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SET-LRP of Bio- and Petroleum-Sourced Methacrylates in Aqueous Alcoholic Mixtures

Adrian Moreno,[†] Nabil Bensabeh,[†] Jaan Parve,[‡] Juan C. Ronda,[†] Virginia Cádiz,[†] Marina Galià,[†] Lauri Vares,[§] Gerard Lligadas,*,[†,∥] and Virgil Percec*,[∥]

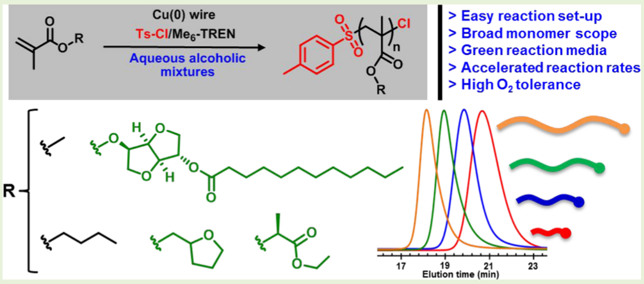
[†]Laboratory of Sustainable Polymers, Department of Analytical Chemistry and Organic Chemistry, University Rovira i Virgili, Tarragona 43007, Spain

[‡]Department of Chemistry and Biotechnology, Tallinn University of Technology, Ehitajate tee 5, Tallinn 19086, Estonia

[§]Institute of Technology, University of Tartu, Nooruse 1, Tartu 50411, Estonia

[∥]Roy & Diana Vagelos Laboratories, Department of Chemistry, University of Pennsylvania, Philadelphia, Pennsylvania 19104-6323, United States

Supporting Information



ABSTRACT: Single-electron transfer-living radical polymerization (SET-LRP) in "programmed" aqueous organic biphasic systems eliminates the judicious choice of solvent and also provides accelerated reaction rates. Herein, we report efforts to expand the monomer scope for these systems by targeting methacrylic monomers and polymers. Various environmentally friendly aqueous alcoholic mixtures were used in combination with Cu(0) wire catalyst, tris(2-dimethylaminoethyl)amine (Me$_6$-TREN) ligand, and *p*-toluenesulfonyl chloride (Ts-Cl) initiator to deliver well-defined polymethacrylates from methyl methacrylate, butyl methacrylate, and other monomers derived from biomass feedstock (e.g., lactic acid, isosorbide, furfural, and lauric acid). The effect of water on the nature of the reaction mixture during the SET-LRP process, reaction rate, and control of the polymerization is discussed. The control retained under the reported conditions is demonstrated by synthesizing polymers of different targeted molar mass as well as quasi-block AB copolymers by "in situ" chain extension at high conversion. These results highlight the capabilities of SET-LRP to provide sustainable solutions based on renewable resources.

INTRODUCTION

The simplest single-electron transfer-living radical polymerization (SET-LRP) methodology involves the use of air-stable Cu(0) wire as a catalyst in a polar solvent/N-ligand mixture that facilitates Cu(I)X disproportionation.[1−7] The SET-LRP reactions are, under these conditions, self-controlled by this special type of redox reaction that simultaneously (re)generates the most active forms of atomic Cu(0) activator and Cu(II)X$_2$ deactivator.[5,6] A number of reports have shown that combinations of water,[8,9] hydrogenated and fluorinated alcohols[10−14] or dipolar aprotic solvents,[15−17] and their mixtures, in combination with N-ligands such as tris(2-aminoethyl)amine (TREN),[18] tris(2-dimethylaminoethyl)-amine (Me$_6$-TREN), and *N*,*N*,*N*′,*N*′,*N*″,*N*″-pentamethyl-diethylamine,[19] give rise to well-defined polymers.[20−23] Conversely, the use of nonpolar and polar nondisproportionating solvents has classically not been recommended because it penalizes the chain end functionality of the targeted polymer.[20,24−26] However, we reported that the transition from organic to certain aqueous-organic reaction mixtures in which a biphasic or triphasic SET-LRP occurs eliminates the judicious choice of solvent.[27−37] In these systems, polymerization takes place in the organic phase and both Cu(I)X and Cu(II)X$_2$ are partitioned from the organic into the water phase where a fast and quantitative disproportionation occurs.[4] Aqueous-organic mixed solvent systems provide important technological advantages in terms of accelerated reaction rates as well as the possibility of "in situ" purification of the resulting polymers from copper salts by organic/aqueous layers separation. Nevertheless, we feel that the most important contribution of this concept, named "programmed" biphasic systems, is that it facilitates the use of any organic solvent regardless of its ability to mediate disproportionation or not. So far, programmed biphasic systems of a variety of organic solvents (e.g., alcohols,[30,31,34,37] acetone,[29] acetonitrile,[27,28] dimethyl sulfoxide (DMSO),[32] and tetrahydrofuran (THF)[32]) have only been applied to the SET-LRP of acrylates.[27−37] Here, we expand the monomer scope for these systems by systematically evaluating the polymerization of both bio- and petroleum-sourced methacrylates in a library of environmentally friendly aqueous alcoholic mixtures.

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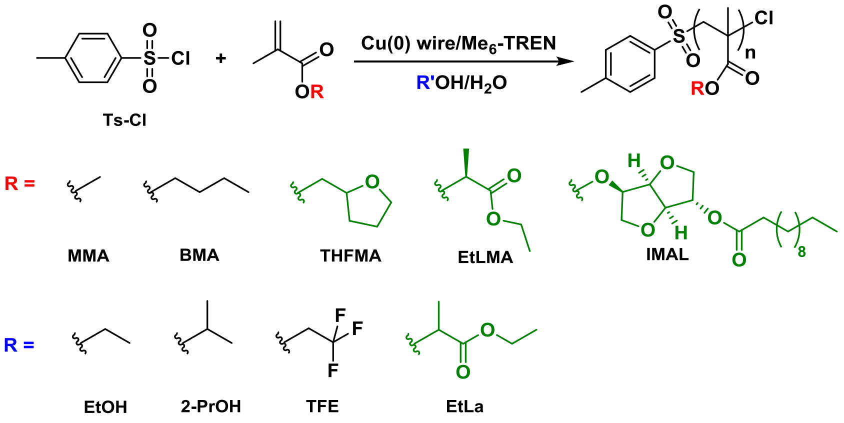
Scheme 1. Cu(0) Wire/Me_6-TREN-Catalyzed SET-LRP of Bio- and Petroleum-Sourced Methacrylates in Aqueous Alcoholic Mixtures Initiated with *p*-Toluenesulfonyl Chloride (Ts-Cl)[a]



[a] Color code: green refers to products that are derived from biomass and black refers to petroleum-sourced products.

EXPERIMENTAL SECTION

Materials. Methyl methacrylate (MMA, 99%) and butyl methacrylate (BMA, 99%) from Sigma-Aldrich were filtered over a short column of basic alumina to remove the radical inhibitor before use. Tetrahydrofurfuryl methacrylate (THFMA, 97%) from Sigma-Aldrich was filtered over basic alumina and distilled under reduced pressure prior to use. D-Isosorbide 2-laurate-5-methacrylate (IMAL) was synthesized according to a previous publication.[38] Ethyl lactate methacrylate (EtLMA) was synthetized by esterification of the corresponding ethyl lactate alcohol with methacrylic anhydride following a previously reported methodology.[39] *p*-Toluenesulfonyl chloride (99%, Ts-Cl, Fluka), tris[2-(dimethylamino)ethyl]amine (Me_6-TREN, 97%, Sigma-Aldrich), hydrazine hydrate (60% hydrazine (N_2H_2), Sigma-Aldrich), 2,2,2-trifluroethanol (TFE, 99%, Merck), dimethyl sulfoxide (DMSO, 99%, Sigma-Aldrich), ethanol absolute grade (EtOH, 99%, Scharlab), and methacrylic anhydride (94%, Sigma-Aldrich) were used as received. Propan-2-ol (2-PrOH, 97%, Scharlab) was distilled before use. Ethyl lactate (natural >98%, EtLa, Sigma-Aldrich) was filtered over basic alumina and distilled to remove peroxide residues. A 20 gauge diameter copper(0) wire with 99.9% purity was purchased from Creating Unkamen and activated following a previous procedure.[40]

Techniques. ^1H NMR spectra analysis was performed on a Varian VNMR-S400 NMR instrument at 25 °C in $CDCl_3$ using tetramethylsilane as an internal standard. Molecular weight analysis was performed via gel permeation chromathography (GPC) using an Agilent 1200 series system equipped with three columns (PLgel 3 μm MIXED-E, PLgel 5 μm MIXED-D, and PLgel 20 μm from Polymer Laboratories) and an Agilent 1100 series refractive-index detector. THF (Scharlab, HPLC grade) was used as an eluent at a flow rate of 1.0 mL/min. The number-average (M_n) and weight-average (M_w) molecular weights of the polymer samples were determined using a poly(methyl methacrylate) (PMMA) standards purchased from American Polymer Standards. Differential scanning calorimetry (DSC) measurements were carried out with Mettler DSC3+ thermal analyzer with N_2 as the purge gas (50 mL/min) and using heating and cooling rates of 30 °C/min in the −50−150 °C temperature range. Calibration was performed using indium standard for heat flow calibration and zinc standard for temperature calibration.

General Procedure for the SET-LRP of Methacrylates in Aqueous Alcoholic Mixtures. Briefly, 1 mL of methacrylate monomer, 0.5 mL of alcohol/water mixture, Me_6-TREN, and Ts-Cl were introduced into a 25 mL Schlenk tube. Then, the reaction mixture was then degassed by 6 freeze−pump (1 min)−thaw cycles. After that, 12.5 cm of hydrazine-activated Cu(0) wire wrapped around a stirring bar was introduced into the Schlenk tube under a positive argon flow and held above with the help of an external magnet. An additional two freeze−pump−thaw cycles were applied. After that the reaction mixture was placed in a thermostated silicon bath at 50 °C. Then, the stir bar wrapped with the Cu(0) wire was dropped gently into the reaction mixture. The introduction of the Cu(0) wire defines $t = 0$. Samples were taken at different reaction times by purging the side arm of the Schlenk tube with argon for 1 min using a deoxygenated glass syringe and a stainless steel needle. The collected samples were dissolved in $CDCl_3$ and quenched by air bubbling. After that the monomer conversion was measured by ^1H NMR spectroscopy. To determine the molecular weight and the polydispersity of the polymer, solvent and residual monomer were removed under vacuum. The samples were then dissolved in THF, passed through a short small basic Al_2O_3 chromatographic column to remove any residual copper, and finally analyzed by GPC.

General Procedure for in Situ Block Copolymerization Experiments. Methacrylic monomer (1 mL), solvent (0.5 mL), ligand (Me_6-TREN), and initiator (Ts-Cl) were transferred into a 25 mL of Schlenk tube. The reaction mixture was deoxygenated as described above. After that the hydrazine-activated Cu(0) wire (12.5 cm of 20 gauge) was introduced and held above with the help of an external magnet under a positive flow of argon. The flask was placed in a thermostated silicon bath at 50 °C. The introduction of the Cu(0) wire into the reaction mixture defines $t = 0$. The SET-LRP was left to proceed until high monomer conversion (>90%). Next, a deoxygenated solution containing the second methacrylic monomer, solvent, and ligand was injected and the reaction was allowed to continue for 24 h at 50 °C. Then, the conversion of the second monomer was determined by ^1H NMR and the polymerization mixture was dissolved in minimum dichloromethane and precipitated in cold methanol. The final polymer was dried under vacuum until constant weight.

RESULTS AND DISCUSSION

Alcohols are Best Solvents of Choice for Sulfonyl Halide-Initiated SET-LRP. Dimethyl sulfoxide (DMSO) and other dipolar aprotic solvents are considered the best organic solvents to practice SET-LRP because they not only destabilize Cu(I)X toward disproportionation but also stabilize nascent Cu(0) nanoparticles.[5] However, the fact that these solvents are under increasing pressure from environmental regulation motivates the use of greener alternatives.[12,41−43] Besides its toxicity, DMSO is compatible with alkyl halide-type initiators but undergoes side reactions with sulfonyl halides.[44] Sulfonyl halide-type initiators are attractive because they easily generate sulfonyl radicals that show lower dimerization tendency than carbon-centered radicals produced from alkyl halide-based initiators. Hence, sulfonyl halides undergo fast and reversible addition to activated olefins, resulting in faster initiation than propagation and thus giving rise to polymers with a narrow

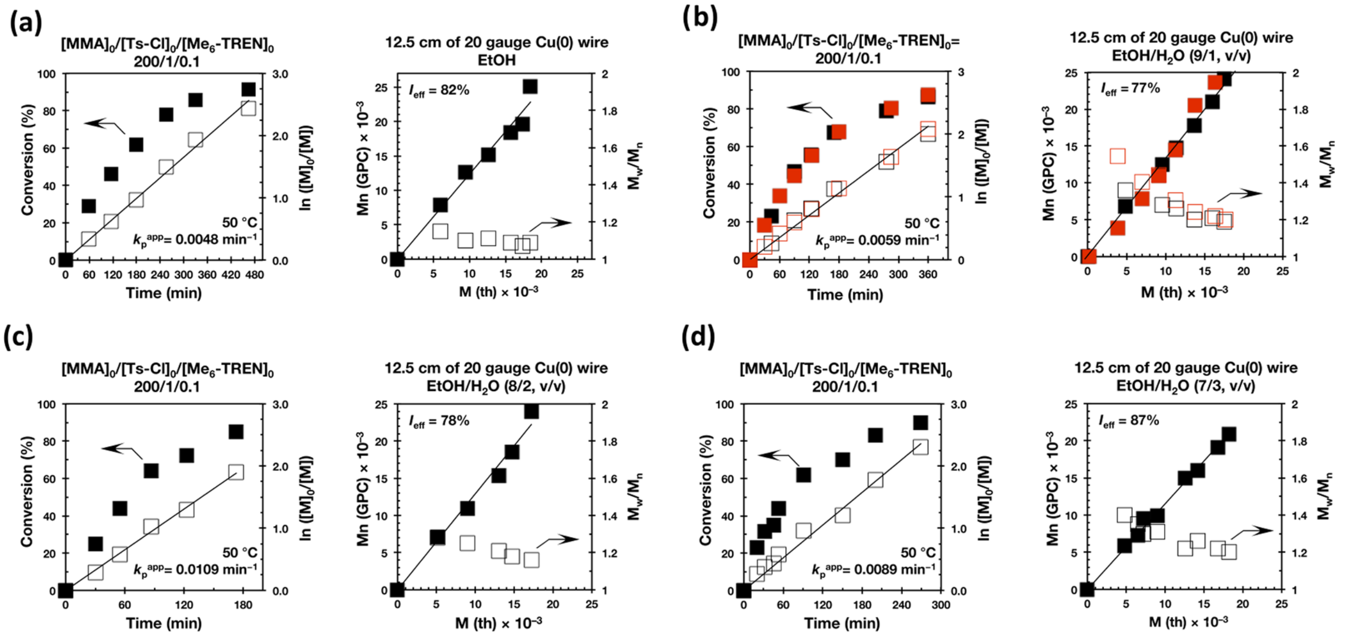


Figure 1. Kinetic plots, molecular weight, and polydispersity evolutions for the SET-LRP of MMA in EtOH/water mixtures initiated with Ts-Cl and catalyzed by hydrazine-activated Cu(0) wire at 50 °C. (a) EtOH, (b) EtOH/water (9/1, v/v), (c) EtOH/water (8/2, v/v), and (d) EtOH/water (7/3, v/v). The v/v ratio must be multiplied by 10 to obtain % solvent/% water. The value of v + v must be divided by 10 to obtain the total volume of solvents, 1 mL. Reaction conditions: MMA = 1 mL (a−d); EtOH = 0.5 mL (a); and EtOH + water = 0.5 mL (b−d). $[MMA]_0/[Ts\text{-}Cl]_0/[Me_6\text{-}TREN]_0$ = 200/1/0.1. Experimental data in different colors were obtained by different researchers.

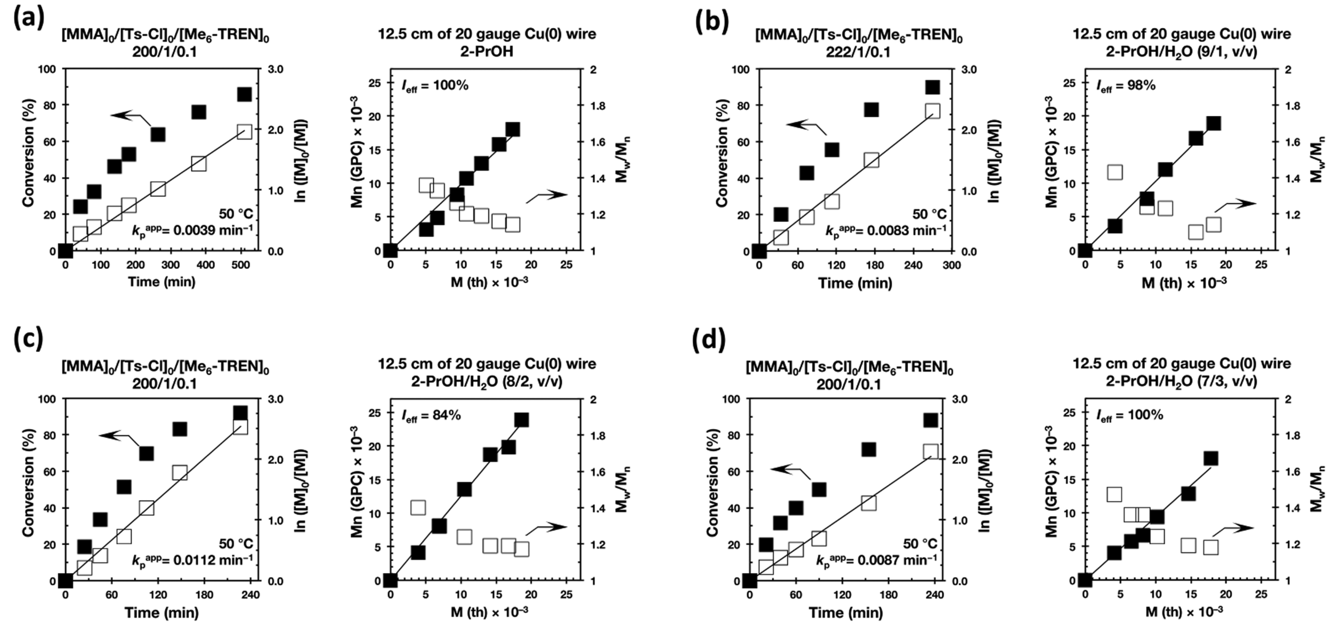


Figure 2. Kinetic plots, molecular weight, and polydispersity evolutions for the SET-LRP of MMA in 2-PrOH/water mixtures initiated with Ts-Cl and catalyzed by hydrazine-activated Cu(0) wire at 50 °C. (a) 2-PrOH, (b) 2-PrOH/water (9/1, v/v), (c) 2-PrOH/water (8/2, v/v), and (d) 2-PrOH/water (7/3, v/v). The v/v ratio must be multiplied by 10 to obtain % solvent/% water. The value of v + v must be divided by 10 to obtain the total volume of solvents, 1 mL. Reaction conditions: MMA = 1 mL, (a−d); 2-PrOH = 1 mL (a); and 2-PrOH + water = 0.5 mL (b−d). $[MMA]_0/[Ts\text{-}Cl]_0/[Me_6\text{-}TREN]_0$ = 200/1/0.1.

molecular weight distribution.[45−48] Sulfonyl halides are excellent initiators for methacrylates, acrylonitrile, and styrene.[49,50] Conversely, alcohols do not react with sulfonyl halides even in the presence of Me_6-TREN and therefore are a better choice to perform clean and efficient SET-LRP using sulfonyl halide-type initiators.[50−52] Indeed, alcoholic solvents also ensure acceptable levels of Cu(I)X disproportionation and low environmental impact.[5,6] Note that SET-LRP of methacrylates has been widely investigated in multiple homogeneous reaction mixtures[19,50,51,53−56] but not in programmed or self-generated biphasic systems.[57]

Cu(0) Wire-Catalyzed SET-LRP of MMA in Aqueous Mixtures of EtOH, 2-PrOH, and TFE Initiated with *p*-Toluenesulfonyl Chloride (Ts-Cl). Methyl methacrylate

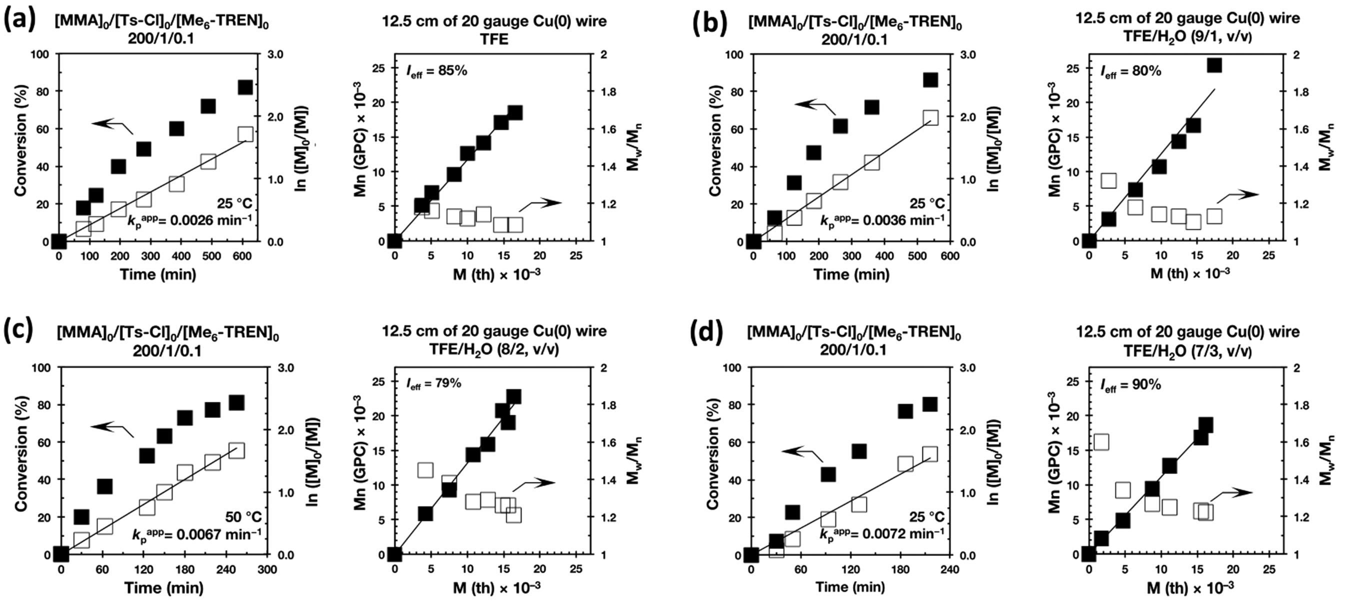


Figure 3. Kinetic plots, molecular weight, and polydispersity evolutions for the SET-LRP of MMA in TFE/water mixtures initiated with Ts-Cl and catalyzed by hydrazine-activated Cu(0) wire at 50 °C. (a) TFE, (b) TFE/water (9/1, v/v), (c) TFE/water (8/2, v/v), and (c) TFE/water (7/3, v/v). The v/v ratio must be multiplied by 10 to obtain % solvent/% water. The value of v + v must be divided by 10 to obtain the total volume of solvents, 0.5 mL. Reaction conditions: MMA = 1 mL (a–d); TFE = 0.5 mL (a); and TFE + water = 0.5 mL (b–d). $[MMA]_0/[Ts\text{-}Cl]_0/[Me_6\text{-}TREN]_0 = 200/1/0.1$.

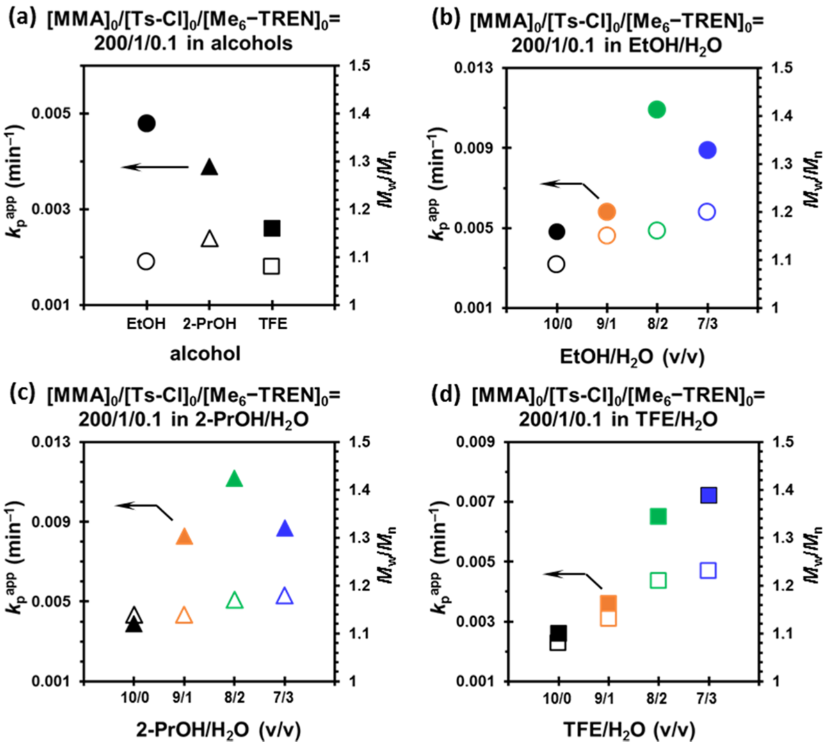


Figure 4. (a) k_p^{app} and M_w/M_n for the SET-LRP of MMA initiated with Ts-Cl and catalyzed by Cu(0) wire at 50 °C in EtOH, 2-PrOH, and TFE. Dependence of k_p^{app} and M_w/M_n with the percentage of water (% H_2O) for the SET-LRP of MMA in (b) EtOH/H_2O, (c) 2-PrOH/H_2O, and (d) TFE/H_2O. Color/shape color: circles, triangles, and squares refer to EtOH, 2-PrOH, and TFE systems, respectively. Filled symbols refers to k_p^{app} y-axis and empty symbols refer to M_w/M_n y-axis. Black symbols refer to pure alcohol, orange symbols refer to alcohol/H_2O (9/1, v/v) mixtures, green symbols refer to alcohol/H_2O (8/2, v/v) mixtures, and blue symbols refer to alcohol/H_2O (7/3, v/v) mixtures.

(MMA) was selected as a model monomer for the first series of experiments. The SET-LRP of MMA was initiated with Ts-Cl and catalyzed with 12.5 cm of hydrazine-activated Cu(0) wire in the presence of Me_6-TREN ligand (Scheme 1). EtOH, 2-PrOH, and TFE were used under the following conditions: $[MMA]_0/[Ts\text{-}Cl]_0/[Me_6\text{-}TREN]_0 = 200/1/0.1$ at 50 °C (Figures 1a, 2a, and 3a, respectively). The use of TFE can be questioned from an economic and sustainability viewpoint, but it is important to highlight that its low boiling point facilitates recycling by distillation from the reaction mixture.

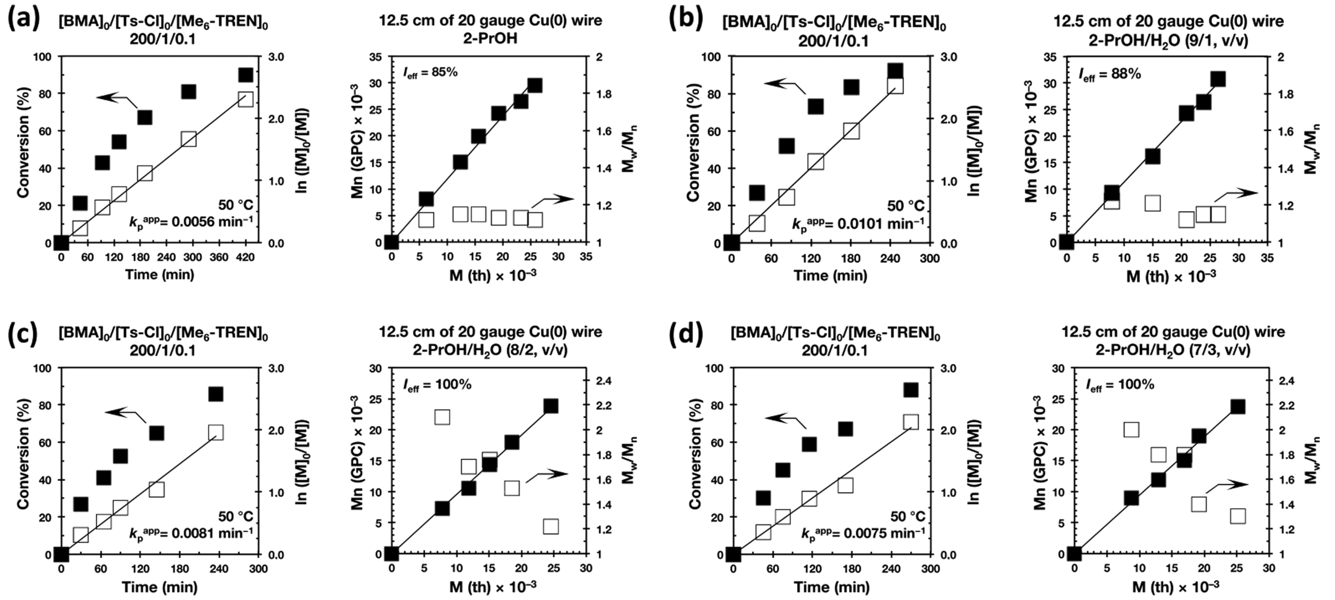


Figure 5. Kinetic plots, molecular weight, and polydispersity evolutions for the SET-LRP of BMA in 2-PrOH/water mixtures initiated with Ts-Cl and catalyzed by hydrazine-activated Cu(0) wire at 50 °C. (a) 2-PrOH, (b) 2-PrOH/water (9/1, v/v), (c) 2-PrOH water (8/2, v/v), and (d) 2-PrOH/water (7/3, v/v). The v/v ratio must be multiplied by 10 to obtain % solvent/% water. The value of v + v must be divided by 10 to obtain the total volume of solvents, 1 mL. Reaction conditions: BMA = 1 mL (a−d); ^{i}PrOH = 0.5 mL (a); and ^{i}PrOH + water = 0.5 mL (b−d). [BMA]$_0$/[Ts-Cl]$_0$/[Me$_6$-TREN]$_0$ = 200/1/0.1.

In agreement with previous data,[50,55] the living character of the SET-LRP of MMA in pure alcohols is supported by a steady apparent rate constant of propagation (k_p) through the entire reaction and linear evolution of number average molecular weight (M_n) of the resulting polymer vs theoretical molecular weight (M_{th}). The experimental data are summarized in Table S1, entries 1, 5, and 9. Since alcohols are good solvents for low-molar-mass poly(methyl methacrylate) (PMMA), all reaction mixtures remained transparent through the entire reaction course. Analysis of the polymerization kinetics revealed both high monomer conversion and comparable molecular weight distributions for the targeted PMMA ($M_w/M_n \sim 1.10$) (Figure 4a). However, it is noteworthy that irrespective of the higher polarity of TFE, the polymerization of MMA was roughly 2-fold slower in TFE (k_p^{app} = 0.0026 min^{-1}) than in EtOH (k_p^{app} = 0.0048 min^{-1}).

Next, aqueous alcoholic mixed solvent system with increasing water composition ratio were investigated. The ratio between alcohol (EtOH, 2-PrOH, and TFE) and water was varied from 9/1 to 8/2 and finally to 7/3 v/v. These experiments were conducted under identical conditions as above. The kinetic plots and the evolution of M_n of the resulting polymer vs M_{th} and M_w/M_n for the SET-LRP of MMA in the three series of mixed solvent systems are depicted in Figures 1b−d, 2b−d, and 3b−d. In the presence of water as a co-solvent, the reactions were in all cases faster than in pure alcohols while retaining LRP features (Figure 4b−d and Table S1). For example, the EtOH/water and TFE/water systems at 9/1 v/v provided reaction rates 1.2× and 1.4× faster (compare Table S1, entries 1, 2, 9, and 10). The acceleration effect in 2-PrOH/water was even higher (2× faster) (compare Table S1, entries 5 and 6). The highest acceleration was observed at a ratio 8/2 v/v for EtOH/water and 2-PrOH/water systems, whereas aqueous TFE systems showed the maximum k_p at 7/3 v/v (Figure 4b−d). Although all tested systems allowed acceptable level of molecular weight control (M_w/M_n < 1.23), it is important to notice a slightly broader molecular weight distribution for systems with a higher water content. Careful visualization of the reaction mixture revealed that in the presence of 10% water, all reaction mixtures remained homogeneous through the entire reaction course. However, at a ratio 8/2 v/v, the mixtures became slightly turbid rather than transparent above approximately 75% conversion. However, GPC analysis of the resulting polymers revealed the formation of PMMA with a narrow molecular weight distribution (Figure S1). Next, the TFE-based system with the highest water content (7/3, v/v) showed increased turbidity during the entire reaction, but bluish water droplets were clearly visible for both 7/3 v/v aqueous ethanolic and 2-propanolic systems. The water droplets contain Cu(II)Br$_2$/Me$_6$-TREN species and probably some traces of alcohol, whereas the organic phase contains alcohols, polymer, and residual MMA. These observations support the biphasic nature of the SET-LRP under these conditions and suggest that a biphasic system with lower particle size is also formed when turbid reaction mixtures were observed. The transition from mono- to biphasic SET-LRP system can explain the above-mentioned M_w/M_n broadening as well as the drop in k_p^{app} observed when transitioning from 8/2 to 7/3 v/v systems for EtOH/water and 2-PrOH/water (Figure 4b,c).

Cu(0) Wire-Catalyzed SET-LRP of BMA in Aqueous Mixtures of 2-PrOH Initiated with Ts-Cl. Butyl methacrylate (BMA) was chosen to estimate the possibilities of aqueous-alcoholic mixtures to deliver hydrophobic polymethacrylates. This study was limited to aqueous mixtures of 2-PrOH.

Figure 5b−d depicts the kinetic experiments for SET-LRP of BMA at a targeted DP (degree of polymerization) of 200 using Ts-Cl as an initiator in three mixtures of 2-PrOH with water. A control experiment in pure 2-PrOH is also included for comparison (Figure 5a). The higher hydrophobicity of BMA forced in this case the appearance of turbidity at lower volume fraction of water (9/1 v/v) (Figure 6a). At higher water contents (8/2 and 7/3 v/v), the reaction mixture occurred through an easily visualizable biphasic regime (Figure 6b). As described

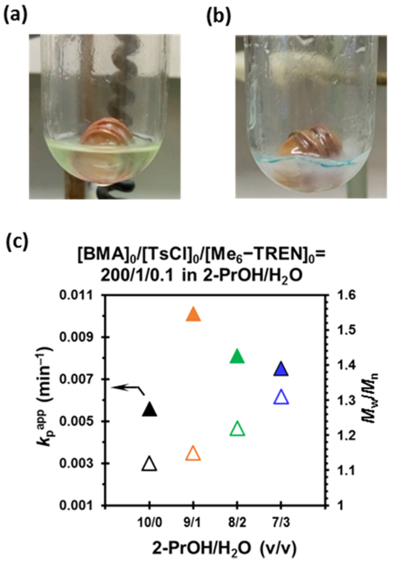


Figure 6. Digital images of the reaction mixture after SET-LRP of BMA initiated with Ts-Cl and catalyzed by Cu(0) wire at 50 °C in 2-PrOH/H_2O (a) 9/1, v/v and (b) 7/3, v/v. (c) Dependence of k_p^{app} and M_w/M_n with the percentage of water (% H_2O) for the SET-LRP of BMA in 2-PrOH/H_2O. Color/shape color: filled symbols refer to k_p^{app} y-axis and empty symbols refer to M_w/M_n y-axis.

above, bluish water droplets separated from the organic phase containing monomer and polymer. As expected, the addition of water to 2-PrOH accelerated the rate of polymerization of BMA (Figure 6c). The addition of 10% water to IPA increased the rate constant from k_p^{app} = 0.0056 to 0.0101 min^{-1} (Table S2, entries 1 and 2). However, k_p^{app} value did not increase further at higher water loadings, although it remained above the value obtained in pure alcohol. Note that regardless of the transition from a mono to biphasic system, the living behavior of this series of experiments is supported by the linear evolution of ln($[M]_0$/[M]) vs time and high I_{eff} (Figure 5).

However, GPC analysis revealed again a slightly higher M_w/M_n as the water content increased (Figure 6c). To assess the potential of the system in maintaining control of various targeted DPs, a series of polymerizations were conducted in 2-PrOH/water (9/1, v/v) targeting DPs from 100 to 600 (Figure 7a). In all cases, no optimized conditions delivered PBMA up to 75 000 g/mol with a high conversion and a narrow molecular weight distribution. Irrespective of the low fraction of water in the reaction mixture, polymerizations at DP = 400 and 600 proceeded in a biphasic system. Furthermore, in situ block copolymerization of low-molar-mass PBMA with an aliquot of MMA injected at high conversion displayed a clear shift of the molecular weight distribution after the chain extension while maintaining low polydispersity (Figure 7b). Also successful was the opposite chain extension from PMMA to PBMA (Figure S2). This supports the high chain end fidelity of the polymethacrylates prepared under these conditions and validates their use in the preparation of block copolymers and of other even more complex architectures such as dendrimers by the TERMINI concept.[58] A large diversity of sulfonyl halide initiators were also developed for other potential applications.[59]

Cu(0) Wire-Catalyzed SET-LRP of MMA and BMA in Aqueous Alcoholic Mixtures without Applying Deoxygenation and Cu(0) Wire Activation Protocols. SET-LRP has been demonstrated along the years to be a readily robust LRP technique.[10,60−64] One of its most appealing characteristics

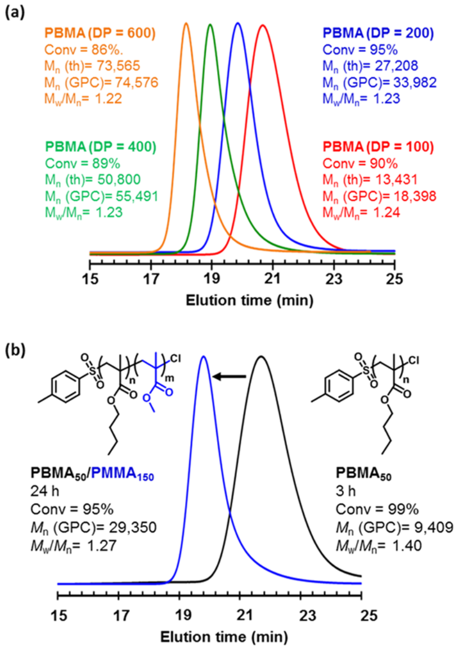


Figure 7. (a) GPC traces of PBMA with different targeted DPs obtained by SET-LRP of BMA initiated with Ts-Cl and catalyzed by Cu(0) wire at 50 °C in 2-PrOH/H_2O (9/1, v/v). (b) GPC traces of polymers before and after in situ block copolymerization of PBMA with PMMA. Initial conditions for block copolymerization: $[BMA]_0$/$[Ts\text{-}Cl]_0$/[Me_6-TREN] = 50/1/0.1 in 2-PrOH/water 9/1, v/v (BMA/solvent = 2/1, v/v). Block copolymerization achieved by addition of MMA (150 equiv) and Me_6-TREN (0.1 equiv) in 2-PrOH/water 9/1, v/v (BMA/solvent = 2/1, v/v).

is its outstanding tolerance to the presence of air in the reaction mixture because the dual activation system based on heterogeneous Cu(0) wire and “nascent” Cu(0) generated by disproportionation.[1,2,4] To avoid time-consuming deoxygenation protocols, which readily limits technological applications, two methodologies were tested for the Cu(0) wire-catalyzed SET-LRP of MMA and BMA in aqueous alcoholic mixtures. Note that no activation protocol was applied to Cu(0) wire neither. First, the polymerization of MMA was conducted with a blanked of argon in an aqueous 2-propanolic solution containing 5 mol % of N_2H_2 as an oxygen scavenger (Figure 8a and Table S3, entry 1).[61] Sulfonyl halides are not compatible with N_2H_2 and other reducing agents and therefore Ts-Cl initiator was replaced in this case by carbon tetrachloride (CCl_4). In the presence of N_2H_2, which reacts with oxygen to form nitrogen and water, the SET-LRP of MMA accomplishes the expected features for a LRP process.

Remarkably, no induction period was observed at the early stages of the polymerization. Two additional experiments were also conducted to highlight that the Cu(0) wire-catalyzed SET-LRP of methacrylates in aqueous alcoholic systems can even be conducted solely using a blanket of inert gas, without external oxygen scavengers or deoxygenation protocols. As can be seen in Figure 8b,c, the only penalty in this case is that the polymerization occurs with a delay of few minutes. After the induction period, the reaction proceeds with comparable k_p^{app} than that obtained in the deoxygenation of the reaction mixture applying several freeze−thaw−pump cycles (e.g., compare Figures 8c with 5c). These results support the industrial applicability of these systems because the freeze−pump−thaw/inert gas bubbling procedures and the Cu(0) activation

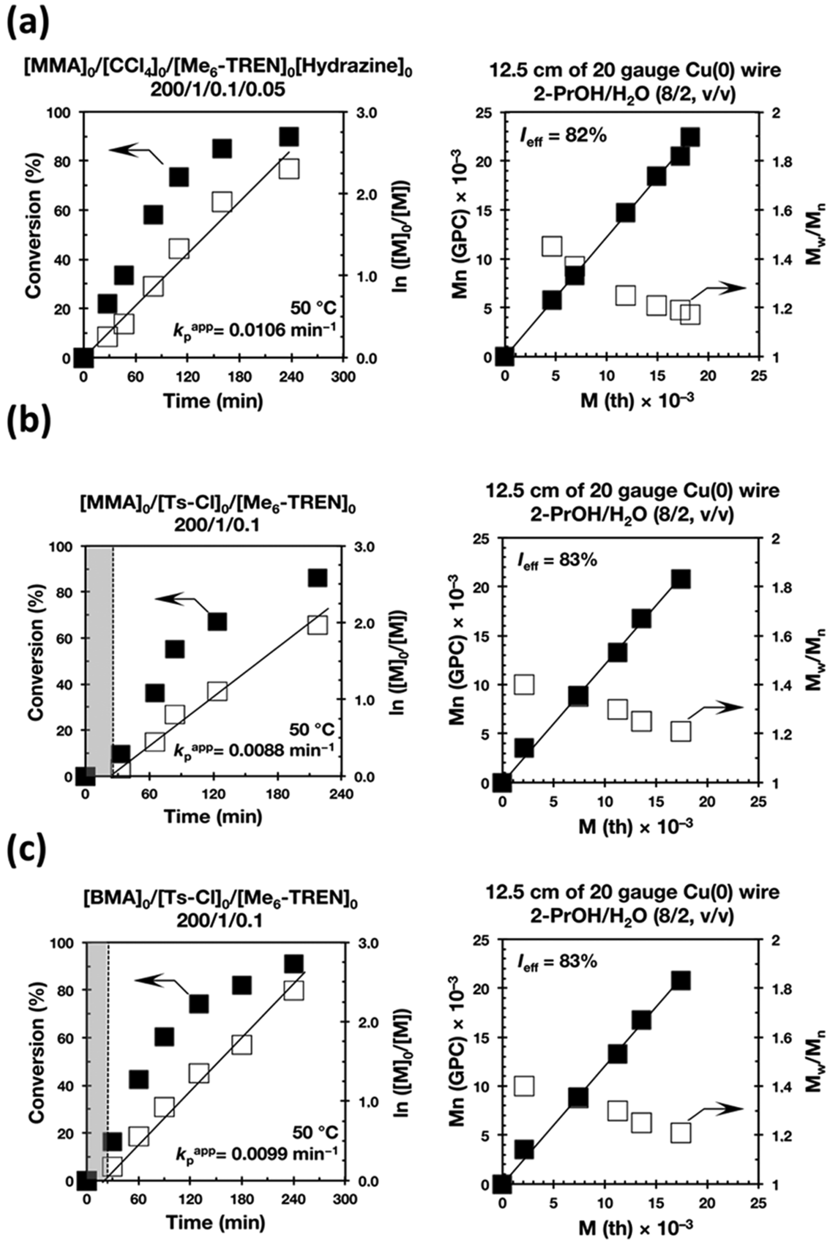


Figure 8. Kinetic plots, molecular weight, and polydispersity evolutions for the SET-LRP of MMA and BMA in 2-PrOH/water mixtures initiated with CCl_4 and Ts-Cl, catalyzed by nonactivated Cu(0) wire at 50 °C without applying deoxygenation protocols. (a, b, and c) 2-PrOH/water (8/2, v/v). The v/v ratio must be multiplied by 10 to obtain % solvent/% water. The value of v + v must be divided by 10 to obtain the total volume of solvents, 1 mL. Reaction conditions: MMA = 1 mL (a, b), BMA = 1 mL (c). 2-PrOH + water = 0.5 mL (a, b, and c). (a) $[MMA]_0/[CCl_4]_0/[Me_6\text{-TREN}]_0/[N_2H_2]$= 200/1/0.1/0.05. (b) $[MMA]_0/[Ts\text{-}Cl]_0/[Me_6\text{-TREN}]_0$ = 200/1/0.1 and (c) $[BMA]_0/[Ts\text{-}Cl]_0/[Me_6\text{-TREN}]_0$ = 200/1/0.1. Gray area indicates period of time with no reaction.

protocols are not mandatory. Note that in this case the time required for the experimental procedure to set up the reaction is shortened from approximately 80−15 min.

Cu(0) Wire-Catalyzed SET-LRP of Biomass-Based Methacrylates in Aqueous Organic Mixtures. Precise synthesis of well-defined biomass-based (co)polymers from abundant, natural, renewable resources is receiving tremendous attention due to the increasing concerns on the depletion of fossil reserves and deteriorating environments.[14,65−69] We feel that SET-LRP has the potential to have a deep impact in the area of renewable resources as demonstrated with glycopolymers.[70−72] The attractiveness of alcoholic water mixtures in the green context encouraged us to target three model methacrylates sourced from various families of biomass types. Isosorbide 2-methacrylate-5-laurate (IMAL) monomer is derived from isosorbide, a bicyclic diol derived from glycose-based polysaccharides, and the C12 fatty acid laurate.[38] Tetrahydrofurfuryl methacrylate (THFMA) is commercially available derivative of furfural, a promising renewable platform compound derived from lignocellulosic biomass, whereas ethyl lactate-derived monomer (EtLMA) is synthesized from the corresponding green solvent produced by the fermentation of biomass raw material (Scheme 1).[73,74] Note that the LRP of the targeted biobased monomers is challenging due to steric hindrance and hydrophobicity. The LRP of IMAL and EtLMA was not reported until now and THFMA only received scarce

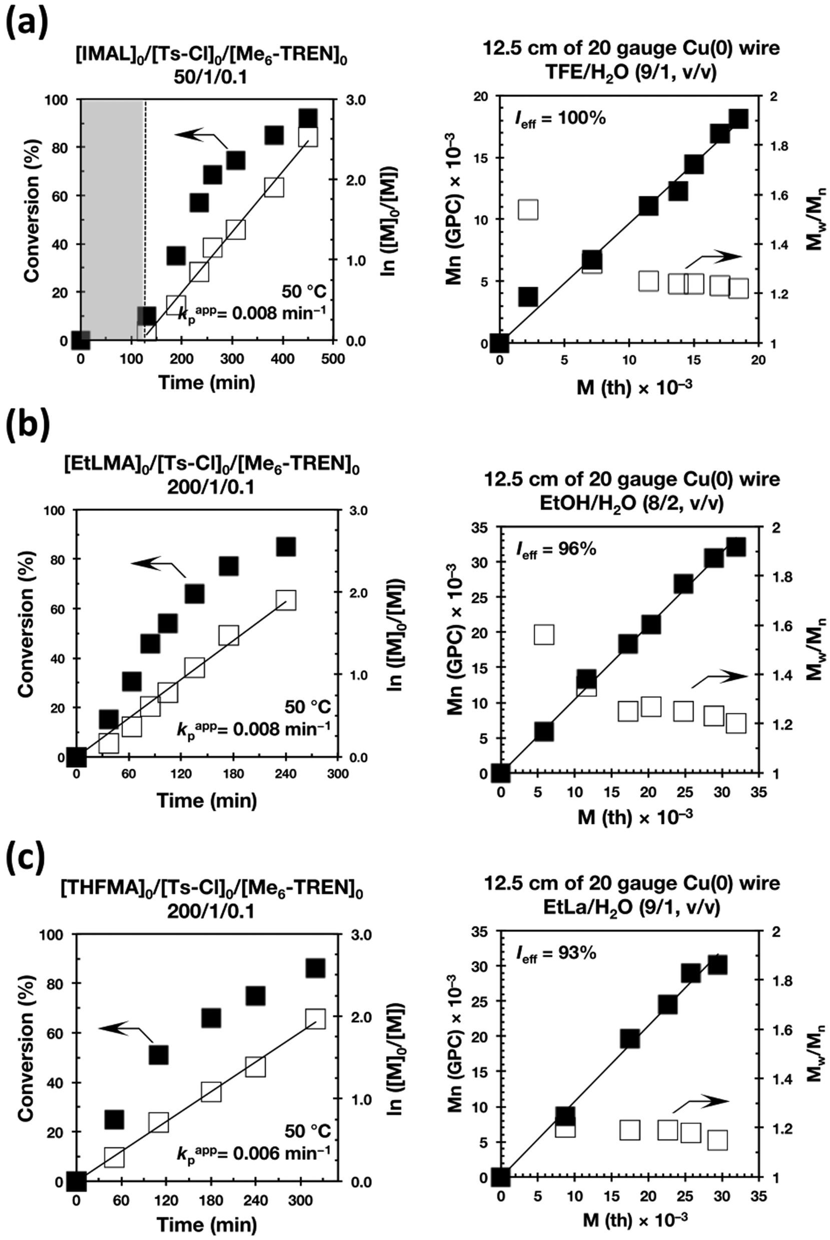


Figure 9. Kinetic plots, molecular weight, and polydispersity evolutions for the SET-LRP of IMAL (a), EtLMA (b), and THFMA (c) in TFE/water mixtures (a), EtOH/water mixtures (b), and EtLa/water mixtures (c) initiated with Ts-Cl and catalyzed by hydrazine-activated Cu(0) wire at 50 °C. (a) TFE/water (9/1, v/v), (b) EtOH/water (8/2, v/v), and (c) EtLa/water (9/1, v/v). The v/v ratio must be multiplied by 10 to obtain % solvent/% water. The value of v + v must be divided by 10 to obtain the total volume of solvents, 1 mL. Reaction conditions: (a) IMAL = 500 mg, (b) EtLMA = 1 mL, and (c) THFMA = 1 mL. (a) TFE + water = 0.25 mL, (b) EtOH + water = 0.5 mL, and (c) EtLa + water = 0.5 mL. Reactions conditions: (a) $[IMAL]_0/[Ts\text{-}Cl]_0/[Me_6\text{-}TREN]_0 = 50/1/0.1$; (b) $[EtLMA]_0/[Ts\text{-}Cl]_0/[Me_6\text{-}TREN]_0 = 200/1/0.1$; and (c) $[THFMA]_0/[Ts\text{-}Cl]_0/[Me_6\text{-}TREN]_0 = 200/1/0.1$. Gray area indicates period of time with no reaction.

attention.[75] The polymerization of IMAL was conducted at $[M]_0/[I]_0 = 50$ to target a polymer of molar mass just below 20 000 g/mol (Figure 9a). A TFE/water (9/1, v/v) mixture was chosen as a reaction media to perform the SET-LRP of this bulky monomer using Cu(0) wire/Me_6TREN as a catalytic system and Ts-Cl as an initiator at 50 °C. A deviation from the general trend was observed in the kinetics of this experiment (Figure 9a).

This system showed an unexpected but reproducible induction period of approximately 100 min, also noticed during the polymerization of other monomers bearing long side chains.[76,77] After that, SET-LRP occurred with a linear dependence of $\ln[M]_0/[M]$ with time up to high conversion. Despite the low water loading used, the high hydrophobicity IMAL forced the formation of a turbid reaction mixture at low conversion that rapidly turned into a biphasic system at around 70% conversion. Even so, the GPC analysis revealed that molecular weight distribution of PIMAL remains narrow during the entire reaction (Figure S3a). The polymerization of the ethyl lactate derivative EtLMA was investigated in a greener reaction mixture (EtOH/water, 8/2 v/v). In this case, polymerization proceed with no induction period and shows first-order kinetic plot (Figure 9b). Also, in this case, molar mass of the resulting polymethacrylate increased monotonically and linearly with theoretical values as indicated by a high I_{eff} (Figure S3b). Comparable results were obtained for the polymerization of THFMA in ethyl lactate containing 10% water (Figure 9c). Our

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laboratories recently reported the potential of ethyl lactate as a green solvent to practice SET-LRP.[42] It important to mention that best results for the ATRP of THFMA allowed only limited monomer conversion both in bulk and solution.[75] Moreover, gel formation was reported when ATRP conditions were applied even at room temperature. Although SET-LRP was conducted at 50 °C, the polymerization of THFMA proceeded with no gel formation and reached almost complete conversion to produce PTHFMA with narrow molecular weight distribution (Figure S3c).

To conclude this study, model block copolymerization experiments were conducted combining both bio- and petroleum-sourced methacrylates. In situ reinitiation experiments from PMA to PTHFMA and from PEtLMA to PIMAL and PTHFMA were carried out in different aqueous alcoholic mixtures (Figure 10). Irrespective of the selected monomers, the reaction mixture composition, and the targeted DPs, ^{1}H NMR analysis revealed a high monomer conversion for SET-LRP reactions. The successful formation of quasi AB block copolymers is supported by a clear and symmetrical displacement of the first block GPC trace of the block A after chain extension. In addition, DSC analysis of quasi-block AB copolymer PMMA-*b*-PTHFMA revealed two distinct glass transition temperatures (T_gs) (Figure S4). These T_gs correspond nicely to each segment, further hinting the suitability of this methodology for the preparation of sustainable block copolymers with microphase separation.

CONCLUSIONS

The SET-LRP of bio- and petroleum-sourced methacrylic monomers in environmentally friendly aqueous alcoholic mixtures is reported. Mixtures of EtOH, 2-PrOH, TFE, and EtLa with water were used to deliver well-defined polymethacrylates from both bio- and petroleum-sourced monomers. All polymerizations were conducted at 50 °C and utilized Ts-Cl as a model initiator, Me_6-TREN as a ligand, and hydrazine-activated Cu(0) wire as a copper source. Increasing the amounts of water promotes the transition from a homogeneous to biphasic reaction mixture. When SET-LRP occurs through a biphasic regime, polymerization occurs in the organic phase, but Cu(I)X/Me_6-TREN disproportionation event takes place in the aqueous layer. Control experiments in pure alcohols demonstrated that the presence of water accelerates the polymerization reaction substantially without compromising the controllability of the reaction. For example, the SET-LRP of BMA at DP = 200 in 2-PrOH/water (9/1, v/v) is 1.8× faster than in pure 2-PrOH. Moreover, employing a blanked of argon allowed to shorten dramatically the SET-LRP experimental procedure (i.e., no Cu(0) wire activation and freeze−thaw−pump cycles/inert gas bubbling protocols are used), highlighting the technological potential of the reported setup. Evidence of retention of functional polymethacrylates end groups is provided by the synthesis of polymers of different targeted DPs (up to 600 for PBMA) as well as the generation of a range of AB block copolymers by in situ chain extension at high conversion. The results reported here expand the monomer scope for programmed biphasic SET-LRP systems and opens new avenues for SET-LRP in the bio-based polymers arena. Considering that SET-LRP can be performed to complete the conversion with no termination[78] even in the presence of air in alcohols, the results reported here are very promising for numerous technological applications.

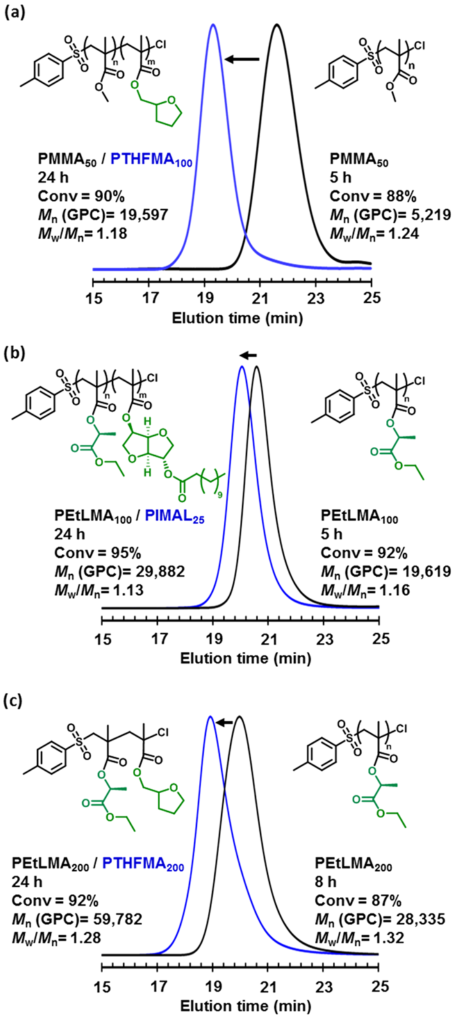

Figure 10. GPC traces of polymers before and after in situ block copolymerization of (a) PMMA with PTHFMA. Initial conditions for block copolymerization: $[MMA]_0/[Ts\text{-}Cl]_0/[Me_6\text{-}TREN]$ = 50/1/0.1 in 2-PrOH/water 9/1, v/v (MMA/solvent = 2/1, v/v). Block copolymerization achieved by the addition of THFMA (100 equiv) and Me_6-TREN (0.1 equiv) in 2-PrOH/water 9/1, v/v (THFMA/solvent = 2/1, v/v). GPC traces of polymers before and after in situ block copolymerization of (b) PEtMA with PIMAL. Initial conditions for block copolymerization: $[EtMA]_0/[Ts\text{-}Cl]_0/[Me_6\text{-}TREN]$ = 100/1/0.1 in TFE/water 9/1, v/v (MMA/solvent = 2/1, v/v). Block copolymerization achieved by the addition of IMAL (25 equiv) and Me_6-TREN (0.1 equiv) in TFE/water 9/1, v/v (IMAL/solvent = 2/1, v/v), and (c) PEtMA with PTHFMA. Initial conditions for block copolymerization: $[EtLMA]_0/[Ts\text{-}Cl]_0/[Me_6\text{-}TREN]$ = 200/1/0.1 in EtLa/water 8/2, v/v (EtLMA/solvent = 2/1, v/v). Block copolymerization achieved by the addition of THFMA (200 equiv) and Me_6-TREN (0.1 equiv) in EtLa/water 8/2, v/v (THFMA/solvent = 2/1, v/v).

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.biomac.9b00257.

Data of kinetic experiments, SET-LRP of MMA in biphasic mixtures, SET-LRP of BMA in biphasic mixtures, SET-LRP of MMA and BMA in biphasic mixtures, SET-LRP of biobased methacrylates in biphasic mixtures; GPC traces; and DSC curves (PDF)

AUTHOR INFORMATION

Corresponding Authors

*E-mail: gerard.lligadas@urv.cat (G.L.).

*E-mail: percec@sas.upenn.edu (V.P.).

ORCID

Marina Galià: 0000-0002-4359-4510

Gerard Lligadas: 0000-0002-8519-1840

Virgil Percec: 0000-0001-5926-0489

Notes

The authors declare no competing financial interest.

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