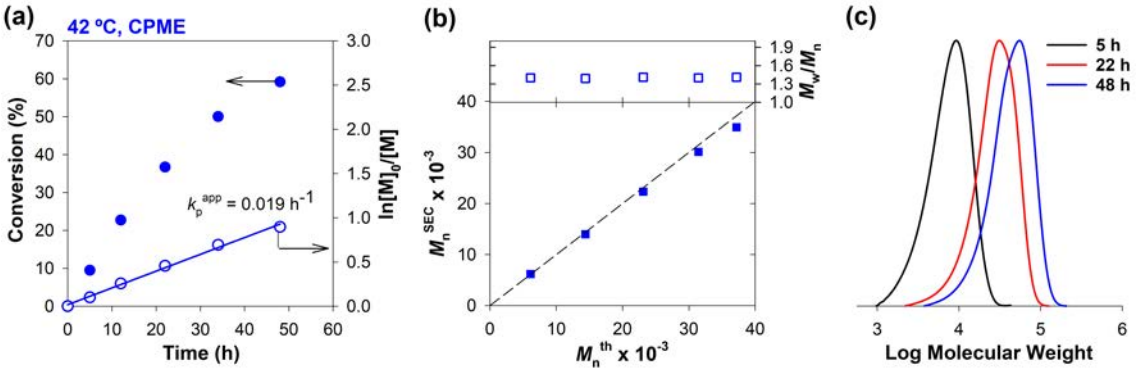


Figure 3. MADIX of VC in CPME at 42 °C initiated by Trigonox 187 W40 and mediated by MEA. (a) Conversion and $\ln[M]_0/[M]$ *vs.* time. (b) M_n^{SEC} and M_w/M_n *vs.* M_n^{th}. (c) Evolution of the SEC traces during the polymerization. Reaction conditions: $[VC]_0/[MEA]_0/[Trigonox]_0$ = 1000/1/0.25; $[VC]_0/[CPME]$ = 1/1 (v/v).

Supplementary experiments were performed targeting different DP_n values of VC. The results showed in Table 5 demonstrate that it is possible to synthesize well-defined PVC with a large range of molecular weights, suggesting that the MEA-mediated MADIX of VC is very robust.

Table 5. Conversion and Polymer Characteristics Obtained for the MADIX of VC in CPME at 42 °C for Different Targeted DP_n values ($[VC]_0/[MEA]_0$).

Entry[a]	$[VC]_0/[MEA]_0$	Time (h)	Conv. (%)	M_n^{th} x 10^{-3}	M_n^{SEC} x 10^{-3}	$Đ$
1	100/1	22	63.0	4.13	4.42	1.28
2[b]	125/1	16	48.8	4.01	4.30	1.26
3	250/1	22	56.7	9.06	9.17	1.35
4	500/1	22	47.1	14.9	14.65	1.36
5	1000/1	22	36.7	23.13	22.34	1.41

[a]Reaction conditions: $[VC]_0/[MEA]_0/[Trigonox]_0 = DP_n/1/0.25$; $[VC]_0/[CPME] = 1/1$ (v/v).

[b]Polymerization temperature, T=30 ºC.

3.6. Determination of the MADIX-derived PVC structure

For a deeper view of the PVC structure obtained by MEA-mediated MADIX, a sample (Table 5, entry 2) was analyzed by ^{1}H NMR spectroscopy (Figure 4). It verified that characteristics signals of the PVC assigned on the spectrum were in total agreement with those reported in the literature.[18-23] The ^{1}H NMR spectrum of the MEA is also included in Figure 4 to confirm the retention of both chain-end functionalities on the polymer. The spectrum of the PVC reveals the resonances of the repeat unit CH_2-CHCl: **e** (1.9-2.7 ppm) and **f** (4.2-4.7 ppm), respectively. The spectrum of the PVC also reveals the resonances of the mediating MEA fragments: **d** at 1.40-1.45 ppm, **a** at 3.60-3.65 ppm, and **c** at 4.65-

4.75 ppm. The signal of $-CH_2$ group **b** is probably hidden in the resonance of the main chain methylene group **e** at 1.9−2.7 ppm. It is also important to mention that signal of $-CH_2$ group **b** from the starting MEA at 3.96 ppm is not visible in the resulted PVC anymore showing that the MEA is consumed completely. The percentage of the chain-end functionality was calculated as follows: percentage functionality = [(*I*(**d**)/3)/(*I*(**a**)/3)] × 100% = 98.4%. The PVC NMR molecular weight was calculated using the equation: M_n^{NMR} = ([*I*(**f**)/(*I*(**d**)/3)] + 1) × MW_{VC} + MW_{MEA} = 4760. Also in the same way, the percentage of the chain-end functionality and M_n^{NMR} of a different PVC sample (Table 2, entry 4) obtained by MEA-mediated MADIX were 98.0% and 5140 respectively, confirming the robustness of these values.

To determine the impact of the MEA-mediated MADIX on the formation of structural defects of the PVC (Table 5, entry 5), the results were compared with PVC (M_n^{SEC} = 25.08 x 10^3; *Đ* = 1.95) synthesized by conventional FRP (Trigonox 187 W40 was used as the initiator) under the same reaction conditions used for MADIX of VC (temperature (42 ºC) and solvent (CPME)). The most representative structural defects that can be easily detected is the –CH=CH-CH_2Cl. Comparing the signal intensities of hydrogen atoms of PVC backbone –CH_2C**H**Cl– (**f**, 4.2-4.7 ppm) and the hydrogen atoms of the –CH=CH-CH_2Cl defect structure (5.70-5.95 ppm for CH=CH (**s1**, Figures 4 and 5) and 4.06-4.11 ppm for CH_2 (**s2**, Figures 4 and 5)) allows determining the structural defects in PVC samples. The –CH_2CHCl-/-CH=CH-CH_2Cl molar ratio is 1000/0.65 for PVC-MEA while this ratio is 1000/1.62 for PVC-FRP. These results showed a reduction in structural defects in the PVC obtained by MEA-mediated MADIX, which is also in agreement with other RDRP techniques as NMP,[23] RAFT[22] and SET-DTLRP[9] at the same temperature.

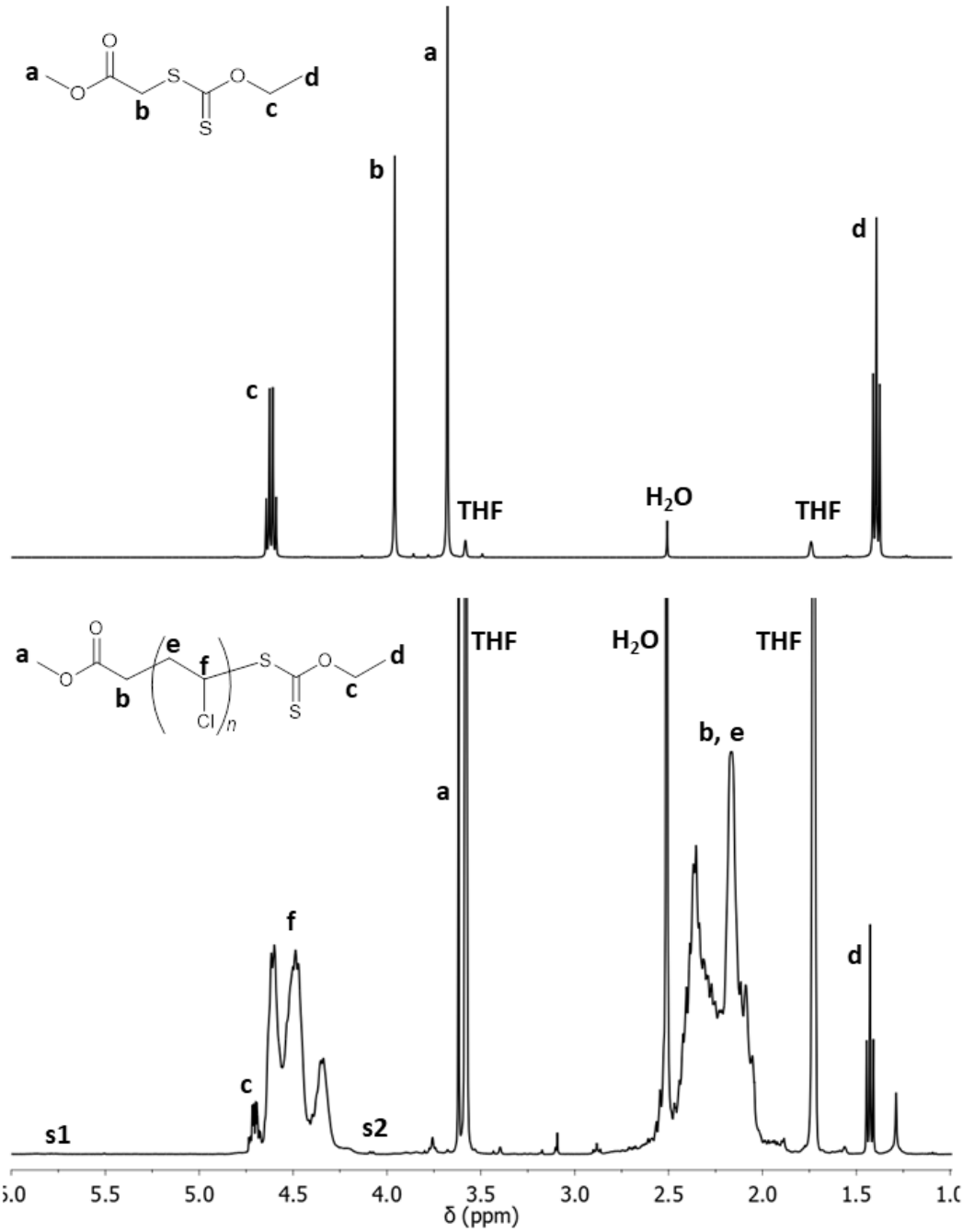


Figure 4. ^{1}H NMR spectra in d_8-THF of (a) the MEA and (b) the purified PVC (M_n^{SEC} = 4.30 x 10^3; $Đ$ = 1.26) obtained in Table 5, entry 2.

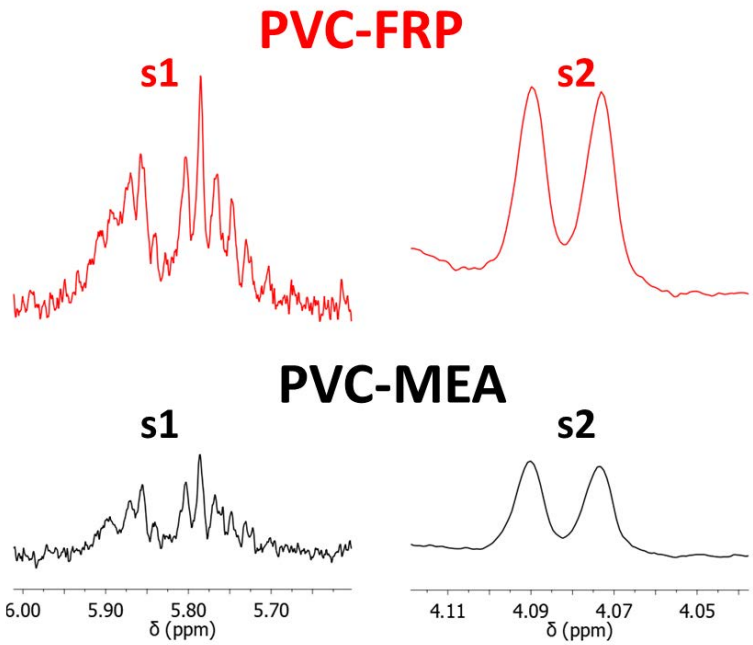


Figure 5. Enlargements of ^{1}H NMR spectra in d_8-THF of the purified PVC (M_n^{SEC} = 22.34 x 10^3; $Đ$ = 1.41) obtained in Table 5, entry 5 (black line or bottom spectra) and a purified PVC (M_n^{SEC} = 25.08 x 10^3; $Đ$ = 1.95) obtained by FRP (red line or top spectra) using the same conditions.

3.7. Evaluation of the MADIX-derived PVC livingness

It is paramount importance for block copolymer synthesis and macromolecular engineering the proof of the livingness of a polymer obtained by a RDRP technique. The living character of the earlier obtained PVC by MEA-mediated MADIX (Table 5, entry 2) was further confirmed by a successful "one-pot" chain extension from xanthate-terminated PVC of VC in CPME at 30 ºC. The SEC traces presented in Figure 6 showed a complete shift of the low molecular weight xanthate-terminated PVC macroinitiator (conv = 48.8%, M_n^{th} = 4.01 x 10^3, M_n^{SEC} = 4.30 x 10^3, $Đ$ = 1.26) towards high molecular weight (conv. = 48.7%, M_n^{th} = 34.74 x 10^3, M_n^{SEC} = 32.25 x 10^3, $Đ$ = 1.36), thus demonstrating the synthesis of an extended PVC-*b*-PVC.

To diversify the range of PVC-based macromolecular architectures, a xanthate-terminated PVC (Table 5, entry 2) macroinitiator (M_n^{SEC} = 4.30 x 10^3, $Đ$ = 1.26) initiated the MADIX of VAc to synthesize PVC-*b*-PVAc ($conv._{VAc}$ = 65%, M_n^{th} = 32.29 x 10^3, M_n^{SEC} = 31.04 x 10^3, $Đ$ = 1.31) and the MADIX of NVCL to synthesize PVC-*b*-PNVCL ($conv._{NVCL}$ = 85%, M_n^{th} = 19.12 x 10^3, M_n^{SEC} = 23.29 x 10^3, $Đ$ = 1.19) diblock copolymers (Table 6). The successful shift towards high molar masses for the SEC traces obtained for the block copolymers of PVAc-*b*-PVC and PNVCL-*b*-PVC compared to the starting PVC-MEA are presented in Figure 6. Thus, it was confirmed the "living" character of the xanthate-terminated PVC macroinitiator and the opportunity of using the described system in the production of novel and unique PVC-based copolymers with unprecedented properties. The chemical structures of PVC-*b*-PVAc block copolymer (Figure 7) and an obtained PVAc by MEA-mediated MADIX (Table 6, entry 2) (Figure 8) were demonstrated by ^{1}H NMR spectroscopy. The preliminary thermal characterization was carried out by DMTA to identify the glass transition temperature (Tg) of the different samples. The DMTA traces revealed Tan δ peaks that are sensitive to the frequency of measurement. The different Tg's are listed in Table 6 and correspond to the maximum temperature of Tan δ at 1Hz. The results obtained suggest that at least for the block copolymer compositions studied the segments of PNVCL and PVAc are miscible with the PVC segment. Further studies will be performed to fully characterize the thermal characteristics these samples.

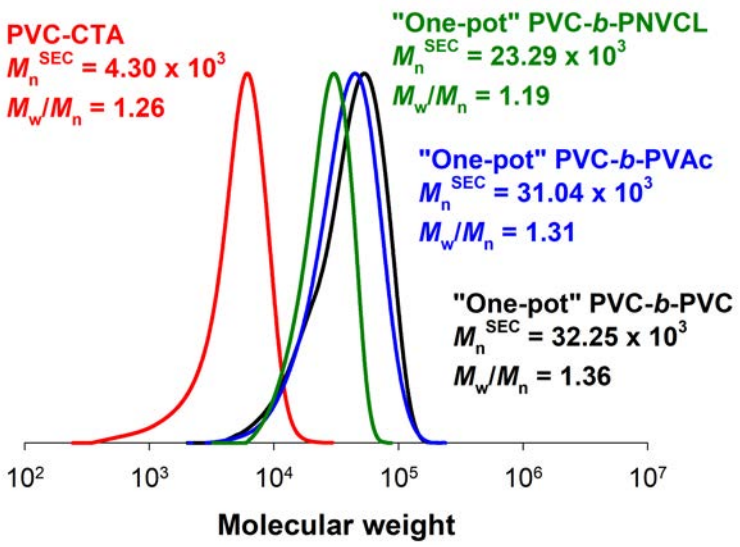


Figure 6. SEC chromatograms of the PVC macroinitiator (conv = 48.8%, M_n^{th} = 4.01 x 10^3, M_n^{SEC} = 4.30 x 10^3, $Đ$ = 1.26) obtained by MEA-mediated MADIX (red line), and the extended PVC-*b*-PVC (conv. = 48.7%, M_n^{th} = 34.74 x 10^3, M_n^{SEC} = 32.25 x 10^3, $Đ$ = 1.36) (black line), PVC-*b*-PVAc (conv.$_{VAc}$ = 65%, M_n^{th} = 32.29 x 10^3, M_n^{SEC} = 31.04 x 10^3, $Đ$ = 1.31) and PVC-*b*-PNVCL (conv.$_{NVCL}$ = 85%, M_n^{th} = 19.12 x 10^3, M_n^{SEC} = 23.29 x 10^3, $Đ$ = 1.19) diblock copolymers after "one-pot" chain extension in CPME.

Table 6. Conversion and Polymer Characteristics Obtained for the Different Temperature-Responsive PVC-Based Copolymers.

Entry	Macro/Copolymer	Conv.$_{VC}$ (%)	Conv.$_{VAc/NVCL}$ (%)	M_n^{th} x 10^{-3}	M_n^{SEC} x 10^{-3}	$Đ$	T_g (°C)
1	PVC_{66}	49.2	--	4.04	4.30	1.26	74.1
2	$PVAc_{112}$	--	93.3	10.24	9.80	1.30	31.2
3	$PNVCL_{124}$	--	93.8	16.51	17.42	1.10	183.4
4	PVC_{66}-*b*-$PVAc_{311}$	49.2	65.0	32.29	31.04	1.31	41.6
5	PVC_{66}-*b*-$PNVCL_{136}$	49.2	85.2	19.12	23.29	1.19	172.1

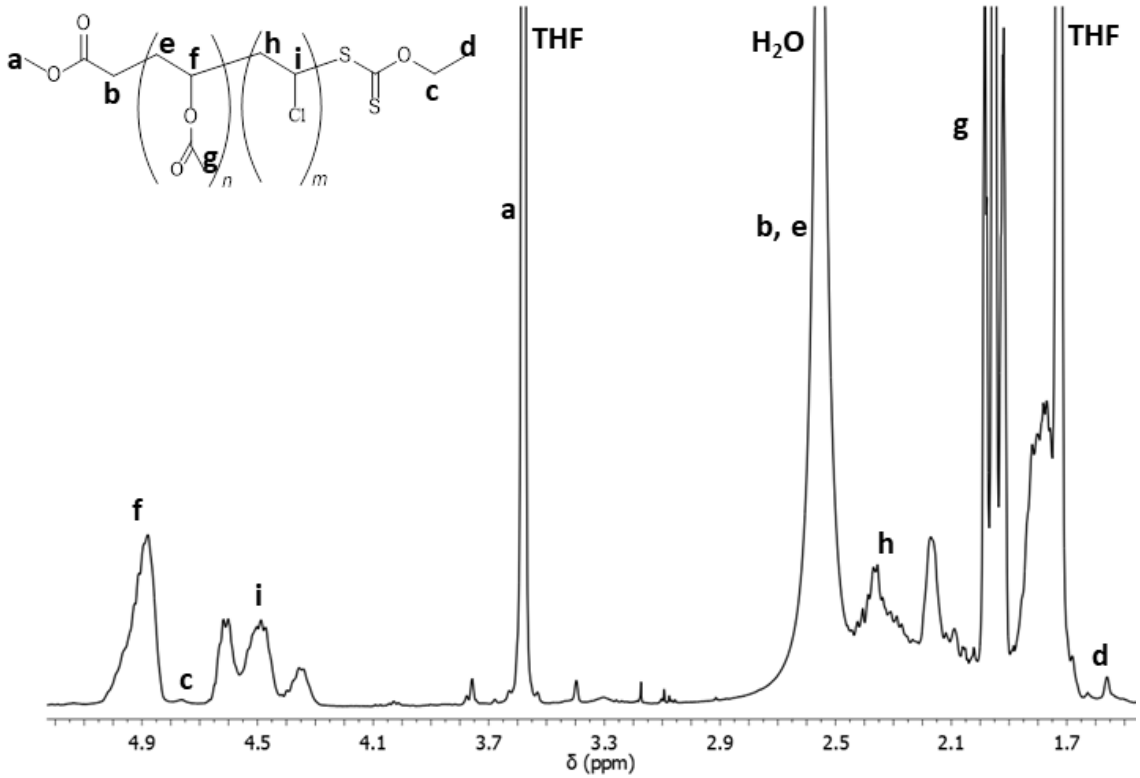


Figure 7. ^{1}H NMR spectrum in d_8-THF of the PVC-*b*-PVAc diblock copolymer (M_n^{SEC} = 31.04 x 10^3, $Đ$ = 1.31) obtained Table 6, entry 4.

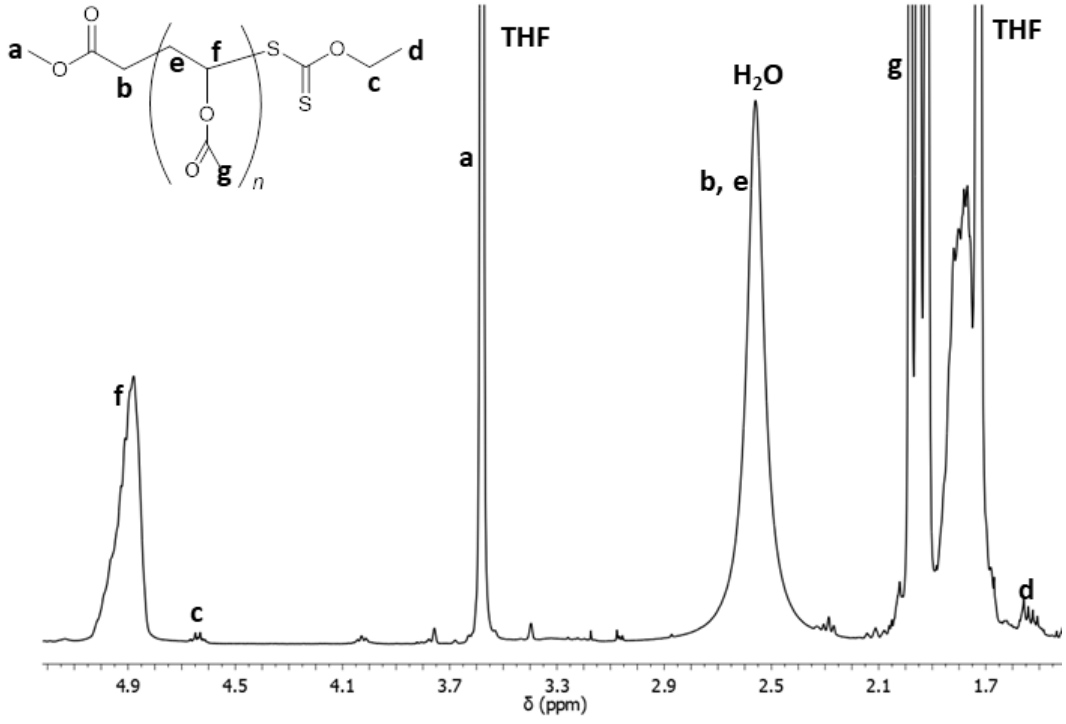
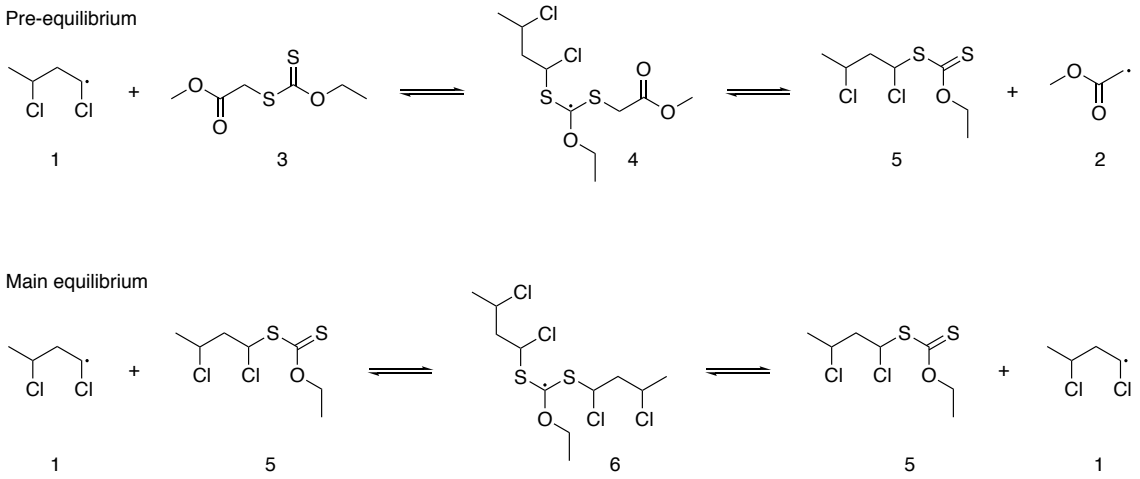


Figure 8. ^{1}H NMR spectra in d_8-THF of the purified PVAc (M_n^{SEC} = 9.80 x 10^3; $Đ$ = 1.30) obtained in Table 6, entry 2.

3.8. Computational Studies on the mechanism of MEA-mediated MADIX of VC.

To understand the polymerization kinetics, Gibbs free energies were calculated for models of the pre- and main equilibria using high-level ab initio molecular orbital theory calculations (Scheme 2, Table 7). The results show that addition of the propagating radical to the initial MADIX agent (1+3 → 4) is marginally thermodynamically unfavorable and hence would occur with a relatively slow rate coefficient. This helps to explain the less than perfect control observed. This thermodynamic unfavorability arises entirely in entropy (see Table S1 of the Supporting Information), which explains why control improves at lower temperatures. The solvent screen in Table 7 indicates that CPME, followed by sulfolane, are the most favorable, consistent with these performing best in the experimental solvent screen. Once the VC dimer radical has added to the MADIX agent, the fragmentation of the leaving group (4 → 5 + 2) is rapid and the transfer reaction can occur. Once this occurs, addition of the vinyl chloride propagating radical to the polyMADIX agent becomes thermodynamically favoured so that control can improve, with CPME and sulfolane again performing among the best, consistent with experiment. The changing effect of the MADIX agent substituent on the reaction stems largely in the entropy with the more flexible polyMADIX agent showing less entropic changes upon addition, though there is also an enthalpic contribution stemming from the saturation effect of multiple lone pair donors on the MADIX-adduct stability.[55, 66] These results suggest even better control might be achievable by changing the leaving group R in S=C(OEt)R to a lone pair donor moiety, provided its stability as a leaving radical remains

greater than that of vinyl chloride. A potential candidate would be R=C(CH$_3$)$_2$Cl or R=CCl$_2$CH$_3$.



Scheme 2. Reactions studied as representative of the pre-equilibrium and main equilibrium in MEA-mediated polymerization of VC.

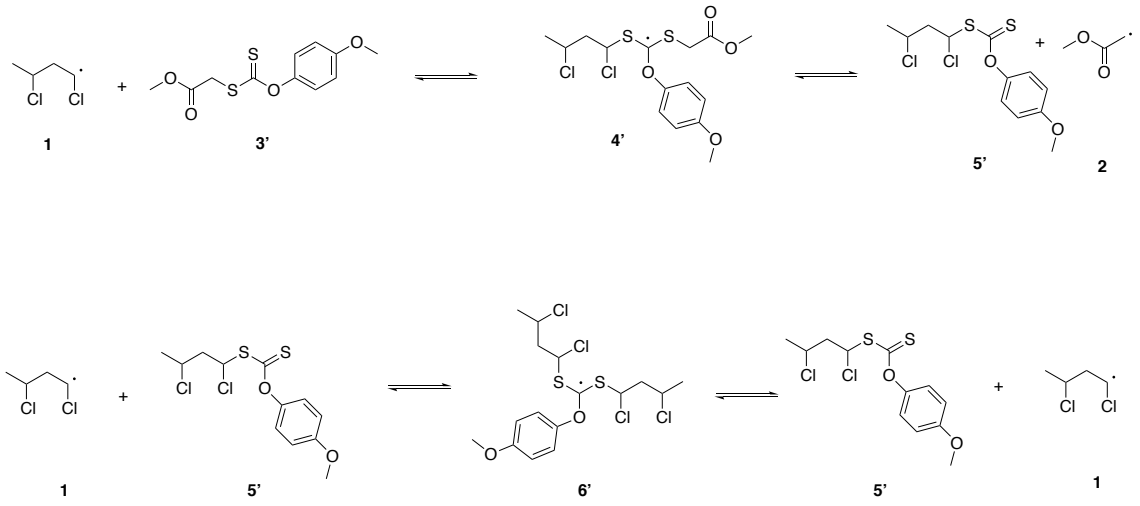
Table 7. Computed Gibbs Free Energies of Reactions (kJ mol^{-1}, 42°C) in the gas-phase and various solvents[a]

Reactions[b]	Gas	THF	DMSO	DMF	Sulfolane	DCM	CPME
1+3 → 4	12.5	17.9	17.4	19.0	14.4	18.8	11.4
4 → 5 + 2	-15.1	-18.5	-17.3	-19.1	-14.3	-20.2	-13.0
1+3 → 5 + 2	-2.7	-0.6	0.0	-0.1	0.1	-1.4	-1.6
1 + 5 → 6	-0.4	-4.0	-6.4	-4.9	-8.4	-1.9	-6.1

[a]Calculations performed at the G3(MP2)-RAD//M06-2X/6-31G(d) level of theory in conjunction with SMD solvent corrections. [b]See Scheme 2.

Alternatively, control could be improved by changing the Z-group on the xanthate, which would have the benefit of improving both the pre- and main-equilibria. the activity of the

xanthate could be improved. One way to achieve this is to activate the MADIX agent toward addition by reducing lone pair donating ability of the xanthate oxygen via cross-conjugation with a π system. One such candidate system, methyl 2-(4-methoxyphenoxycarbonothioylthio)acetate, uses this approach to the extent that it has been effective in control of ethylene.[30] Model pre- and main- equilibria for this xanthate with PVC are shown in Scheme 3 with corresponding reaction energies in Table 8. From Table 8 it is clear that the addition reactions are more exergonic and hence expected to be faster, thus allowing superior control across the range of solvents tested.



Scheme 3. Reactions studied as representative of the pre-equilibrium and main equilibrium in methyl 2-(4-methoxyphenoxycarbonothioylthio)acetate-mediated polymerization of vinyl chloride.

Table 8. Computed Gibbs Free Energies of Reactions for methyl 2-(4-methoxyphenoxycarbonothioylthio)acetate (kJ mol^{-1}, 42°C) in the gas-phase and various solvents.[a]

Reactions[b]	Gas	THF	DMSO	DMF	Sulfolane	DCM	CPME
1+3' → 4'	2.4	2.4	0.6	2.2	-1.8	2.8	-4.3
4' → 5' + 2	-6.1	-2.2	-1.7	-1.7	-1.7	-2.0	-2.0
1+3' → 5' + 2	-8.5	-4.5	-2.3	-3.9	0.1	-4.8	2.3
1 + 5' → 6'	-11.3	-13.8	-15.0	-13.8	-16.9	-12.8	-17.1

[a]Calculations performed at the G3(MP2)-RAD//M06-2X/6-31G(d) level of theory in conjunction with SMD solvent corrections. [b]See Scheme 3.

3.9. Experimental testing of methyl 2-(4-methoxyphenoxycarbonothioylthio)acetate

To confirm the controlling ability of the methyl 2-(4-methoxyphenoxycarbonothioylthio)acetate-mediated MADIX polymerization of VC additional experiments were performed (Table 9). Results showed that the methyl 2-(4-methoxyphenoxycarbonothioylthio)acetate-mediated MADIX (Table 9, entry 1) was able to improve the control ($Đ$ = 1.27) and the rate of the polymerization (conv.$_{VC}$ = 46.5%, 7 h) of VC compared to the MEA (Table 5, entry 1), $Đ$ = 1.28 and conv.$_{VC}$ = 63.0% after 22 h.

Table 9. Conversion and Polymer Characteristics Obtained for the Methyl 2-(4-methoxyphenoxycarbonothioylthio)acetate-mediated MADIX of VC in CPME at 42 °C.

Entry[a]	$[VC]_0/[M\text{-}2]_0/[Trig.]_0$[b]	Time (h)	Conv. (%)	M_n^{th} x 10^{-3}	M_n^{SEC} x 10^{-3}	$Đ$
1	100/1/0.25	7	46.5	3.18	2.89	1.27
2	150/1/0.25	10	44.4	4.44	4.25	1.31

[a]Reaction conditions: $[VC]_0$/[CPME] = 1/1 (v/v).

[b]M-2: methyl 2-(4-methoxyphenoxycarbonothioylthio)acetate; Trig.: Trigonox 187 W40 .

Regarding the results obtained with methyl 2-(4-methoxyphenoxycarbonothioylthio)acetate-mediated MADIX polymerization of VC more detailed experimental and computational studies using these and new xanthate structures are currently underway.

4. Conclusions

The MEA-mediated polymerization of VC was successful performed at ambient temperature (30-42°C) using a "green" solvent as CPME. Careful choice of polymerization conditions (initiator type and its concentration, solvent nature, monomer concentration and temperature) is required to achieve low dispersities ($Đ \sim$ 1.2-1.3). Computational studies confirm the results of the solvent screen and suggest that changes to the initial MADIX leaving or stabilizing groups could further improve control. The structural characterizations (^{1}H-NMR) suggested the high preservation of the chain-end functionalities and the formation of very small content of structural defects. MEA-terminated PVC macroinitiators were successfully used in "one-pot" chain extension experiments to produce different PVC-based diblock copolymers (PVC-*b*-PVC, PVC-*b*-PVAc, and PVC-*b*-PNVCL). This work is of outstanding importance to have access new generation of high value materials comprising PVC segments that could take advantage of the outstanding features of C-Cl bonds. The use of xanthates/MADIX technique could open the door to all its benefits compared to other RDRP methods and enlarge the range of PVC application.

ASSOCIATED CONTENT

Supporting Information

Complete computational data are presented. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

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