



Cite this: *Chem. Commun.*, 2023, 59, 8168

Received 4th March 2023,
Accepted 24th May 2023

DOI: 10.1039/d3cc01087b

rsc.li/chemcomm

Step-growth polymerization by the RAFT process

Joji Tanaka, ^{*a} Jiajia Li, ^{ab} Samantha Marie Clouthier ^a and Wei You ^{*a}

Reversible Addition-Fragmentation Chain Transfer (RAFT) step-growth polymerization is an emerging method that synergistically combines the benefits of RAFT polymerization (functional group and user-friendly nature) and step-growth polymerization (versatility of the polymer backbone). This new polymerization method is generally achieved by using bifunctional reagents of monomer and Chain Transfer Agent (CTA), that efficiently yield Single Monomer Unit Insertion (SUMI) adducts under stoichiometrically balanced conditions. This review covers a brief history of the RAFT-SUMI process and its transformation into RAFT step-growth polymerization, followed by a comprehensive discussion of various RAFT step-growth systems. Furthermore, characterizing the molecular weight evolution of step-growth polymerization is elaborated based on the Flory model. Finally, a formula is introduced to describe the efficiency of the RAFT-SUMI process, assuming rapid chain transfer equilibrium. Examples of reported RAFT step-growth and SUMI systems are then categorized based on the driving force.

^a Department of Chemistry, University of North Carolina, Chapel Hill, NC 27599, USA. E-mail: joji@email.unc.edu, wyou@unc.edu

^b State and Local Joint Engineering Laboratory for Novel Functional Polymeric Materials, Jiangsu Key Laboratory of Advanced Functional Polymer Design and Application, Department of Polymer Science and Engineering, College of Chemistry, Chemical Engineering and Materials Science, Soochow University, Suzhou, China

1. Introduction

1.1 From RAFT chain-growth to RAFT step-growth

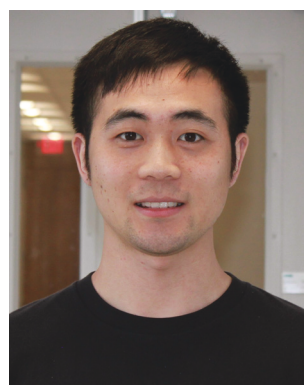
Polymer chemistry has been a growing field in synthetic chemistry with the emergence of novel polymerization methods to design materials with unique features and properties.^{1–4} Broadly speaking, most of these polymerization methodologies can be categorized into two common classes based on the polymerization mechanism and molecular weight evolution: step-growth and chain-growth. We note that there have been



Joji Tanaka

Joji Tanaka completed his MChem at the University of Warwick in 2013, working under Prof. David M. Haddleton for his final year thesis. At the same university, he obtained his PhD under the guidance of Prof. Sébastien Perrier and Dr Paul Wilson in 2018. Currently, he works at the University of North Carolina (UNC) at Chapel Hill with Prof. Wei You. He was responsible for writing the NSF grant titled “RAFT Step-Growth

Polymerization” (CHE-2108670), which was successfully funded in 2021 and has since led the RAFT step-growth team in the You group. His research focuses on designing novel methodologies via the RAFT process, mathematical modelling, and alternative characterization strategies.



Jiajia Li

Jiajia Li received his BS degree in Chemistry from Soochow University, Suzhou, China, in 2015. He completed his PhD in Polymer Chemistry at Soochow University (2020) under the guidance of Prof. Jian Zhu. He was a joint PhD student at the University of Warwick under the supervision of Prof. Sébastien Perrier from 2019 to 2020. After finishing his postdoctoral studies at Soochow University with Prof. Jian Zhu from 2020 to 2022, he moved to

the University of North Carolina at Chapel Hill to work with Prof. Wei You. His current interest focuses on reversible deactivation radical polymerization, living cationic polymerization and photopolymerization-based 3D printing.

disputes on these terminologies and IUPAC has recommended the use of polyaddition and chain polymerization, respectively.⁵

Chain-growth is a process where the polymer chains are seeded from an initiating source and the polymer chains grow by addition of the monomer to the chain end until the propagating end is terminated. Controlling this chain-growth process (*e.g.*, living/controlled anionic/cationic/radical polymerization, ring-opening metathesis polymerization (ROMP), *etc.*) allows uniform growth of polymer chains, synthesis of block copolymers and complex polymer architectures, for a variety of applications.⁶ The main drawback of chain-growth is the rather limited scope of the polymer backbone functionality, as the main chain is composed solely of the polymerized monomer units.

Step-growth on the other hand, grows by reacting two end groups together where all growing species have two reactive chain ends; however, compared to chain-growth, high conversion is required to gain appreciable molecular weight. Historically, this has been carried out *via* polycondensation, which typically requires harsh reaction conditions and is limited by low functional group tolerance.⁷ Nevertheless, in contrast to chain growth, unique polymer backbones can be constructed for targeted applications as the functionalities can be placed independently between the two reacting sites – if such functionalities, built into the design of step-growth monomers, can remain intact under the polymerization conditions.

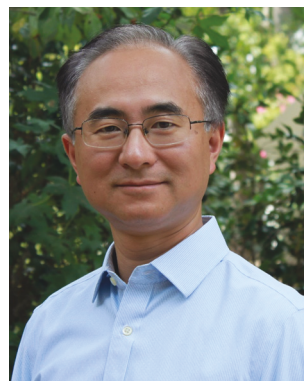
Free radical polymerization is a chain-growth process that has had implications in both academia and industry.⁸ Many vinyl monomers can be polymerized through free radical polymerization without being hindered by common impurities.⁸ Therefore, controlling this process through Reversible Deactivation Radical Polymerization (RDRP) methods has been a breakthrough since the late 20th century.⁹ One of the leading platforms that has gained particular attention is Reversible-Addition Fragmentation Chain Transfer (RAFT) polymerization.¹⁰

The RAFT process is mediated by thiocarbonylthio based Chain Transfer Agents (CTA) that seed chain-growth polymerization and govern the chain transfer exchange *via* an intermediate compound.^{11,12} Among all RDRP methods, RAFT polymerization is considered to be the most user-friendly and versatile, allowing control over a wide selection of monomer families by choosing the appropriate CTA.^{9,13} Furthermore, owing to the relatively high functional group tolerance of the thiocarbonylthio group, RAFT polymerization has enabled engineering of well-defined polymers with a variety of functionalities placed on the side chains and end groups of the polymers. However, inherent to the chain-growth nature of RAFT polymerization, such polymers usually consist of inert carbon atoms (*e.g.*, C–C single bond); this unfortunate fact has posed significant challenges to applications where degradable functionality is crucial such as tissue engineering and plastics recycling.¹⁴ To address this challenge, we recently discovered



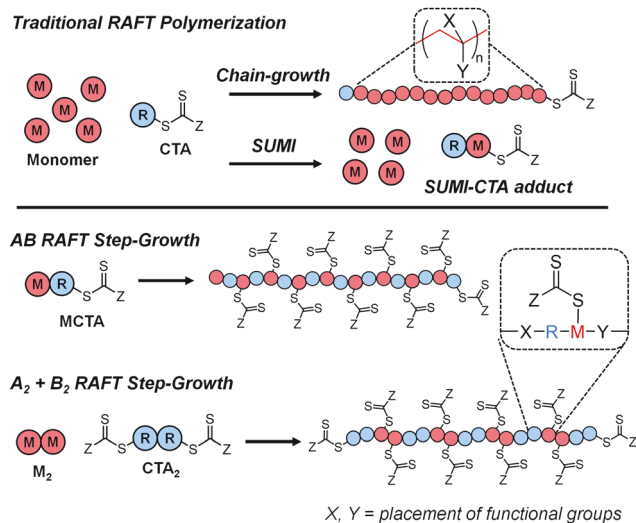
Samantha Marie Clouthier

Samantha Marie Clouthier obtained her BSc from Cornell University in 2021. She is currently a graduate student pursuing her PhD at the University of North Carolina at Chapel Hill under the supervision of Prof. Wei You. She is a 2023 recipient of the National Science Foundation (NSF) Graduate Research Fellowship Program (GRFP). Her research is focused on photo-mediated RAFT step-growth polymerization.



Wei You

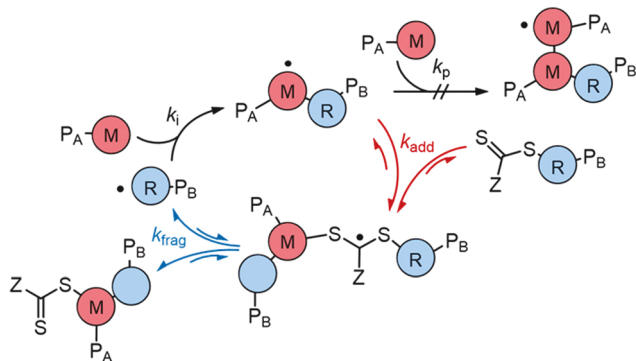
Wei You received his BS degree in Polymer Chemistry from the University of Science and Technology of China in 1999. He then obtained his PhD in 2004 under the guidance of Professor Luping Yu at the University of Chicago. After finishing his postdoctoral training at Stanford University in 2006 with Professor Zhenan Bao, he joined the University of North Carolina at Chapel Hill as an Assistant Professor in Chemistry in July 2006. He was promoted to the rank of Associate Professor in 2012 and then Full Professor in 2017. He has published over 180 papers in three main areas: conjugated polymers for optoelectronics (particularly polymer solar cells), new polymerization methodologies and their applications, and organic/inorganic hybrid 2D perovskites. He was an Associate Editor for Polymer Chemistry (RSC) (2013–2022) and has been serving as Specialty Chief Editor for Optoelectronic Materials, Frontiers in Electronic Materials since July 2020. He also served on the advisory board for Macromolecules (ACS) and ACS Applied Energy Materials (ACS). He is a Fellow of Royal Society of Chemistry (FRSC) (2017), and is one of the “World Highly Cited Researchers” as determined by the Web of Science Group (2019–2022).



Scheme 1 Illustration of chain-growth, SUMI and step-growth by the RAFT process and placement of functional groups. Reproduced with permission from ref. 16 Copyright 2021, with permission from American Chemical Society.

RAFT step-growth polymerization (or SUMI polyaddition¹⁵) via the Single Monomer Unit Insertion (SUMI) process, using stoichiometrically equivalent bifunctional reagents of CTA and monomer functional groups (Scheme 1).¹⁶

This unique step-growth polymerization proceeds *via* the chain transfer cycle (Scheme 2), analogous to thio-ene step-growth¹⁷ and closely related to metal catalyzed radical polyaddition.^{18–20} In theory, RAFT step-growth polymerization would inherit key benefits from both RAFT (*e.g.*, functional group tolerance and user-friendly nature) and step-growth (*e.g.*, functional backbone) to allow a great versatility in the polymer chain design by incorporating desired chemical functionalities pre-embedded in the bifunctional reagents. Furthermore, the CTA is formed *in situ* at each repeat unit of the backbone after



Scheme 2 RAFT step-growth mechanism. The RAFT step-growth mechanism proceeds through a cycle of the radical addition (k_i) between the two end group species: monomer and $R^\bullet$, forming the backbone radical, followed by chain transfer with the CTA end group through reversible addition (k_{add}) and fragmentation (k_{frag}) of the intermediate, to regenerate the $R^\bullet$ species and yield the polymer backbone. Reproduced with permission from ref. 21 Copyright 2022, with permission from American Chemical Society.

the RAFT step-growth polymerization, enabling further architectural control by a second polymerization step *via* RAFT chain-growth.

1.2 Scope of the review

In this review, we highlight the recent developments of RAFT step-growth as a platform for facile synthesis of a functional linear backbone and graft copolymers. We start with a brief discussion of the historical context of the RAFT-SUMI process, though a more detailed review can be found elsewhere.^{15,22} We then revisit the characterization of step-growth molecular weight by conventional size exclusion chromatography (SEC) analysis, which is applicable to other step-growth approaches. After going through details of a variety of RAFT step-growth systems, we summarize the mechanistic classification of the RAFT-SUMI/step-growth polymerization, with an aim to expand the monomer scope.

2. RAFT-SUMI process

2.1 Historical context of RAFT-SUMI

The term RAFT-SUMI was first coined in 2011 by Moad;²³ however, the first example of the RAFT-SUMI reaction can be dated back to 1988 when Zard and co-workers demonstrated the addition of xanthate to a number of vinyl compounds (*e.g.*, vinyl acetate, *N*-methylmaleimide) for organic synthesis.^{24,25} Importantly, Zard recognized the radical nature enabled chain process, and the low steady state concentration of the intermediate radical species in the proposed reaction mechanism.²⁴ Such insight eventually led to the independent discovery of Macromolecular Design by Interchange of Xanthate (MADIX) controlled polymerization (identical process to RAFT polymerization) by Rhodia (now Solvay).²⁶

RAFT has gained popularity since its emergence in 1998,¹⁰ Klumperman and co-worker carefully studied the early kinetics of polymerization of styrene with a RAFT agent, cyanoisopropyl dithiobenzoate (AD in Fig. 1) in 2004. They showed that in the initial stage of the polymerization, the as formed $R^\bullet$ (cyanoisopropyl radical, A in Fig. 1) almost exclusively added to one styrene unit, and formed the SUMI product (ASD in Fig. 1), prior to the formation of higher order adducts (*e.g.*, AS_2D) (higher order adducts were possible in this case since the ratio of $[M]$ vs. $[CTA]$ was ~ 5).²⁷ Almost simultaneously, Chen *et al.* applied the identical RAFT agent to a styrene-functionalized coumarin (but with 1:1 stoichiometry) and obtained the SUMI-CTA adduct with 85% yield.²⁸ Klumperman later showed such SUMI reactions also occurred with other dithiobenzoate CTA agents and methyl acrylate,²⁹ and with vinyl acetate/*N*-vinylpyrrolidone in the presence of xanthates.³⁰ Klumperman further explored the detailed mechanism and kinetics of the SUMI reaction (or “initialization period” as referenced in their work), and pointed to the importance of (a) relative stability of different radicals and (b) relative rate difference, to achieve a high SUMI-CTA adduct yield.³¹

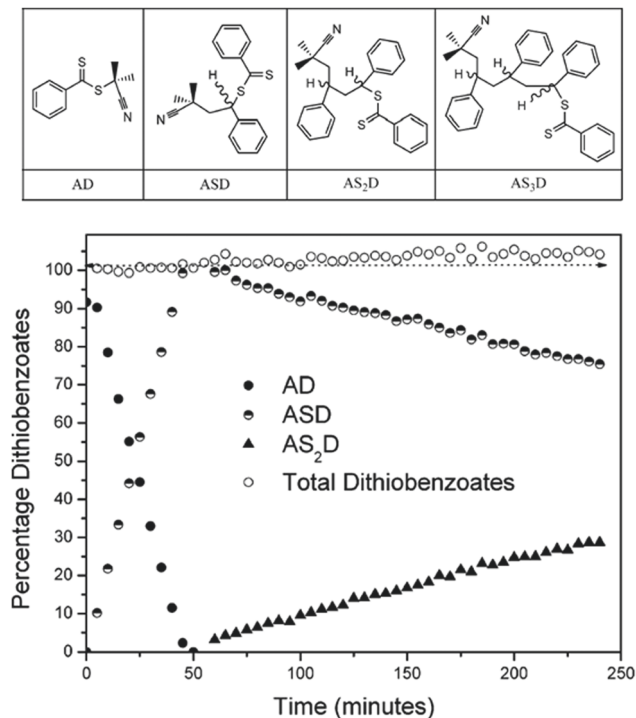


Fig. 1 Relative concentration of dithiobenzoate species vs. time in RAFT polymerization of the styrene. Reproduced with permission from ref. 27 Copyright 2004, with permission from American Chemical Society.

In 2011, Chen *et al.* reported the first example of SUMI between a vinylthiophene and trithiocarbonate based RAFT agent,³² which later extended to styrene and *N*-isopropylacrylamide (NIPAM), including successive SUMI of styrene followed by NIPAM.²³ Recognizing the opportunity to create sequence-defined oligomers, other researchers have done significant work to further understand the SUMI process and its utilization, in particular, Moad,^{33–35} Xu^{36–40} and Junkers.^{41,42} Much progress has been summarized in two excellent review articles.^{22,33}

2.2 Choosing the appropriate pairing of monomer and CTA for RAFT step-growth

Though the process of SUMI is neither chain-growth nor step-growth by itself, this highly efficient reaction could be harnessed using bifunctional reagents (AB type and A₂ + B₂ type) of CTA and a monomer, to achieve step-growth polymerization. In addition to using bifunctional reagents, we would like to emphasize two key characteristic criteria to transform the RAFT-SUMI process into RAFT step-growth polymerization: (1) quantitative transformation of CTA and monomer pairs into a SUMI-CTA adduct under balanced stoichiometric conditions with minimal side reactions; and (2) as the polymerization proceeds through step-growth, high conversion ($p > 0.95$) is necessary to obtain appreciable molecular weight (*i.e.*, polymer). These two criteria can be fulfilled by screening a selection of CTAs for a given monomer, which has been demonstrated with maleimides and acrylic monomers as detailed below.^{16,21}

In the first demonstration of RAFT step-growth polymerization,¹⁶ Tanaka *et al.* carried out the initial CTA screening with

maleimides used as the monomer unit, as a quantitative SUMI-CTA adduct yield was previously reported by Xu *et al.* with CTA_{1A}.³⁸ Using *N*-ethylmaleimide as a model monomer (M₁), various trithiocarbonate based CTAs with different R-groups were screened (CTA_{1A}–CTA_{1E}). With AIBN as the external radical source, the quantitative SUMI-CTA adduct yield was observed with CTA_{1A} as expected (Fig. 2A); however, CTA_{1B}, which only structurally differs from CTA_{1A} by an additional carboxylic acid (the “handle” used to conveniently create AB or A₂ monomers), resulted in significantly slower kinetics (Fig. 2B). This was attributed to slower monomer addition due to increased radical stability of this R[•] species contributed by the additional neighboring conjugation (*i.e.*, COOH). Serendipitously, CTA_{1C}, whose reactivity lies between the former two CTA's,⁴³ was found to yield a quantitative SUMI-CTA adduct yield (Fig. 2C). In contrast, CTA_{1D} with one less methyl substituent, resulted in significantly lower yield with a higher consumption of the monomer than the CTA (Fig. 2D), indicative of multiple monomer addition, which was believed to be limited by the chain transfer equilibrium. Furthermore, CTA_{1E}, which does not favor chain transfer exchange with the monomer, resulted in retarded homopolymerization (Fig. 2E).

Compared to maleimides, acrylates are considered to be a more challenging class of monomers for the RAFT step-growth process owing to the high k_p of acrylates (*i.e.*, homopropagation, Scheme 2). Yet as mentioned earlier, Klumperman reported the formation of a SUMI-CTA adduct of acrylates using dithiobenzoate based CTA bearing cyano-stabilized tertiary radical fragmentation.²⁹ To expand RAFT step-growth polymerization to acrylic monomers, Archer *et al.* screened a selection of CTAs with butyl acrylate (BA) as the model monomer.²¹ In their study, 4-cyano-4-(((dodecylthio)carbonothioyl)thio)pentanoic acid (CTA_{1F}), bearing similar cyano-stabilized tertiary radical (R[•]), only showed a limited rate of product formation (Fig. 3A). This was attributed to the slow radical addition of the generated cyano-stabilized tertiary radical to acrylic monomer to form more reactive carbonyl ester stabilized secondary radicals. Coincidentally, CTA_{1C}, which was ultimately used for RAFT step-growth with maleimides, was observed with quantitative formation of SUMI CTA adduct with BA and equal consumption of monomer and CTA as well (Fig. 3C).²¹ Interestingly, CTA_{1B} which bears intermediate reactivity between CTA_{1A} and CTA_{1C},⁴³ was found to generate even lower yields than the former two CTAs (Fig. 3B). Additionally, CTA_{1D} and CTA_{1E} resulted in similar characteristics to the RAFT-SUMI study with maleimides, where multiple monomer additions and retarded homopolymerization were observed, respectively (Fig. 3D and E).²¹

3. Characterization of RAFT step-growth polymers

In this section, we discuss the classical theoretical description of step-growth polymerization and its application in

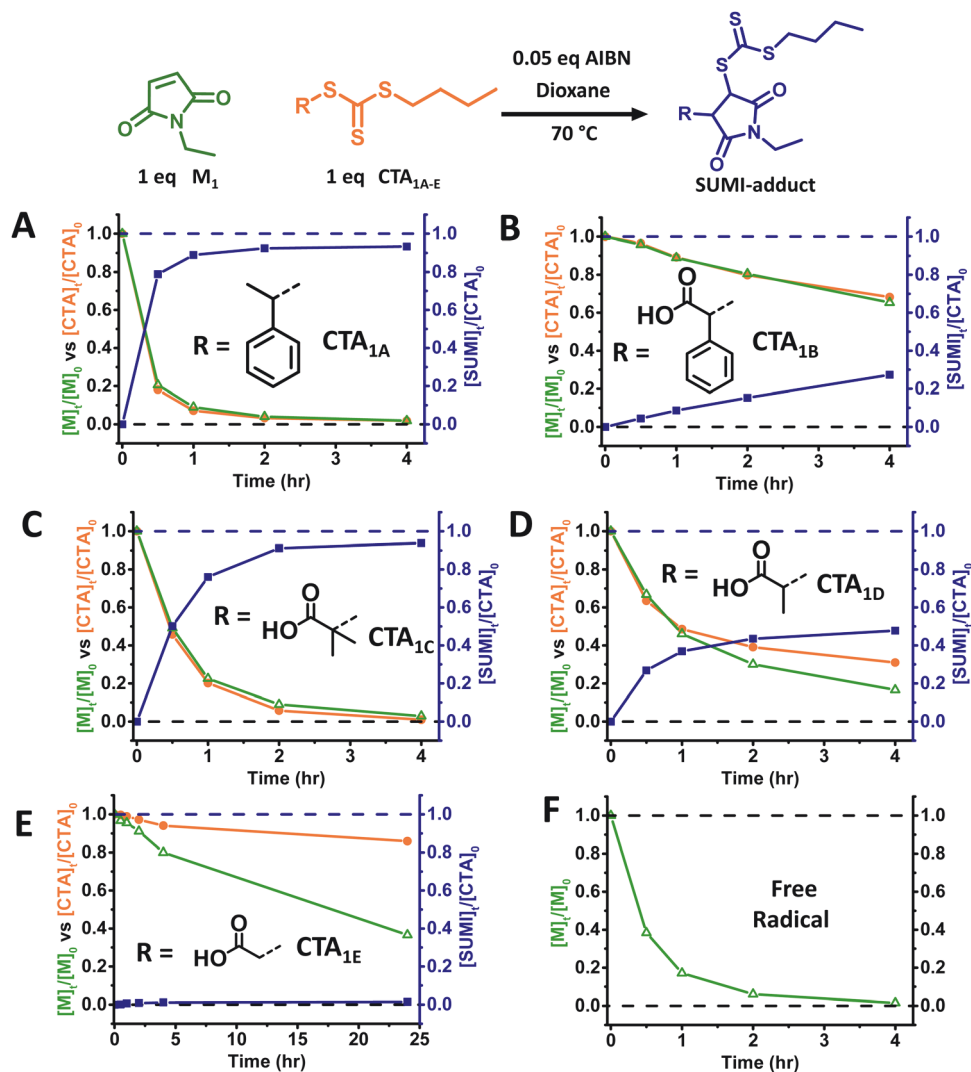


Fig. 2 Kinetic study of the RAFT-SUMI process with maleimide, where stoichiometrically equivalent amounts of maleimide to CTA were used. Adapted with permission from ref. 16 Copyright 2021, with permission from American Chemical Society.

characterizing molecular weight evolution. Further details can be found in other literature sources.⁴⁴

3.1 Definition of molecular weight averages

Following the molecular weight evolution with monomer conversion/extent of reaction (p) provides crucial insights into the polymerization mechanism. In contrast to proteins/DNAs where the molecular weight is a discrete value, synthetic polymers are characterized by their molecular weight averages due to the distribution of different chain lengths. Three different molecular weight averages are typically described for polymers: the number-average (M_n), weight-average (M_w) and Z-average (M_z):

$$M_n = \frac{\sum M_x n_x}{\sum n_x} \quad (1)$$

$$M_w = \frac{\sum M_x^2 n_x}{\sum M_x n_x} \quad (2)$$

$$M_z = \frac{\sum M_x^3 n_x}{\sum M_x^2 n_x} \quad (3)$$

where n_x represents the number of a particular species (x -mer) with a defined molecular weight (M_x for x -mer). Different characterization methods provide information on one or multiple molecular-weight averages; for example, ¹H-NMR (*via* end group analysis) can be used to estimate M_n .

Size exclusion chromatography (SEC) analysis is typically used to characterize the molecular weights of polymers, which is convenient and offers rich information based on the separation by hydrodynamic size of the polymeric species in solution (*i.e.*, the eluent). In a SEC equipped with a differential refractometer (dRI), a molecular weight distribution can be obtained as the dRI detector response is proportional to the weight concentration of the measured species.⁴⁵ In practice, molecular weights from SEC analysis are estimated by comparing the elution of volume of the sample polymer with a known molecular weight of narrow standards (conventional SEC), or by

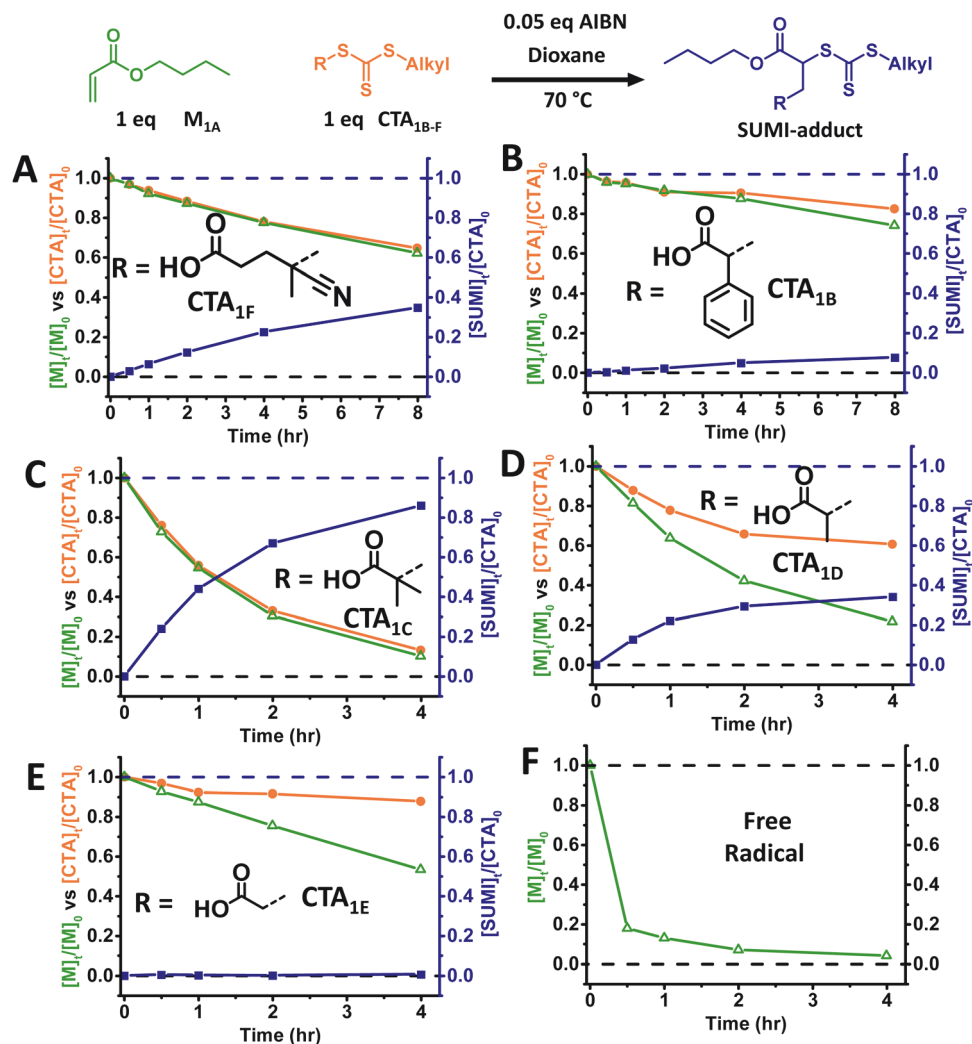


Fig. 3 Kinetic study of the RAFT-SUMI process with butyl acrylate, where stoichiometrically equivalent amounts of BA to CTA were used. Adopted with permission from ref. 21 Copyright 2022, with permission from American Chemical Society.

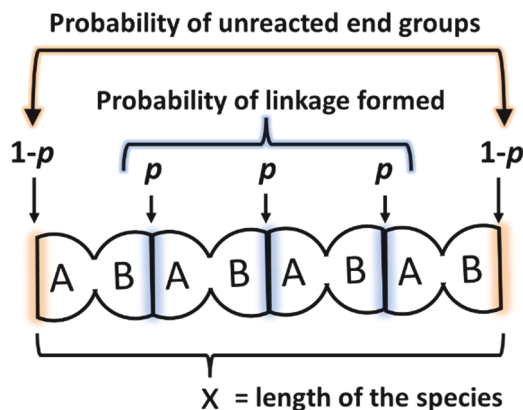
a light scattering detector (LS) which measures absolute molecular weight. Importantly, as SEC analysis measures the molecular weight distribution, all three molecular weight averages above can be determined simultaneously.

Historically, the molecular weight evolution has been characterized by following M_n and M_w with p , with the dispersity ($\bar{D} = \frac{M_w}{M_n}$) describing the difference between these two or the breadth of the molecular weight distribution. Arguably this is acceptable for living/controlled (chain-growth) polymerization systems, where molecular weight distribution follows Poisson distribution and M_n proceeds to increase linearly with monomer conversion and $\bar{D}$ is concurrently decreasing. However, following just M_n and M_w (or $\bar{D}$) has limitations in characterizing the skewness and the shape of the molecular weight distribution. To overcome this, some attention has been given to characterizing higher moments of the molecular weight distribution such as M_z ; however it is often neglected.⁴⁶ In the case of step-growth polymerization, we believe that one

needs to obtain all three molecular weight averages to have better and more comprehensive insights.

3.2 Molecular weight evolution of step-growth polymerization with balanced stoichiometry

For step-growth polymerization, Flory described the molecular weight distribution of linear step-growth polymerization in one of his classical papers.⁴⁷ Suppose a polymer sample has a total of N_0 structural units distributed in a variety of x -mers (e.g., trimer, tetramer, etc.), and a particular x -mer has a quantity of n_x (i.e., $N_0 = \sum n_x x$). Flory started by determining the probability that a particular structural unit (A-B in Scheme 3) – if selected randomly from these N_0 structural units – is part of an x -mer. This probability is essentially the ratio of the total number of structural units in these x -mers vs. the total number of structural units (N_0). Since each structural unit has an identical molecular weight, this probability is the weight fraction of the x -mer (w_x). On the other hand, based on a simple AB step-growth polymerization model where p represents the



Scheme 3 Illustration of the probability of x -mer formation in step-growth polymerization. All species have two unreacted end groups.

probability of reaction between A and B occurring, and thus $(1 - p)$ represents the probability that a reaction had not occurred at each end group, the probability of each particular configuration of x -mer is $p^{x-1}(1 - p)^2$ (Scheme 3). Since there are x possible configurations of x -mers, the probability for any of the x configurations existing is therefore $xp^{x-1}(1 - p)^2$. Thus we have:

$$w_x = xp^{x-1}(1 - p)^2 \quad (4)$$

And the number of x -mers (n_x) is then given by

$$n_x = \frac{N_0 w_x}{x} = N_0 p^{x-1}(1 - p)^2.$$

For AB step-growth polymers, each molecular average (M_n , M_w and M_z) can be calculated for a given conversion (p) by substituting M_x with xM_0 (M_0 is the molecular weight of the AB monomer or average molecular weight of the $A_2 + B_2$ comonomers) and substituting n_x with the term $N_0 p^{x-1}(1 - p)^2$. According to the summation of the substituted terms, M_n , M_w and M_z will become:

$$M_n = M_0 \frac{\sum xp^{x-1}(1 - p)^2}{\sum p^{x-1}(1 - p)^2} = M_0 \frac{1}{1 - p} \quad (5)$$

$$M_w = M_0 \frac{\sum x^2 p^{x-1}(1 - p)^2}{\sum xp^{x-1}(1 - p)^2} = M_0 \frac{1 + p}{1 - p} \quad (6)$$

$$M_z = M_0 \frac{\sum x^3 p^{x-1}(1 - p)^2}{\sum x^2 p^{x-1}(1 - p)^2} = M_0 \frac{1 + 4p + p^2}{(1 - p^2)} \quad (7)$$

It is important to note that the molecular distribution (eqn (1)) and the molecular weight averages (eqn (5)–(7)) reflect the crude polymerization reaction mixture, accounting for the initial species ($x = 1$, *i.e.*, monomer) but not accounting for the purification process. Therefore, we emphasize that when monitoring the molecular weight evolution by SEC analysis, suitable column resolution is crucial to analyze the whole distribution of the crude polymer in order to apply these equations. It is noteworthy that molecular weight analysis by light scattering is limited due to changes of the dn/dc and insensitivity of light scattering to low molecular weight species;

therefore, conventional SEC analysis is recommended when comparing experimental results with Flory's theory. Furthermore, another important consideration is that the cyclization (formation of cyclic species) is not considered in the theoretical description of eqn (4)–(7). Cyclization results in species with no end groups to further react, which can be considered as dead chains. Though the presence of high molecular weight cyclic species is indistinguishable from linear equivalents, oligomeric species can be observed from SEC analysis. In some cases, these species can be seen in $^1\text{H-NMR}$ spectra due to restricted bond rotation.⁴⁸

A common misconception of the step-growth polymers is that dispersity, $\mathcal{D}$ ($= M_w/M_n = 1 + p$) is 2 (when p is unity); however, this is only true in the absence of cyclization. In the cases where oligomeric cyclic species are observed, the M_n would be much lower than expected (if correctly analyzed), whereas the M_w is affected less as a higher molecular species is weighted more according to its definition (eqn (3)); therefore, the presence of cyclic species should result in dispersity much greater than 2. On the contrary, dispersity can be observed to be less than 2 after the removal of low molecular weight species during purification.

3.3 Accounting for imbalanced stoichiometry

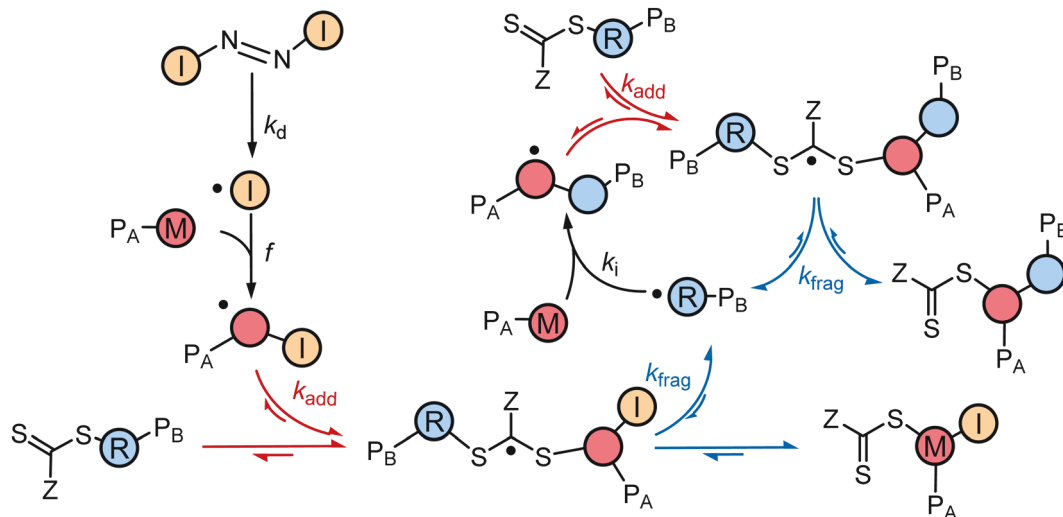
The equations used for AB step-growth (eqn (4)–(7)) can be applied directly for $A_2 + B_2$ comonomer type step-growth with balanced stoichiometry (with M_0 being the average molecular weight of the $A_2 + B_2$ comonomers). However, with imbalanced stoichiometry, complication arises with defining molecular weight distribution and molecular weight averages due to the formation of three possible combinations of end group species. Indeed, using stoichiometric excess of one comonomer (*e.g.*, B_2) results in polymeric species predominantly bearing these end group species (B) at high conversion, with no counterpart (A) to react, thereby resulting in limited molecular weight. Nonetheless, the impact of the imbalanced stoichiometry on M_n can be accounted for by the definition below, where r is the molar ratio of the two comonomers ($r = N_A/N_B$) and it is always less than 1:

$$M_n = M_0 \frac{1 + r}{1 + r - 2rp} \quad (8)$$

Though there are no simple equations to define higher order molecular weight averages (M_w , M_z) of $A_2 + B_2$ step-growth polymerization with imbalanced stoichiometry, it is stated that the p can be replaced with $r^{1/2}p$ in eqn (6) and (7) (except when $r^{1/2}p \ll 1$) to obtain satisfactory theoretical values.⁴⁷

3.4 Accounting for imbalanced stoichiometry from thermal initiation of diazo initiators

Using an external initiator (such as AIBN) in the RAFT step-growth polymerization would in theory result in an imbalance in stoichiometry due to the loss of one monomer functionality (Scheme 4). The resulting initiator-monomer adduct can be considered as a monofunctional (macro)reagent. Generally speaking, in step-growth polymerization where a monofunctional



Scheme 4 Illustration of initiator derived imbalanced stoichiometry. Reproduced with permission from ref. 49 Copyright 2022, with permission from Royal Society of Chemistry.

agent (*e.g.*, B') is present, the stoichiometric ratio of functional groups, r can be redefined as:⁴⁴

$$r = \frac{N_A}{N_B + 2N_{B'}} \quad (9)$$

where N_A and N_B are the relative moles of the functional groups of the bifunctional reagents in A₂ and B₂ respectively, and $N_{B'}$ is the moles of monofunctional reagent with the same functionality as B₂. A coefficient "2" is used for $N_{B'}$ since the monofunctional reagent has the same quantitative effect in limiting the molecular weight as the excess bifunctional reagent (B₂). Using this principle and without considering the effects from radical termination, the imbalance in stoichiometry from external initiation in the RAFT step-growth polymerization can be estimated accordingly (assuming CTA as the excess bifunctional reagent):

$$r_{th} = \frac{[M]_0}{[CTA]_0 + 4f([I]_0 - [I]_t)} \quad (10)$$

where $[M]_0$ and $[CTA]_0$ are the initial molar concentrations of monomer and CTA functional groups within the bifunctional reagents (*i.e.*, A and B in eqn (9)), whilst $[I]_0$ and $[I]_t$ is the molar concentration of the initiator at the beginning of the reaction and at time t . Since two radicals are generated from one molecule of azo initiator with efficiency f , to react with a monomer (M₂) and form the initiator adduct, a factor of "4" (*i.e.*, 2×2) is used in eqn (10) rather than "2" in eqn (9). The initiator remaining ($[I]_t$) can be calculated for a specific time, t , with first-order decay with the rate constant, k_d :

$$[I]_t = [I]_0 e^{-k_d t} \quad (11)$$

The rate constant (k_d) for the initiator decomposition can be calculated for specific temperature using the Arrhenius equation (eqn (11)) from the 10 h half-life decomposition temperature and activation energy, both of which are provided by the chemical suppliers.⁵⁰

Furthermore, substituting eqn (11) into eqn (10), the overall imbalanced stoichiometry can be estimated from the initial molar ratio of CTA to monomer ($r_0 = [M]_0/[CTA]_0$) and initiator to monomer ($[I]_0/[M]_0$):

$$r_{th} = \frac{1}{\frac{1}{r_0} + 4f \frac{[I]_0}{[M]_0} (1 - e^{-k_d t})} \quad (12)$$

It is important to note that the initiation efficiency is dependent on the monomer and conditions. Furthermore, the key limitation in this approach (eqn (12)) is the estimation of f at high monomer conversion. Typically, to account for the loss of radicals from side reactions following the thermal decomposition of the initiator, full initiation efficiency ($f = 1$) is not adopted for diazo-initiators. A value of 0.65 has been recommended as the highest value for these family of initiators by Moad.⁵¹ Assuming a maximum f value of 0.65 has provided relatively good agreement of experimental and theoretical M_w for RAFT step-growth polymerization for acrylates²¹ and maleimides.^{16,52} However, it is important to note that the initiation efficiency f is expected to fall when the monomer concentration becomes a limiting factor; thus not accounting for this fact leads to overestimation of initiator derived end groups. Therefore, assuming f to be a constant value (*e.g.*, 0.65) leads to lower r_{th} and lower theoretical molecular weight than what should be expected, particularly when the polymerization is left for a period of time after high monomer conversion is reached whilst a relatively high abundance of remaining initiator is still present.¹⁶

3.5 Mark-Houwink analysis

Topology of the polymer plays a significant role in the solution viscosity, as it impacts the hydrodynamic volume. Mark-Houwink analysis is a powerful tool to confirm the formation of linear polymers. The Mark-Houwink equation (also known as Landau-Kuhn-Mark-Houwink-Sakurada equation) describes

the relationship between intrinsic viscosity ($[\eta]$) of the polymer in a solution with the molecular weight (M) of the polymer accordingly:

$$[\eta] = KM^\alpha \quad (13)$$

The coefficient (K) and exponent (α) parameter can be determined from the log-log plot of intrinsic viscosity as a function of molecular weight; this plot can be obtained from multi-detector SEC analysis. The slope of this log-log plot corresponds to the α parameter, which is the exponent term for evolution of intrinsic viscosity with molecular weight. Typically for linear polymers, this value is between 0.5 to 0.8, depending on the solvent interaction and flexibility of the polymer backbone. In contrast, branched polymers exhibit lower intrinsic viscosity relative to their molecular weight due to their more compact hydrodynamic radius and yield α values less than 0.5.⁵³

4. RAFT step-growth with more activated monomers (MAMs)

In this section we will focus on RAFT step-growth polymerization with more activated monomers (MAMs), which are a class of monomers where the vinyl group is conjugated with radical stabilizing moieties such as aromatics and esters. MAMs typically include styrene, (meth)acrylates, (meth)acrylamides, among others. To date, RAFT step-growth polymerization has been demonstrated with two families of MAMs, acrylate and maleimides.

4.1 RAFT step-growth with maleimides

Having a more reactive vinyl group, MAMs typically can readily homopolymerize (high k_p), which is not ideal for RAFT step-growth. Therefore, the first report on RAFT step-growth focused on maleimides since maleimides are known to bear low k_p . As mentioned earlier, CTA_{1C} was found to yield a quantitative SUMI-CTA adduct with a model maleimide monomer; thus tethering the two functionalities together, MCTA_A (structure in Chart 1) was designed to be the first AB type RAFT step-growth monomer.¹⁶ Successful RAFT AB step-growth polymerization was observed, manifested by the evolution of molecular weight averages with conversion following predicted step-growth molecular weight averages from eqn (5)–(7) (Fig. 4A). However, the low molecular weight cyclic species (formed during the polymerization) resulted in significant deviation of M_n from ideal step-growth molecular weight evolution. Nonetheless, the higher order molecular weight averages such as M_w and M_z gave more reasonable agreement. It should be noted that, by further considering the imbalanced stoichiometry due to an exogenous initiator ($r_{th} = 0.949$, eqn (12), Table 1), the theoretical M_w ($M_{w,th} = 18k$, Table 1) was much closer to the experimental value ($M_w = 9.9k$, Table 1) than the experimental value without considering initiation ($M_{w,th} = 49k$, Table 1). Furthermore, polymerization conducted at a higher concentration of AB monomers was found to be optimal for yielding

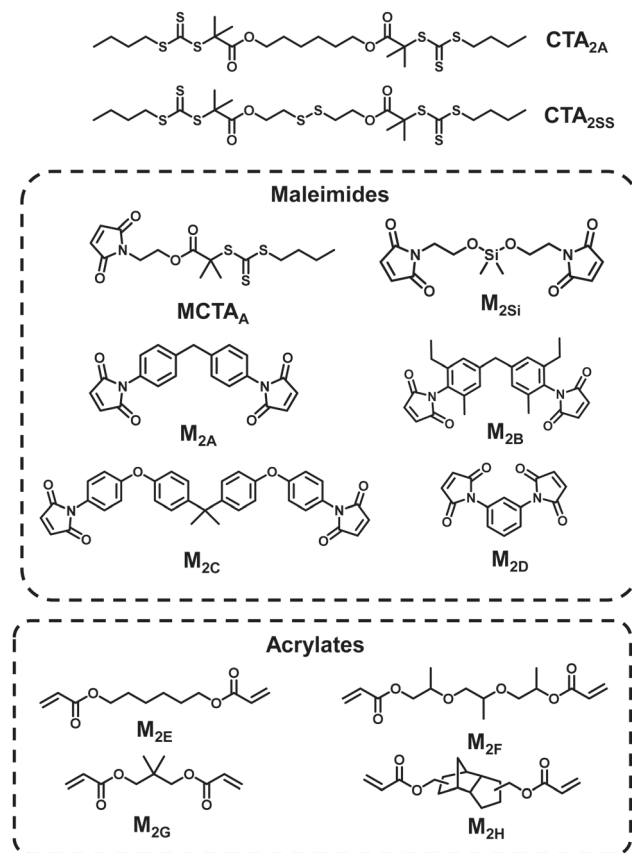


Chart 1 More activated monomers (MAMs) in RAFT step-growth.

higher molecular weight polymers with lower initiator equivalence, whereas lowering the initial concentration of the polymerization resulted in more noticeable presence of the cyclic species, which is a classical step-growth feature. Surprisingly, despite the high tolerance of the RAFT process, conducting this particular RAFT step-growth polymerization in DMSO or DMF had an undesirable loss of control, which was not observed when using toluene or dioxane as the solvent; this unusual behavior was speculated to be side reactions of maleimide monomers in polar solvents.

In the same report,¹⁶ Tanaka *et al.* further investigated the RAFT step-growth polymerization with A₂ + B₂ type comonomers using bifunctional pairs of monomers (M_{2Si}) and CTA (CTA_{2A}). Compared to the AB type step-growth, a lower fraction of cyclic species was observed as the probability of the chain ends to cyclize is reduced by a factor of two, resulting in better agreement of M_n , M_w and M_z/M_w with expected values (Fig. 4B). Additionally, using excess bifunctional CTA to limit the molecular weight was successfully demonstrated. Furthermore, using eqn (12) to estimate the overall imbalance of stoichiometry, the theoretical M_w values were significantly closer to the experimental values across a range of different stoichiometric ratios of CTA and monomer (Table 1). Finally, Mark-Houwink analysis of both AB and A₂ + B₂ step growth polymers revealed an α value of 0.6 (Fig. 4C), consistent with the solution behavior of linear polymers.

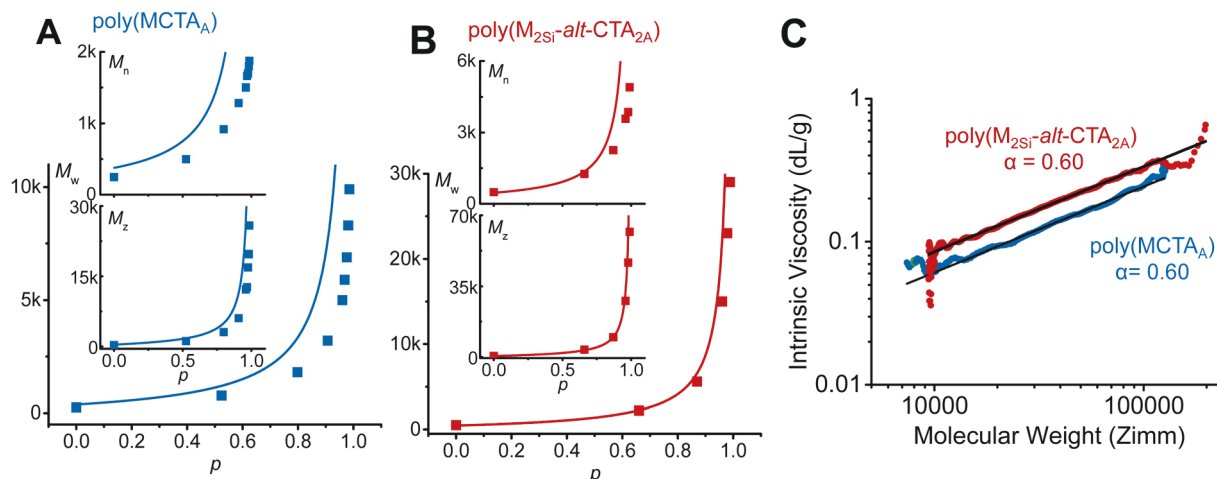


Fig. 4 Molecular weight evolution of the first AB and $A_2 + B_2$ RAFT step-growth and Mark-Houwink plot of the isolated polymers. Adapted with permission from ref. 16 Copyright 2021, with permission from American Chemical Society.

Table 1 RAFT step-growth polymerization with maleimides

Entry	Structure ^a	p^b	r_{th}^c	$M_{w,th}^d$	$M_{w,th}(r_{th})^e$	$M_{w,SEC}^f$	M_w/M_n^f	M_z/M_w^f
1	Poly(MCTA _A)	0.985	0.949	49k	18k	9.9k	5.28	2.61
2	Poly(M _{2Si} -alt-CTA _{2A})	0.989	0.949	84k	25k	29k	5.92	2.13
		($r_0 = 0.98$) ^g	0.975	26k	15k	12.4k	3.66	1.83
		($r_0 = 0.96$) ^g	0.972	19k	12.5k	11.4k	4.13	1.87
		($r_0 = 0.934$) ^g	0.983	18.3k	11.6k	8k	3.08	1.77
		($r_0 = 0.818$) ^g	0.983	8.0k	6.6k	5.2k	2.67	1.75
3	Poly(M _{2A} -alt-CTA _{2A})	0.993	0.949	134k	28k	24.9k	3.52	1.83
		($r_0 = 0.98$) ^g	0.994	59k	23k	20.2k	3.08	1.74
		($r_0 = 0.935$) ^g	0.996	25k	15k	13.7k	2.88	1.71
		($r_0 = 0.818$) ^g	0.998	9.4k	7.6k	8.0k	2.32	1.65
4	Poly(M _{2B} -alt-CTA _{2A}) ^h	0.942	0.891	23k	9.3k	13.1k	2.16	1.73
5	Poly(M _{2C} -alt-CTA _{2A}) ⁱ	0.992	0.970	144k	50k	56k	5.11	2.12
6	Poly(M _{2D} -alt-CTA _{2A})	0.967	0.949	25.5k	14k	13k	4.85	1.95

^a Unless stated otherwise, all reactions were carried out under the same conditions ($[M_2]_0 : [CTA_2]_0 : [AIBN]_0 = 0.5 \text{ M} : 0.5 \text{ M} : 0.05 \text{ M}$) at 70°C for 4 hours. ^b Conversion determined by $^1\text{H-NMR}$. ^c Theoretical estimate (from eqn (12)) of the imbalanced stoichiometry taking the initiator into consideration. ^d Theoretical M_w (from eqn (6)) without considering initiation. ^e Theoretical M_w considering imbalanced stoichiometry (from eqn (12)) by replacing p with $r_{th}^{1/2}p$ in eqn (6). ^f Experimental obtained from SEC analysis. ^g Polymerization carried out with excess CTA ($r_0 = [M]_0/[CTA]_0$). ^h After 21 hours of polymerization. ⁱ After 2 hours of polymerization.

The main drawback to the original report was the difficulty in preparing maleimide based monomers, which required multiple synthetic steps, limiting the overall utility and scalability. To overcome this problem, Boeck *et al.* explored the use of commercially available and affordable *N*-aromatic bis-maleimides.⁵² Successful RAFT step-growth polymerization was demonstrated with *N,N'*-(1,4-phenylene)dimaleimide, M_{2A} together with CTA_{2A} (Chart 1), as the evolution of molecular weight averages with monomer conversion tracked well with predicted values (Fig. 5A). Similar to the original report, eqn (12) was found to be effective in predicting the overall imbalance of stoichiometry (Table 1). Additionally, given the affordability of M_{2A} (0.59 \$ per g), polymerization at multigram scale was reported with successfully isolating 8.1 g (81% yield) of P(M_{2A} -alt-CTA_{2A}) (Fig. 5F).

Bis(3-ethyl-5-methyl-4-maleimidophenyl) methane (M_{2B} , Chart 1) and 2,2-bis[4-(4-maleimidophenoxy) phenyl]propane (M_{2C} , Chart 1) that were structurally analogous to M_{2A} , also

demonstrated successful RAFT step-growth polymerization (Fig. 5B and C), however, with contrasting kinetics. The polymerization of M_{2B} , having alkyl *ortho*-substituents, was considerably slower in rate; however, SEC analysis disclosed noticeably less oligomeric cyclic species, yielding $\bar{D}$ values of the reaction mixture closer to the expected value of 2 for step-growth. It was speculated that the steric hindrance in M_{2B} , imparted by the alkyl-substituents, would reduce the rate of the end group addition (*i.e.*, $R^\bullet$ to M) and thus result in a lower rate of polymerization; however, the same steric hindrance would also reduce the flexibility of the linear polymeric chain and lower the probability of cyclization occurring. On the other hand, M_{2C} , bearing an *O*-phenyl substituent *para* to the maleimide unit, was reported to reach high conversion ($p = 0.995$) and high molecular weight after just 2 hours using the same reaction conditions, suggesting the *O*-phenyl substituent *para* to the maleimide unit increases the monomer reactivity. It is important to note that M_z/M_w values were also higher than

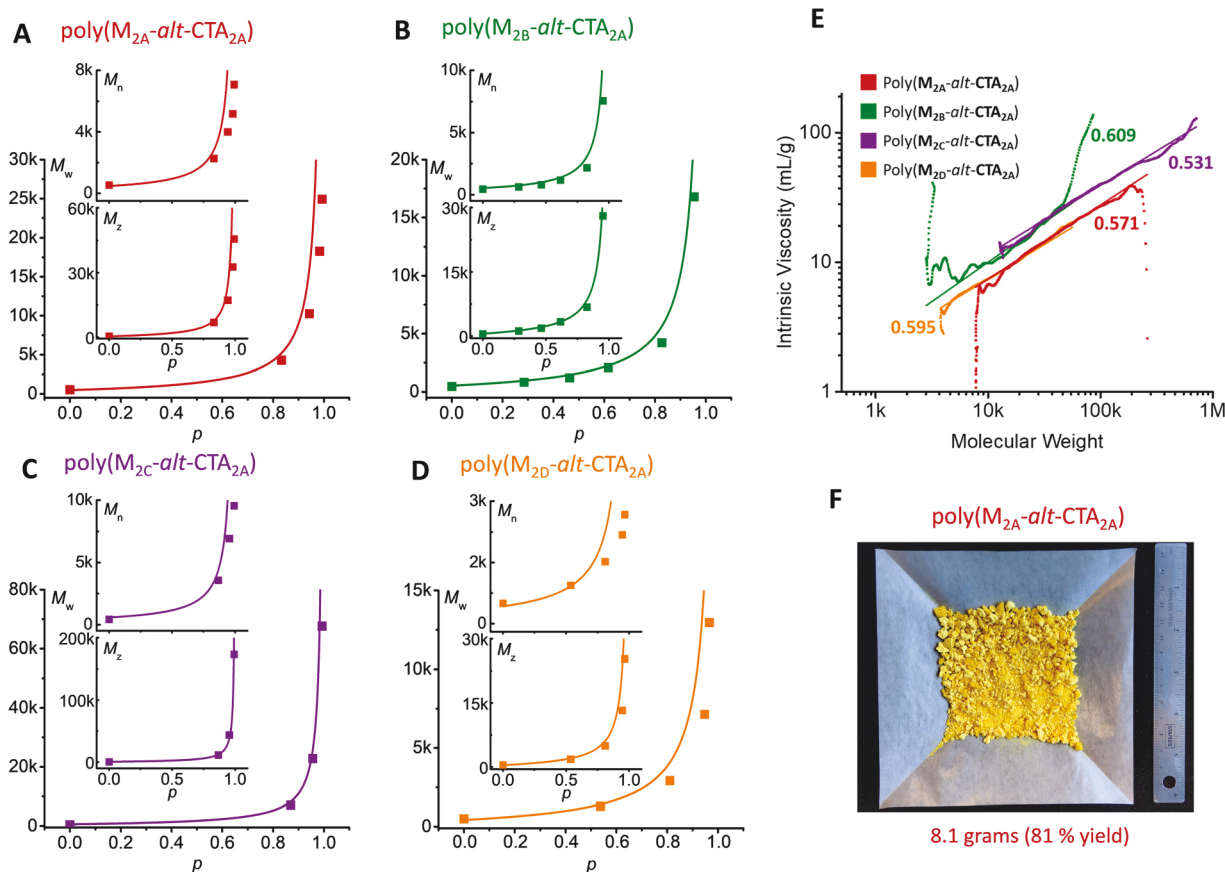


Fig. 5 Molecular weight evolution of RAFT step-growth with commercially available bis-maleimides and the Mark-Houwink plot of the isolated polymers. Upscaled synthesis of $\text{P}(\text{M}_{2\text{A}}\text{-alt-CTA}_{2\text{A}})$. Adapted with permission from ref. 52 Copyright 2022, with permission from Royal Society of Chemistry.

expected, suggesting some deviation from linear step-growth molecular weight evolution due to possible branching.

The 4,4-substituted phenylene bismaleimide, $\text{M}_{2\text{D}}$ (Chart 1), which bears maleimide substituents attached on the same aromatic ring, was able to reach high conversion within 4 hours in *m*-cresol ($p = 0.967$); however, relatively lower M_n was observed (Fig. 5D), owing to the noticeably higher presence of oligomeric cyclic species by SEC, likely promoted by proximity and orientation of the maleimide units on $\text{M}_{2\text{D}}$.

Finally, it is worth noting that Mark-Houwink analysis confirmed linear topology (Fig. 5E) for the RAFT step-growth polymers from all the commercially bismaleimides investigated (Chart 1).

4.2 RAFT step-growth with acrylates

As discussed above, limiting homopropagation is crucial to avoid the possible branching *via* multiple monomer addition; therefore, intuitively high k_p monomers are less ideal. Yet high k_p monomers such as acrylates have been observed to undergo a selective initialization period (SUMI process)²⁹ due to the higher chain transfer efficiency of certain RAFT agents. Interestingly, the same CTA ($\text{CTA}_{1\text{C}}$) previously employed with maleimides, also found potential utility to achieve RAFT step-growth with acrylic monomers (see Section 2.2). In contrast to maleimides, acrylates are a class of monomers that are synthetically easy to prepare. Furthermore, compared to bis-maleimides,

there is an even greater diversity of inexpensive and commercially available diacrylates.

Archer *et al.* successfully achieved RAFT step-growth polymerization of acrylates by using $\text{CTA}_{2\text{A}}$ and hexanediol diacrylate as a model monomer ($\text{M}_{2\text{E}}$ in Chart 1), reaching high conversion ($p = 0.98$) after 4 hours with step-growth molecular weight evolution (Fig. 6A). In contrast to maleimides, RAFT step-growth polymerization of diacrylates was not affected by polar solvents such as DMF and DMSO. Interestingly, the rate was maintained when changing the concentration of the polymerization (but keeping the initiator concentration constant); by contrast, changing the concentration of the initiator (but keeping its equivalence to a CTA constant) resulted in a dramatic effect in rate. These results are different from traditional RAFT chain-growth kinetics, where the rate is often dependent on the ratio of CTA to initiator according to the intermediate termination model,⁵⁴ which is typically observed for the relatively stable RAFT intermediate described in RAFT main equilibrium (degenerative chain transfer). The rate dependence of CTA to initiator ratio was not observed in these reported RAFT step-growth systems (maleimides and acrylates discussed here), which is likely due to the rapid fragmentation of the $\text{R}^{\bullet}$ group.

A library of polymer backbones was successfully prepared from other commercially available diacrylate monomers ($\text{M}_{2\text{F-H}}$) under the same reaction conditions, and all maintained

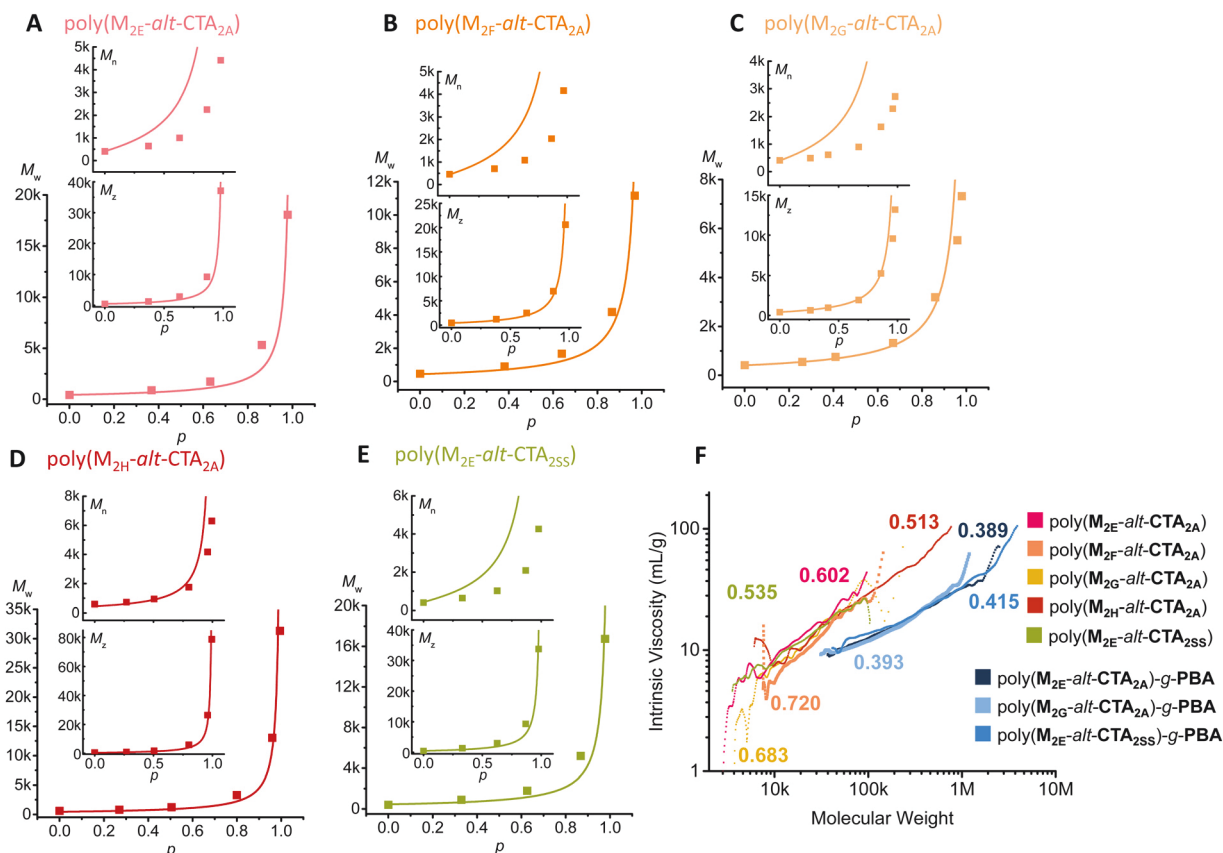


Fig. 6 Molecular weight evolution of RAFT step-growth with commercially available diacrylates and the Mark-Houwink plot of the isolated polymers and graft copolymers. Adapted with permission from ref. 21 Copyright 2022, with permission from American Chemical Society.

Table 2 RAFT step-growth polymerization with diacrylates

Entry	Structure ^a	p^b	r_{th}^c	$M_{w,\text{th}}^d$	$M_{w,\text{th}}(r_{\text{th}})^e$	$M_{w,\text{SEC}}^f$	M_w/M_n^f	M_z/M_w^f
1	Poly($\text{M}_{2\text{E}}\text{-alt-CTA}_{2\text{A}}$)	0.980	0.974	90k	36.3k	18.0k	4.10	2.06
2	Poly($\text{M}_{2\text{F}}\text{-alt-CTA}_{2\text{A}}$)	0.969	0.974	28.2k	19.8k	11.2k	2.68	1.85
3	Poly($\text{M}_{2\text{G}}\text{-alt-CTA}_{2\text{A}}$)	0.98	0.974	39.6k	23.8k	7.3k	2.69	1.80
4	Poly($\text{M}_{2\text{H}}\text{-alt-CTA}_{2\text{A}}$)	0.995	0.974	178k	48.6k	31.3k	4.97	2.51
5	Poly($\text{M}_{2\text{E}}\text{-alt-CTA}_{2\text{SS}}$)	0.978	0.974	42.0k	25.3k	16.8k	3.93	2.02

^a Unless stated otherwise, all reactions were carried out under the same conditions ($[\text{M}_2]_0 : [\text{CTA}_2]_0 : [\text{AIBN}]_0 = 1.0 \text{ M} : 1.0 \text{ M} : 0.05 \text{ M}$) at 70°C for 4 hours. ^b Conversion determined by $^1\text{H-NMR}$. ^c Theoretical estimate (from eqn (12)) of the imbalanced stoichiometry taking the initiator into consideration. ^d Theoretical M_w (from eqn (6)) without considering initiation. ^e Theoretical M_w considering imbalanced stoichiometry (from eqn (12)) by replacing p with $r_{\text{th}}^{1/2}p$ in eqn (6). ^f Experimental obtained from SEC analysis.

step-growth molecular weight evolution (Fig. 6B-E). Furthermore, Mark-Houwink analysis of the diacrylate RAFT step-growth polymers (Fig. 6F) revealed exponent parameters of 0.5–0.72, consistent with the expected linear polymers. It is worth noting that, compared to bismaleimides, the experimental M_w were typically lower than the expected values despite taking imbalanced stoichiometry from initiation into account (Table 2).

5. RAFT step-growth polymerization with Less Activated Monomers (LAMs)

Less Activated Monomers (LAMs) are a class of unconjugated monomers (e.g., vinyl esters, vinyl amides, vinyl imides, allyl

monomers, etc.) that bear less reactive vinyl bond towards radical reaction. Typically, these LAMs exhibit low k_p values or cannot be readily homopolymerized through a radical mechanism ($k_p \sim 0$), thus favoring the formation of a RAFT-SUMI adduct and suitable for RAFT step-growth polymerization (*vide supra*).

5.1 RAFT step-growth polymerization with vinyl ethers

The first RAFT-SUMI reaction between LAMs and xanthates was demonstrated by Zard and coworkers in 1988 (Section 2.1),²⁴ however, this early discovery was not utilized to achieve RAFT step-growth polymerization until 2022, when Li and Zhu reported the RAFT step-growth polymerization with a vinyl ether and a xanthate CTA bearing secondary carboxylate.⁵⁵

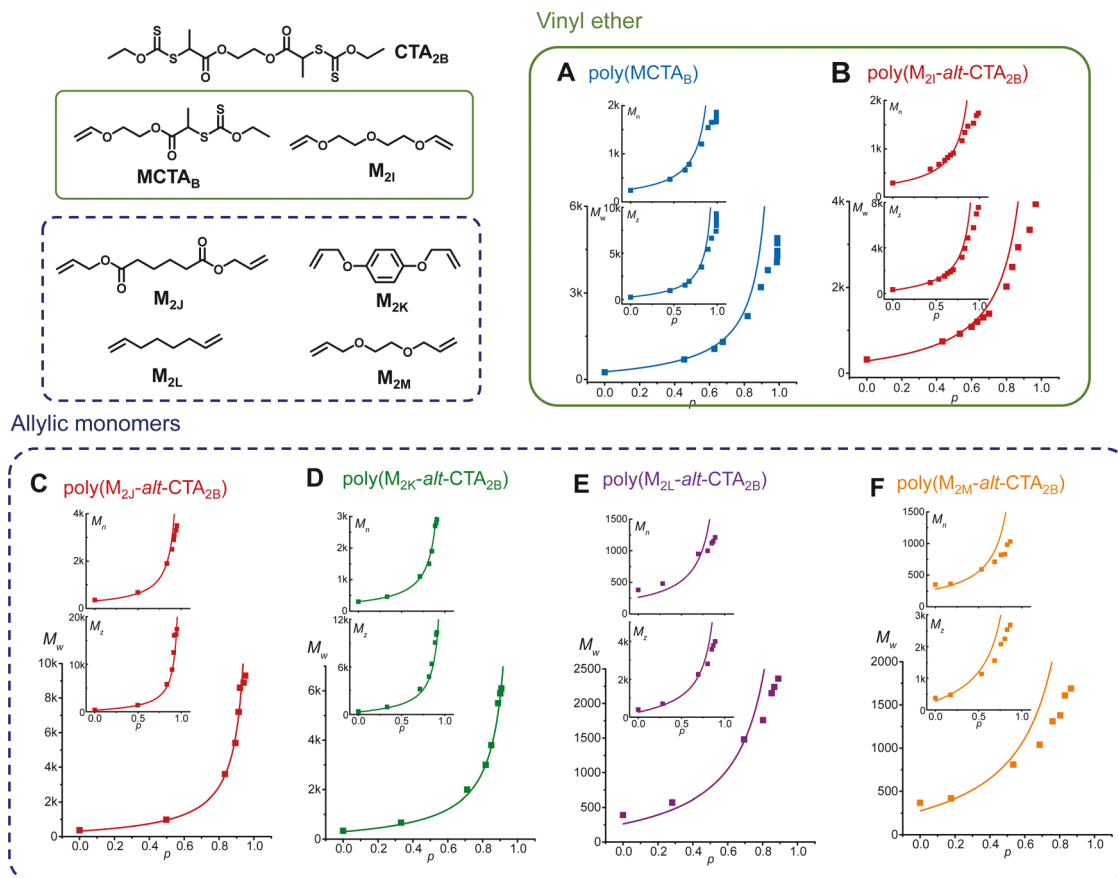


Fig. 7 Molecular weight evolution of the RAFT step-growth with LAMs. Adapted with permission from ref. 55 and 56 Copyright 2022 and 2023, with permission from American Chemical Society and Wiley.

Successful step-growth polymerization was demonstrated with both AB type ($MCTA_B$ in Fig. 7) and $A_2 + B_2$ type step-growth monomers (M_{2I} and CTA_{2B} in Fig. 7) using photo-iniferter (initiator, chain transfer agent, and terminator, *vide infra*) conditions. However, the polymerization rate was much slower when compared with the polymerizations using MAMs, even under thermally initiated conditions with AIBN.⁵⁵ Nonetheless, evolution of all three molecular weight averages indicated the successful step-growth (Fig. 7A and B).

5.2 RAFT step-growth polymerization with allylic monomers

More recently, the same group further expanded the monomer scopes for RAFT step-growth polymerization to allylic monomers (Fig. 7).⁵⁶ Efficient formation of RAFT-SUMI adduct was observed using previously employed xanthate based CTA with stoichiometrically equivalent 1-hexene as the model monofunctional monomer. RAFT step-growth polymerization was then successfully carried out with a series of bifunctional allyl monomers and the xanthate CTA, indicated by the evolution of molecular weight averages with conversion (Fig. 7C–F). Furthermore, the polymerization rate decreased in the order of $M_{2J} > M_{2K} > M_{2L} \approx M_{2M}$, which was attributed to the decreased monomer activities for radical addition reaction.

6. Light-mediated RAFT step-growth polymerization

6.1 Photo-iniferter RAFT step-growth polymerization

Photo-mediated polymerizations provide various benefits, including spatiotemporal control, support of greener practices, and use of mild conditions.⁵⁷ Historically, thiocarbonylthio compounds have been used to generate radicals under irradiation and initiate polymerization without the use of exogenous radical sources,⁵⁸ even before the discovery of RAFT polymerization. This was first demonstrated by Otsu who termed this concept as iniferter (now commonly referred to as photo-iniferter).⁵⁸ After the discovery of RAFT polymerization, numerous photo-iniferter polymerization using common RAFT agents were reported with UV-light and gamma radiation.^{59,60} Mechanistically, the direct photo-cleavage of the RAFT agent can occur by accessing the $\pi-\pi^*$ symmetry allowed transition, which requires UV irradiation. More recently, by exploiting specific RAFT agents that absorb light in the visible region, RAFT-iniferter was extended to visible light by accessing $n-\pi^*$ symmetry (or dipole) forbidden transition.^{61–64}

Photo-iniferter was recently applied to RAFT step-growth as well,^{49,65} where initiation can occur through two possible activation pathways, either *via* the end group CTA (Fig. 8A,

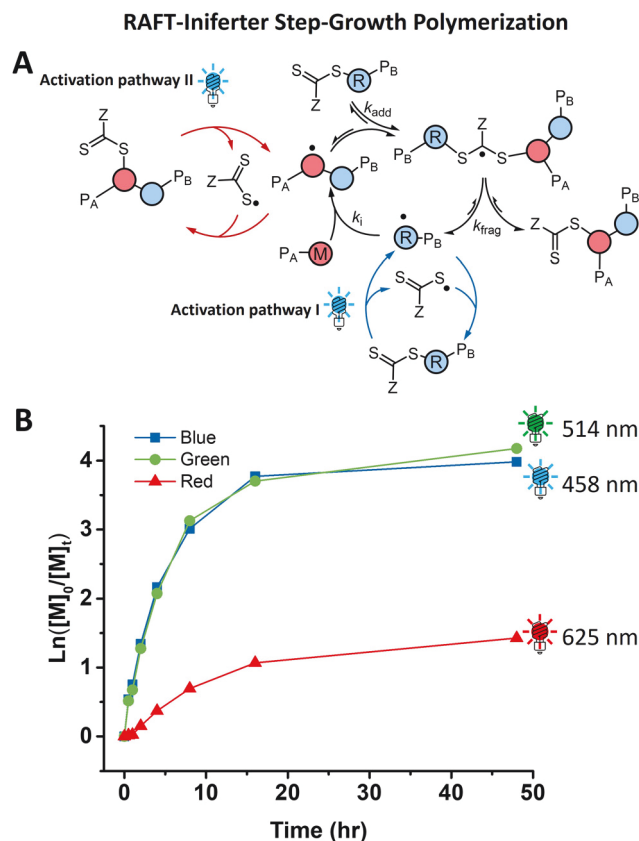


Fig. 8 (A) Illustration of the RAFT-iniferter step-growth mechanism and (B) semi-logarithmic plot. Adapted with permission from ref. 49 Copyright 2022, with permission from Royal Society of Chemistry.

Activation pathway I) or backbone CTA (Fig. 8A, Activation pathway II), generating radical intermediates in the RAFT step-growth cycle.⁴⁹

In one report,⁴⁹ Clouthier *et al.* employed a bifunctional maleimide monomer (M_{2A}) and bifunctional trithiocarbonate based RAFT agent (CTA_{2A}) to attempt RAFT step-growth polymerization under blue, green, and red light. The polymerization proceeded to high conversion under blue and green light conditions ($p > 0.98$); however, under red light, the polymerization reached low conversion and molecular weight ($p = 0.76$, $M_w = 3.1k$), which was attributed to the minimal overlap of the CTA with the red LED emission spectra. Nevertheless, the polymerization proceeded with step-growth molecular weight evolutions for all three wavelengths. Interestingly, fitting the kinetics of the polymerization with a semi-logarithmic plot presented a plateau, indicating a deviation from first order kinetics. This deviation was attributed to the fact that the tertiary radical (from end group CTA) is more stable than the secondary radical (from backbone CTA), resulting in preference of photo-fragmentation of the end group CTA (Activation pathway I). Although kinetics vary between photo-reactor conditions,⁶⁶ Aerts *et al.* also observed a similar trend in the RAFT-iniferter SUMI system for green and blue light conditions, where a plateau in the semi-logarithmic plot occurred at higher conversion ($p > 0.65$);

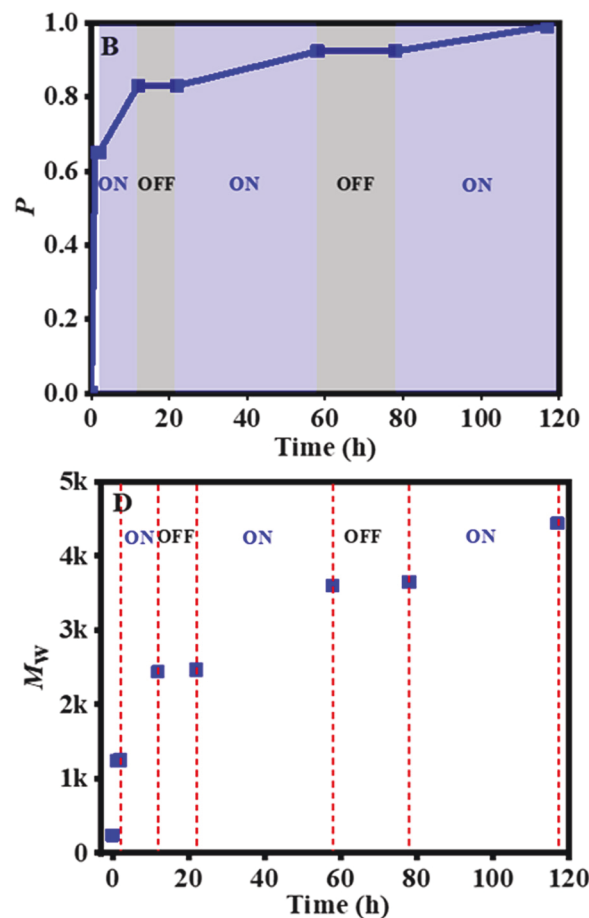


Fig. 9 Demonstration of temporal control with RAFT iniferter step-growth. Adapted with permission from ref. 55 Copyright 2022, with permission from American Chemical Society.

this was attributed to SUMI-CTA adduct absorbing light at the expense of the initial CTA.³⁵

In another report,⁵⁵ Li *et al.* demonstrated temporal control of RAFT-iniferter AB step-growth with $MCTA_B$ by conducting photochemical “on/off” experiments, where the polymerization halted in the dark (“off” phase) and continued to proceed under the presence of light (“on” phase, Fig. 9). Additionally, owing to the oil state of the $MCTA_B$, direct bulk polymerization was demonstrated.⁵⁵

6.2 PET-RAFT step-growth polymerization

In contrast to RAFT-iniferter, where the light directly fragments the CTA, another related technique recently emerged proceeding *via* photo-induced electron/energy transfer (PET), where photo-excited photo-catalyst fragments the CTA upon transfer of an electron or triplet energy to a CTA.⁶⁷ The initial PET-RAFT (chain-growth polymerization) was implemented with an iridium based photocatalyst ($\text{fac-Ir}(\text{ppy})_3$) to polymerize a wide range of conjugated and unconjugated monomers from various CTAs.⁶⁸ PET-RAFT was then extended to aqueous media using a water-soluble ruthenium based photocatalyst ($\text{Ru}(\text{bpy})_3^{2+}$) to polymerize a wide range of MAMs.⁶⁹ In a more recent study,

the specific initiation mechanism of these two catalysts (fac-Ir(ppy)₃ and Ru(bpy)₃²⁺) was proposed to proceed through triplet energy transfer.⁷⁰ Moreover, zinc centered metalloporphyrin based catalyst has been highly attractive for PET-RAFT with trithiocarbonates based CTAs;⁷¹ in particular, due to its low cost and oxygen tolerance, zinc tetraphenylporphyrin (ZnTPP) has been utilized by many researchers.⁷² Additionally, various organic based photocatalysts have been explored for PET-RAFT.⁷³

Recently, Clouthier *et al.* demonstrated the PET-RAFT step-growth polymerization of a bismaleimide monomer (M_{2A}) and CTA_{2A}, with ZnTPP as the photocatalyst under blue, green, and red-light conditions.⁴⁹ In contrast to photo-iniferter RAFT step-growth, the mechanism is proposed to occur with thiocarbonylthiolate anion fragmentation (Fig. 10A, activation pathway I/II), which has been speculated to have higher stability than thiocarbonylthiyl radicals and therefore would improve the chain end fidelity.⁷⁴ The polymerization proceeded to high conversion with step-growth molecular weight evolution, under all three different wavelengths. However, the initial rates for PET-RAFT step-growth (under blue and green light) were slower than the catalyst free conditions (*i.e.*, RAFT-iniferter step-growth, Fig. 8B); this observation contrasts with traditional RAFT chain-growth kinetics where PET-RAFT was faster than RAFT-iniferter.⁷⁵ Nonetheless, the polymerization proceeded under pseudo-first order kinetics with respect to monomer

under all three light conditions (Fig. 10B), indicating constant reactive radical intermediates throughout the polymerization, which is consistent with reported PET-RAFT kinetics.^{36,76} However, the kinetics for PET-RAFT step-growth showed a slight deviation from linearity of the semi-logarithmic plot at high conversion (Fig. 10B), which was attributed to the preference for photo-fragmentation of the end group CTA (Fig. 10A, Activation pathway I).⁴⁹

Although photo-mediated RAFT step-growth polymerization was expected to provide higher molecular weights by eliminating the possible stoichiometric imbalance from thermal initiators, Clouthier *et al.* did not observe this improvement in molecular weight, which was attributed to monomer impurity and the difficulty in achieving stoichiometric balance. To further investigate end-group fidelity of photo-mediated RAFT step-growth, the authors employed an AB type monomer, which by nature is stoichiometrically balanced, to polymerize *via* PET-RAFT step-growth. Yet a difference of a factor of two between the theoretical and experimental molecular weight ($M_{w,th} = 70k$, $M_w = 30k$) was still observed, which was attributed to the formation of cyclic species.⁴⁹

7. Graft copolymers from RAFT step-growth polymers

Graft copolymers have attracted interest in various fields in academia, owing to unique solution, bulk, and colloidal properties, where applications can be found in drug delivery to plastics.^{77–79} However, preparing this molecular architecture can be challenging, as it requires construction of the main chain backbone and polymeric side chains (also known as grafts) on a single macromolecule. Three prevailing synthetic approaches have been actively pursued: (a) polymerizing the mainchain backbone with macromonomers (Graft-through), (b) polymerizing the grafts from the mainchain backbone (Graft from), and (c) attaching end-group functional pre-grafts to the mainchain backbone (Graft-to). In all three approaches, post-polymerization modification or two orthogonal polymerization techniques are employed.⁸⁰

Owing to the retention of the CTA functionality, the RAFT step-growth polymers can be used to directly graft from the backbone *via* RAFT chain-growth polymerization without any additional step in between, thereby greatly simplifying the preparation of such complex polymers (Chart 2). One characteristic feature of successful synthesis of the graft copolymers is the clear shift in the molecular weight distribution *via* SEC analysis. Additional evidence can be obtained from absolute M_n (determined by light scattering) being consistent with the theoretical molecular weight; the latter can be calculated from monomer conversion of the monomers for the graft and absolute M_n of the precursor mainchain backbone. It is important to note that, appropriate polymerization conditions have to be carefully chosen to minimize intermolecular brush–brush coupling from radical termination events between graft chain ends.

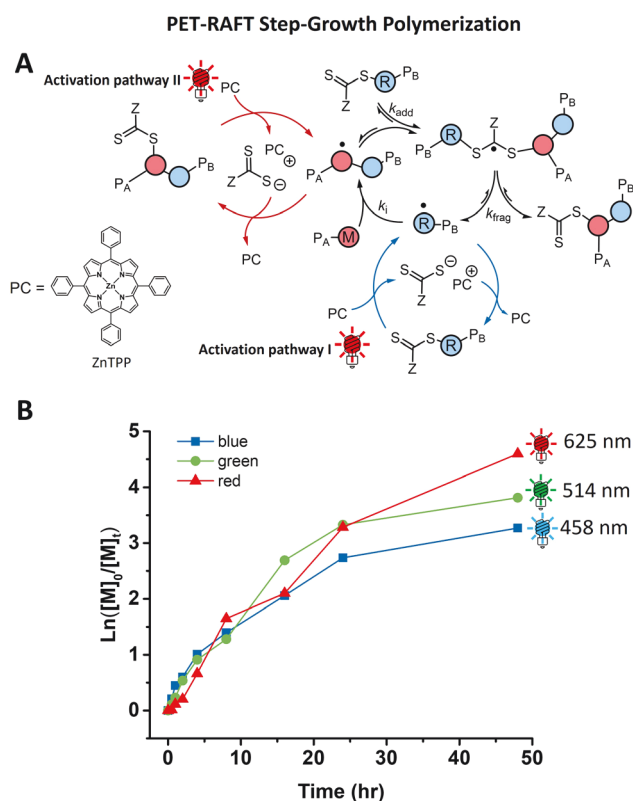


Fig. 10 (A) Illustration of the PET-RAFT step-growth mechanism and (B) semi-logarithmic plot. Adapted with permission from ref. 49 Copyright 2022, with permission from Royal Society of Chemistry.

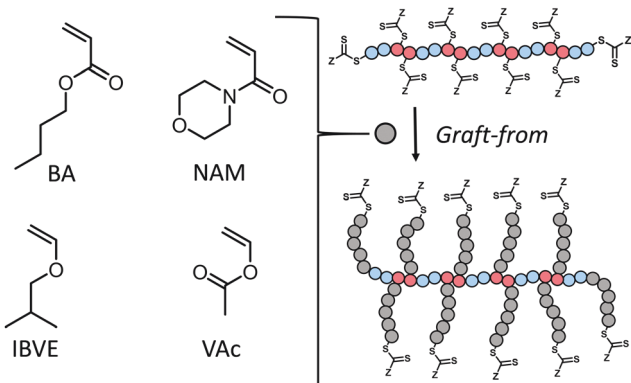


Chart 2 Reported monomers for graft copolymerization with RAFT step-growth polymers: butyl acrylate (BA), *N*-acryloyl morpholine (NAM), vinyl acetate (VAc) and isobutyl vinyl ether (IBVE).

7.1 Grafting from a maleimidic RAFT step-growth backbone

Butyl acrylate (BA) graft copolymers have been reported by grafting from $P(M_{2Si}-alt-CTA_{2A})$ and $P(M_{2A}-alt-CTA_{2SS})$ backbones,^{16,49} whilst a *N*-acryloyl morpholine (NAM) graft copolymer has been reported by grafting from the $P(M_{2A}-alt-CTA_{2A})$ backbone.⁵² In all cases, a successful shift in the molecular weight distribution *via* SEC was observed; additionally, $P(M_{2A}-alt-CTA_{2A})$ -*g*-PNAM revealed the expected increase in absolute M_n ($M_{n,LS} = 205k$, $M_{n,th} = 213k$).⁵²

Furthermore, taking advantage of the scalability of the RAFT step-growth backbone (*e.g.*, using commercially available bismaleimides), Boeck *et al.* achieved multigram preparation of a poly(*N*-acryloyl morpholine) (PNAM) graft copolymer (15 g, 93% recovery).⁵² It is worth noting that PNAM has attracted great interest for biomedical applications as a potential alternative to polyethylene glycol (PEG).⁸¹ Following end-group removal to allow aqueous solubility, dynamic light scattering (DLS) analysis revealed this PNAM graft copolymer had a *Z*-average hydrodynamic diameter of 22 nm with a polydispersity index (PDI) of 0.210. A single macromolecule of this size can be used for applications in tumor targeted drug delivery,^{82,83} highlighting the potential utility of RAFT step-growth polymers.

7.2 Grafting from an acrylic RAFT step-growth backbone

BA graft copolymers have also been reported by grafting from $P(M_{2E}-alt-CTA_{2A})$, $P(M_{2E}-alt-CTA_{2SS})$ and $P(M_{2G}-alt-CTA_{2A})$ backbones.²¹ In all cases, a successful shift in the molecular weight distribution *via* SEC was observed. Additionally, the related Mark-Houwink plot revealed a decrease in the α value, suggesting more compact behavior of such graft copolymers in solution (Fig. 6F).

7.3 Grafting from a vinyl ether RAFT step-growth backbone

The step-growth backbone formed between vinyl ether and xanthate based CTA, $P(MCTA_B)$, presents a unique opportunity to graft other monomers *via* cationic or radical RAFT chain-growth polymerization. For example, cationic RAFT polymerization was carried out with isobutyl vinyl ether (IBVE) catalyzed

by $ZnCl_2$, whilst radical RAFT polymerization was carried out with vinyl acetate (VAc) with thermal initiation by AIBN. A clear shift in SEC traces was observed in both cases (Fig. 11).⁶⁵

7.4 Grafting from an allylic RAFT step-growth backbone

RAFT step-growth backbones based on allylic monomers, such as $P(M_{2I}-alt-CTA_{2B})$, $P(M_{2K}-alt-CTA_{2B})$, $P(M_{2L}-alt-CTA_{2B})$ and $P(M_{2M}-alt-CTA_{2B})$ (Fig. 7), have been successfully grafted with vinyl acetate (VAc). Additionally, fluorescent acrylate was grafted onto a Living Polymer Network (LPN) (Fig. 12A, *via* allylic based RAFT step-growth) using a digitally masked photolithography with a commercial 3D printer (Fig. 12B). The LPN was prepared from a trifunctional vinyl monomer and CTA_{2B} , and a type I photo-initiator, 2,4,6-trimethylbenzoyldiphenyl phosphine oxide (TPO), to accelerate the photo crosslinking process.⁵⁶

7.5 Degradable graft copolymers

A unique feature of the brush polymers *via* grafting from the RAFT step-growth backbone is the ability to incorporate specific functionality into the polymer backbone, specifically, *via* the installation of these functionalities into the initial bifunctional reagents (CTA_2 or M_2). Moreover, $A_2 + B_2$ RAFT step-growth allows the modular placement of functionality *via* either bifunctional monomer unit (M_2) or bifunctional CTA unit (CTA_2) or even both.

Placement of functionality along the M_2 unit of the graft copolymer backbone was demonstrated in the original report, with a bismaleimide based RAFT step-growth backbone.¹⁶ PBA graft copolymer, $P(M_{2Si}-alt-CTA_{2A})$ -*g*-PBA, which bears cleavable silyl ether within each repeat unit along the length of the backbone, demonstrated rapid stimuli triggered degradation into well-defined linear polymers ($M_n = 9.0k$, $D = 1.08$) (Fig. 13A); this value was consistent with the expected molecular weight for two PBA grafts ($M_{n,th} = 4.9k$ per grafts) upon cleavage of the backbone.

Furthermore, the functionality placed in the CTA_2 unit of the graft copolymer backbone was demonstrated in a later report, with the diacrylate based RAFT step-growth backbone.²¹ PBA graft copolymer, $P(M_{2E}-alt-CTA_{2SS})$ -*g*-PBA, which bears cleavable disulfide within each repeat unit along the length of the backbone, also demonstrated stimuli triggered degradation into well-defined linear polymers ($M_n = 11k$, $D = 1.12$). Again, this value was close to the expected molecular weight of 2 polymeric side chains ($M_{n,th} = 4.0k$ per side chain) (Fig. 13B). More recently, UV light was used to partially degrade disulfide functionality in the CTA_2 of the PBA graft copolymer prepared from the $P(M_{2A}-alt-CTA_{2SS})$ backbone.⁴⁹

8. Classification of RAFT step-growth and RAFT-SUMI

In this section, we present classification of RAFT step-growth and RAFT-SUMI based on the driving force. Particularly, we

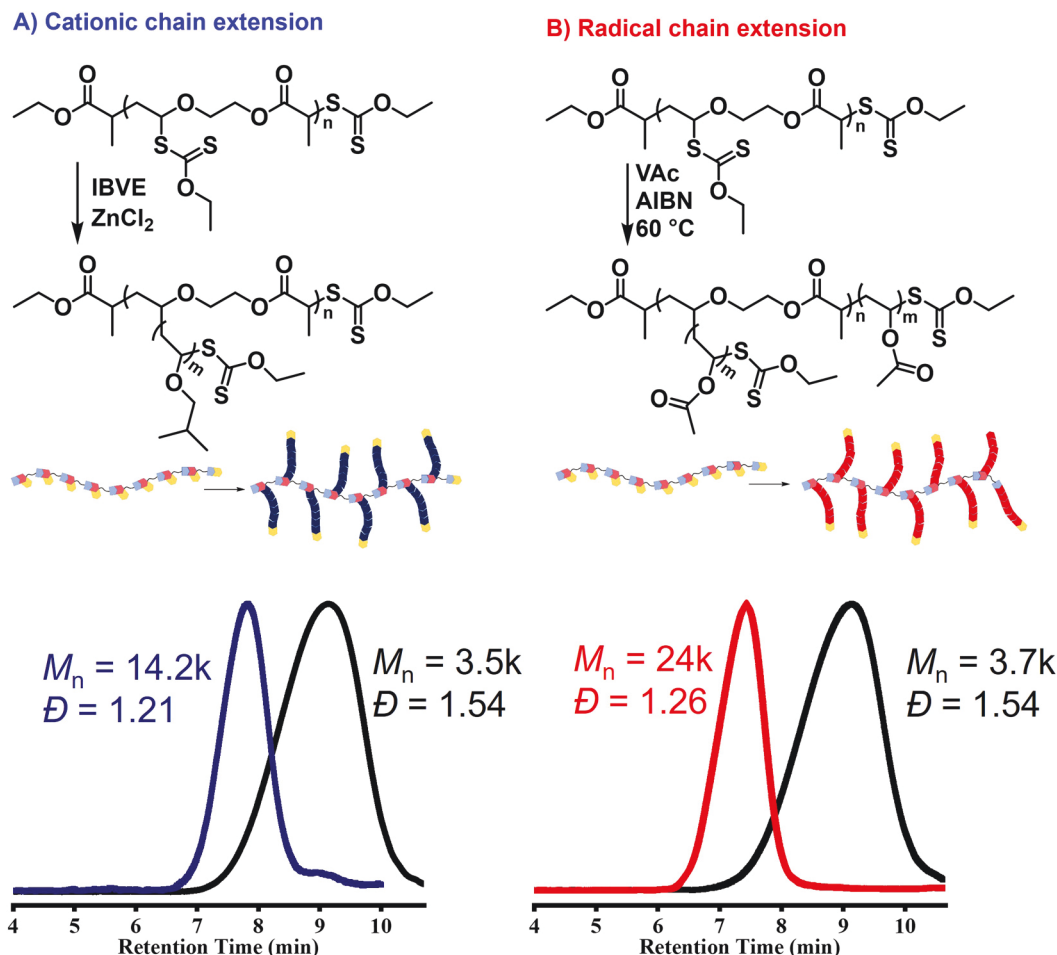


Fig. 11 SEC traces of IBVE (A) and VAC (B) graft copolymer and its precursor backbone. Adapted with permission from ref. 65 Copyright 2022, with permission from American Chemical Society.

suggest using the term ' $C_{\text{tr}}/C_{\text{tr}}'$ ' as a parameter that governs the efficiency of a given monomer and CTA to undergo the RAFT-SUMI process.

8.1 $C_{\text{tr}}/C_{\text{tr}}'$ defining the efficiency of the RAFT-SUMI process

In the literature, kinetic modeling of the RAFT-SUMI process through numerical analysis has been well-established by Moad *et al.*^{23,84} Their work has led to insightful validation of the importance of specific rate constants in the RAFT-SUMI mechanism. One of the major parameters that has been given high attention is the chain transfer constant (C_{tr}), which by itself describes the likelihood of forward chain transfer (k_{tr}) over homopropagation (k_{p}). Moad *et al.* emphasized that C_{tr} should be sufficiently high to permit one monomer to be inserted per activation cycle ($k_{\text{p}} \ll k_{\text{tr}}$).³³ Additionally, they highlighted that the efficiency of the SUMI process benefits from rapid $\text{R}^\bullet$ addition to the monomer (k_{i}).³³ On the other hand, Xu *et al.* have experimentally validated the importance of the equilibrium between forward and reverse chain transfer ($k_{\text{tr}}/k_{\text{tr}}'$) in their investigations, specifically comparing the SUMI process of *N*-substituted maleimides with CTA bearing primary and

secondary benzyl radical fragmentation.^{38,85} Moreover, Xu *et al.* focused on the RAFT-SUMI process using low k_{p} monomers to minimize homopropagation. Furthermore, iterative SUMI was achieved by employing specific pairing of the monomer to fragmentation of the CTA to promote high k_{i} .³⁶

The question naturally arises: "for a given CTA and monomer pair, how do all the rate constants (that have been identified to play an important role) orchestrate the efficiency of the SUMI process?" Surprisingly, to date, there has been no simple formula that describes the efficiency of the SUMI process. In answering this question, we first define the likelihood of SUMI occurring over homopropagation as a measure of efficiency of the SUMI process. This can be simply defined by a ratio of the key steps that we define for each process, specifically the bimolecular reaction of monomer between $\text{R}^\bullet$ species and $\text{M}^\bullet$ species:

$$L_{\text{SUMI}} = \frac{k_{\text{i}}[\text{M}][\text{R}^\bullet]}{k_{\text{p}}[\text{M}][\text{M}^\bullet]} \quad (14)$$

Herein, we use L_{SUMI} to define the likelihood of occurrence of SUMI over homopropagation.

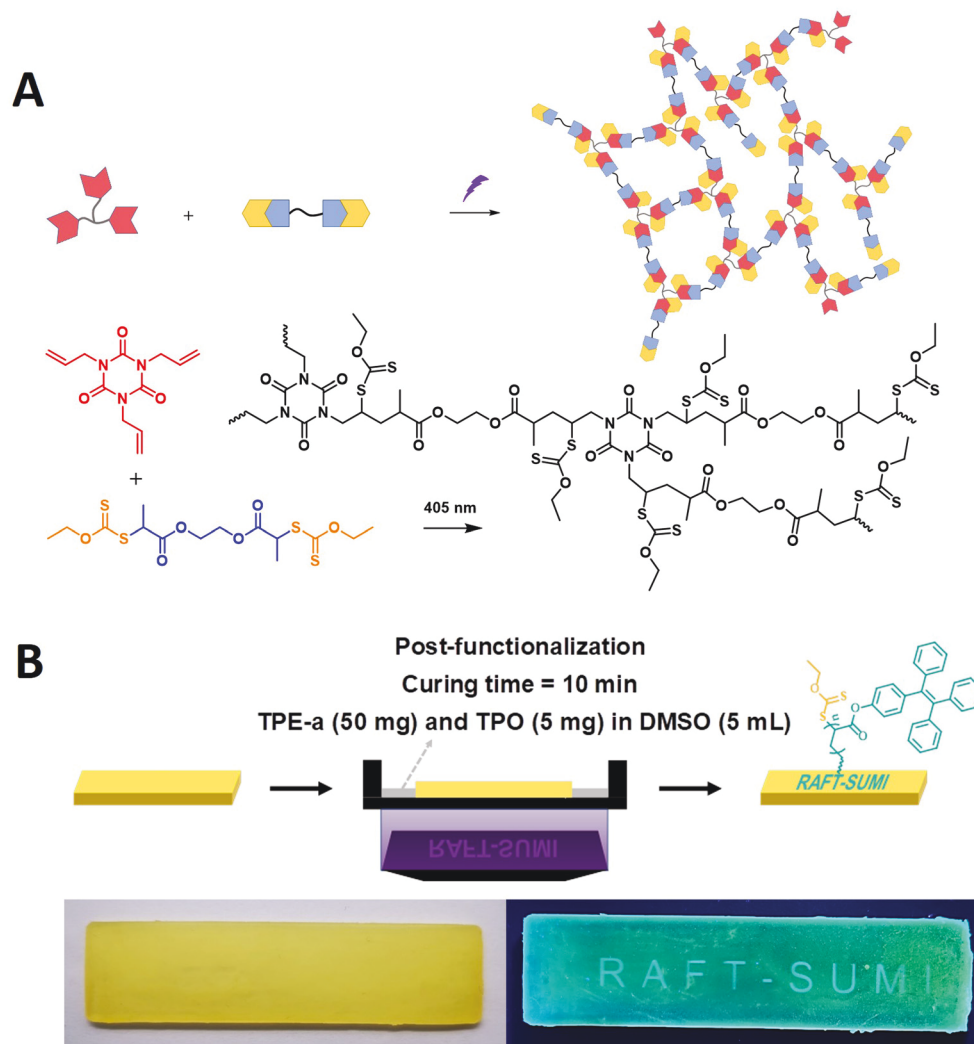


Fig. 12 The postfunctionalization process with a fluorescent acrylate monomer. The film after surface modification under natural light and the film after surface modification under UV light ($\lambda_{\text{max}} = 365 \text{ nm}$). Adapted with permission from ref. 56 Copyright 2023, with permission from Wiley.

Here, we make a key assumption that the chain transfer process of the CTA outweighs all other processes such that the equilibrium between forward and reverse chain transfer is instantaneously reached:

$$k_{\text{tr}}[\text{M}^\bullet][\text{RZ}] = k_{-\text{tr}}[\text{R}^\bullet][\text{MZ}] \quad (15)$$

where MZ represents the fragmentation product between CTA with $\text{M}^\bullet$, and RZ represents the fragmentation product between CTA with $\text{R}^\bullet$ (Scheme 5). By definition, $k_{\text{tr}}/k_{-\text{tr}}$ describes the equilibrium constant of chain transfer, K_{eq} :

$$K_{\text{eq}} = \frac{k_{\text{tr}}}{k_{-\text{tr}}} = \frac{[\text{MZ}][\text{R}^\bullet]}{[\text{RZ}][\text{M}^\bullet]} \quad (16)$$

Please note that K_{eq} is a thermodynamic relationship primarily driven by the relative stability difference between $\text{R}^\bullet$ and the monomer adduct radical species ($\text{M}^\bullet$ in Scheme 5), which can be intuitively described by the effect of the substituents on relative radical stability.

By rearrangement of eqn (16), $[\text{R}^\bullet]/[\text{M}^\bullet]$ can be expressed as $K_{\text{eq}}[\text{RZ}]/[\text{MZ}]$, which is then substituted into eqn (14) to result in eqn (17):

$$L_{\text{SUMI}} = \frac{k_i}{k_p} K_{\text{eq}} \frac{[\text{RZ}]}{[\text{MZ}]} \quad (17)$$

More importantly, this equation unifies all rate constants that were identified to play an important role, as a single constant to define the efficiency of SUMI to occur for a given monomer and CTA pairing. It is noteworthy that this unification of the three parameters: k_i , k_p and K_{eq} (or $k_{\text{tr}}/k_{-\text{tr}}$) can be simply described from the ratio of the forward and reverse chain transfer constants ($C_{\text{tr}}/C_{-\text{tr}}$, where $C_{\text{tr}} = k_{\text{tr}}/k_p$ and $C_{-\text{tr}} = k_{-\text{tr}}/k_i$):

$$\frac{C_{\text{tr}}}{C_{-\text{tr}}} = K_{\text{eq}} \frac{k_i}{k_p} \quad (18)$$

It is worth noting that the premise of eqn (17) assumes that chain transfer equilibrium is rapidly reached and therefore only applicable with a suitable Z-group for a given monomer

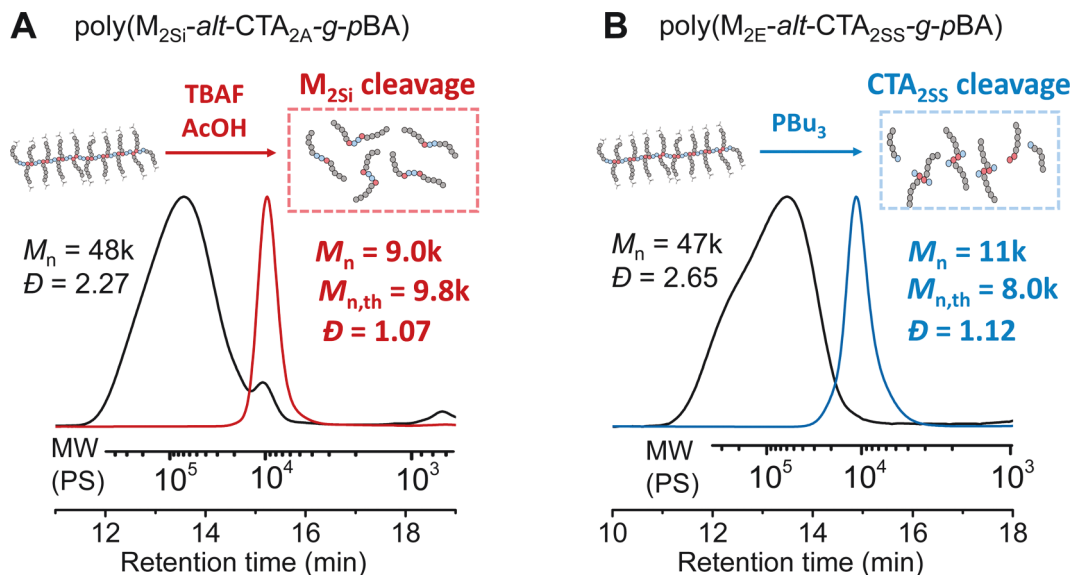
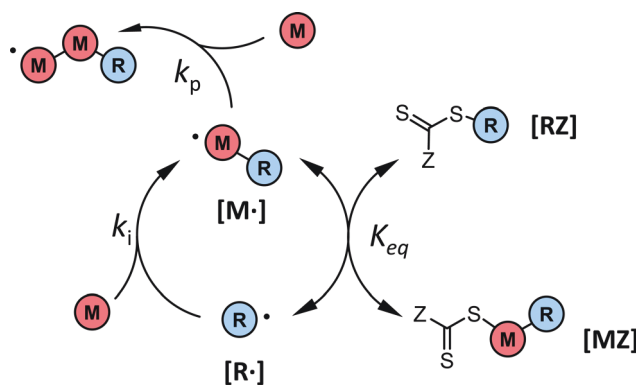


Fig. 13 Preparation of graft copolymers with a degradable backbone. Cleavable unit introduced through the M_2 unit (A) and CTA_2 unit (B). Adapted with permission from ref. 16 and 21 Copyright 2021 and 2022, with permission from American Chemical Society.



Scheme 5 Illustration of relevant parameters in determining the likelihood of RAFT-SUMI over homopropagation (L_{SUMI}).

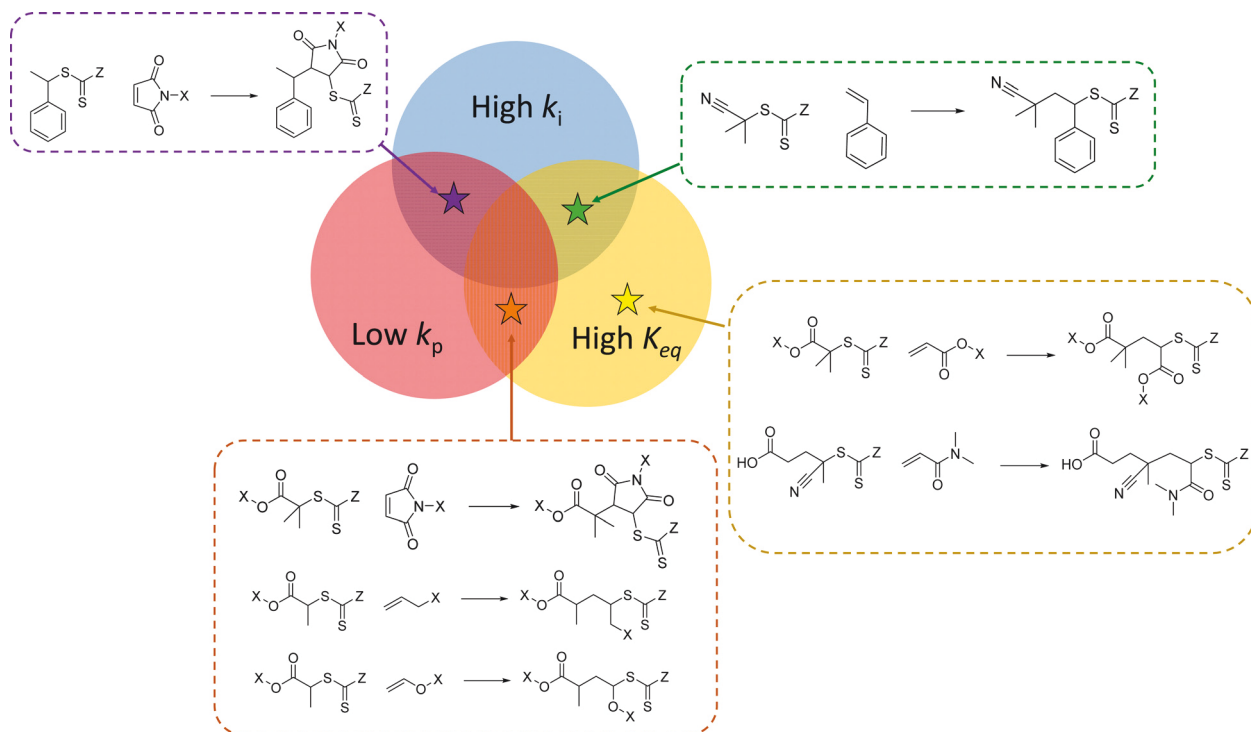
class (as it depends on $C=S$ reactivity). It is important to note that neither radical termination nor retardation by the formation of the chain transfer intermediate adduct is considered. In addition, the likelihood of SUMI over homopropagation defined in the formula above (L_{SUMI}) depends on the concentration of the initial CTA ($[RZ]$) and monomer adduct/macro-CTA ($[MZ]$), whilst being independent of the monomer concentration. It is also worth noting that the stoichiometry of the monomer to CTA will affect the $[RZ]/[MZ]$ ratio as the limiting reagent is fully consumed. For example, if the monomer is the limiting reagent, L_{SUMI} is higher at high monomer conversion, than the case if CTA was the limiting reagent. This is because in the former case, the presence of unreacted CTA will result in a relatively higher ratio of $[RZ]/[MZ]$; by contrast, when CTA is the limiting reagent, there will be the presence of unreacted monomer after the full consumption of the initial CTA (RZ) and this will result in a low L_{SUMI} value.

8.2 Classification of RAFT step-growth and SUMI based on k_i , k_p and K_{eq}

It is important to note that, according to eqn (17), the efficiency of the SUMI process falls with increasing formation of monomer-adduct (MZ) and consumption of the initial CTA (RZ). Indeed, for a high yielding RAFT-SUMI process, C_{tr}/C_{-tr} would have to be sufficiently high, such that the odds of SUMI occurring over homopropagation is still high even at high CTA conversions. Assuming all reported RAFT step-growth and RAFT-SUMI bears high C_{tr}/C_{-tr} , we can intuitively categorize most of the reported examples into three overlapping classes (Scheme 6) based on three parameters k_i , k_p and K_{eq} that we believe gives rise to high C_{tr}/C_{-tr} (eqn (18)).

For example, the reported RAFT-SUMI of acrylate²¹ or acrylamide-based²³ monomers using CTA bearing tertiary carboxyalkyl or cyanoalkyl stabilized fragmentation, respectively, can be classified under the high K_{eq} category (higher radical stability of the $R^\bullet$ species relative to $M^\bullet$ promoting high K_{eq}). Other reported examples can be categorized as combinations of at least two classes. Examples of RAFT step-growth and RAFT-SUMI with low k_p monomers have been demonstrated with either high k_i or high K_{eq} . For example, RAFT step-growth of maleimides with CTA bearing tertiary carboxyalkyl fragmentation,^{16,52} and vinyl ethers/allyl monomers with CTA bearing secondary carboxyalkyl fragmentation,^{55,56} would fall under the overlapping class of low k_p and high K_{eq} (Scheme 6).

On the other hand, Xu *et al.* demonstrated the RAFT-SUMI process of CTA bearing secondary benzyl radical fragmentation with *N*-substituted maleimides, which is driven largely by relatively high k_i and low k_p ³⁸ (Scheme 6). To achieve low k_p , one could employ beta-alpha substituted monomers;³⁶ furthermore, employing monomers of different electronic properties (*e.g.*, indene *vs.* maleimide) could promote higher k_i to k_p .⁸⁵ All these examples would fall under the overlapping class of high k_i and low k_p .



Scheme 6 Qualitative classification of RAFT-SUMI and RAFT step-growth systems based on the driving force.

Finally, the example of RAFT-SUMI of styrene with CTA bearing tertiary cyanoalkyl fragmentation mentioned above (Fig. 1), can be categorized as an overlapping class of high K_{eq} (owing to more favorable fragmentation) and high k_i (considering the monomer addition to R^* is more rapid than the homopropagation) (Scheme 6).

8.3 Example of high C_{tr}/C_{-tr} RAFT-SUMI with reported kinetic rate constants

We emphasize that relating SUMI efficiency with C_{tr}/C_{-tr} (eqn (18)) is mostly practical for qualitative discussions, as determining the value of C_{tr}/C_{-tr} for a given monomer and CTA pair can be difficult. Generally, rate constants can vary with methods used to determine the values and are dependent on experimental conditions. Additionally, it is worth noting that the k_p is chain length dependent for many classes of monomers, where the first propagation step ($k_p(1)$) is often faster than subsequent propagation steps ($k_p > 1$).²³ When quantitatively assessing the C_{tr}/C_{-tr} value, $k_p(1)$ should be considered, especially for classes of monomers that are not radically homopolymerizable where $k_p > 1$ is negligible.³⁶

Moad *et al.* reported a comparison of the SUMI process of NIPAM and styrene with a CTA bearing tertiary substituted cyano-stabilized fragmentation (Table 3 and Fig. 14).²³ In both cases, relatively high K_{eq} values are determined from the ratio of the reported k_{tr} and k_{-tr} , which contribute to promoting high C_{tr}/C_{-tr} values. However, the C_{tr}/C_{-tr} value is higher for styrene than for NIPAM by an order of magnitude, as the value for k_p is significantly higher for NIPAM than for styrene whilst k_i is noticeably higher for styrene than for NIPAM. The latter

Table 3 Kinetic parameters of RAFT-SUMI with styrene vs. NIPAM

Styrene		
NIPAM		
Rate constant/units ^a	Styrene	NIPAM
$k_i/M^{-1} s^{-1}$	5.2×10^3	8.0×10^2
$k_p/M^{-1} s^{-1}$	8.4×10^2	1.60×10^3
$k_{tr}/M^{-1} s^{-1}$	1.5×10^6	2.0×10^6
$k_{-tr}/M^{-1} s^{-1}$	8.5×10^3	8.0×10^3
K_{eq} ^b	176	250
C_{tr}/C_{-tr} ^c	1092	125

^a Rate constants obtained from ref. 23. The k_p tabulated above is a specific value for the first monomer propagation step (to form DP of 2).

^b Equilibrium constant obtained from k_{tr}/k_{-tr} . ^c Calculated from eqn (18).

explains the faster RAFT-SUMI kinetics for styrene (Fig. 14), when considering monomer addition to R^* to be the rate determining step. Interestingly, NIPAM with a C_{tr}/C_{-tr} value of 125 was reported with an isolated SUMI-CTA adduct yield of ~80% (Fig. 14);²³ by contrast, styrene, with a C_{tr}/C_{-tr} value of 1092, reveals a more quantitative SUMI-CTA adduct yield,

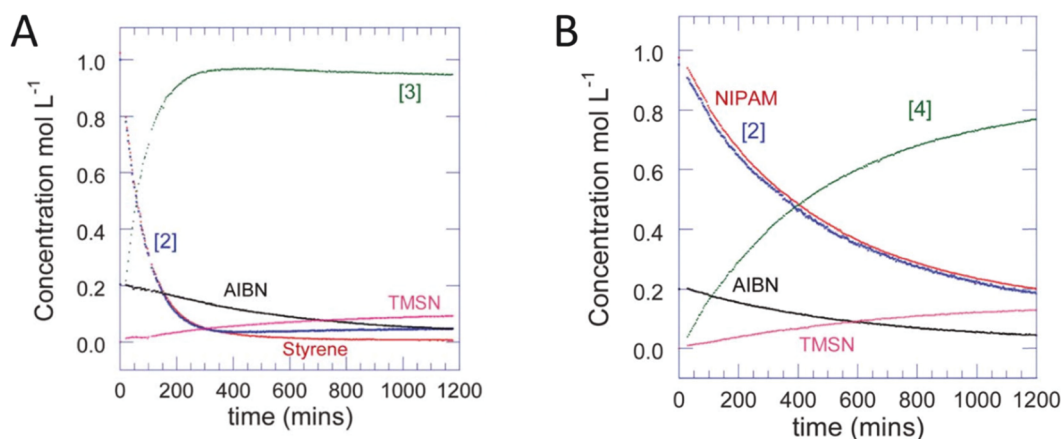


Fig. 14 RAFT-SUMI kinetics of (A) Styrene and (B) NIPAM using trithiocarbonate based CTA bearing tertiary cyano-stabilized fragmentation. Figure adapted from ref. 23 Copyright 2012, with permission from Royal Society of Chemistry.

which was consistent with a similar report by McLeary (using a more active Z-group, Fig. 1).²⁷ Thus based on these reports, we suggest that C_{tr}/C_{-tr} would be required to be higher than $\sim 10^2$ to allow efficient RAFT-SUMI at high CTA consumption. We emphasize that our suggestion is highly subjected to the reported yields and relative SUMI kinetics which can be limited by radical termination reactions.

9. Conclusions

At the time of this review, RAFT step-growth polymerization has been successfully demonstrated with several monomer families, including maleimides, acrylates, vinyl ethers and allylics. In theory, an appropriate pair of monomer and CTA that generates quantitative SUMI-CTA adduct yields with monomer conversion can be designed into bifunctional reagents (AB , or $A_2 + B_2$) to allow successful RAFT step-growth polymerization. Given the prior literature reports on RAFT initialization and the SUMI process, we predict an expansion of the monomer scope for RAFT step-growth polymerization. Furthermore, we anticipate further development and identification of new monomer and CTA pairs for an efficient RAFT-SUMI process, by judiciously selecting the relevant parameters (k_i , k_p and K_{eq}) to achieve high efficiency (C_{tr}/C_{-tr}). It is important to note that selectivity may arise from the activation-deactivation process (iniferter, redox or PET) in some cases where the chain transfer process is limited.

From a practical perspective, RAFT step-growth polymerization synergistically combines features of traditional RAFT polymerization (high functional group tolerance and user-friendly nature) and traditional step-growth (versatility in backbone design) and offers new opportunities to prepare complex architectures with synthetic ease. We anticipate the broad application of the linear and graft copolymers from RAFT step-growth polymerization in materials science, for example, drug-delivery, by taking advantage of the versatility of the backbone to introduce biodegradability.

Finally, we would like to emphasize the characterization of step-growth polymerization by following M_n , M_w and M_z rather than traditional characterization with M_n and D only. This practice allows better comparison of experimental data with Flory's classical model of the expected linear molecular weight evolution to evaluate step-growth polymerization.

Conflicts of interest

The authors declare the following competing financial interest(s): J. T. and W. Y. are named inventors on a provisional patent application described in this work.

Acknowledgements

This work was financially supported by the National Science Foundation (NSF) under Award CHE-2108670.

References

- 1 V. P. Beyer, J. Kim and C. R. Becer, *Polym. Chem.*, 2020, **11**, 1271–1291.
- 2 N. Corrigan, J. Yeow, P. Judzewitsch, J. Xu and C. Boyer, *Angew. Chem., Int. Ed.*, 2019, **58**, 5170–5189.
- 3 J. Yeow, R. Chapman, A. J. Gormley and C. Boyer, *Chem. Soc. Rev.*, 2018, **47**, 4357–4387.
- 4 S. Oliver, L. Zhao, A. J. Gormley, R. Chapman and C. Boyer, *Macromolecules*, 2019, **52**, 3–23.
- 5 C. H. Chan, J.-T. Chen, W. S. Farrell, C. M. Fellows, D. J. Keddie, C. K. Luscombe, J. B. Matson, J. Merna, G. Moad, G. T. Russell, P. Théato, P. D. Topham and L. Sosa Vargas, *Polym. Chem.*, 2022, **13**, 2262–2270.
- 6 R. B. Grubbs and R. H. Grubbs, *Macromolecules*, 2017, **50**, 6979–6997.
- 7 L. Billiet, D. Fournier and F. Du Prez, *Polymer*, 2009, **50**, 3877–3886.
- 8 M. Destarac, *Polym. Chem.*, 2018, **9**, 4947–4967.
- 9 N. Corrigan, K. Jung, G. Moad, C. J. Hawker, K. Matyjaszewski and C. Boyer, *Prog. Polym. Sci.*, 2020, **111**, 101311.
- 10 J. Chiefari, Y. K. Chong, F. Ercole, J. Krstina, J. Jeffery, T. P. T. Le, R. T. A. Mayadunne, G. F. Meijs, C. L. Moad, G. Moad, E. Rizzardo and S. H. Thang, *Macromolecules*, 1998, **31**, 5559–5562.
- 11 J. Chiefari, R. T. A. Mayadunne, C. L. Moad, G. Moad, E. Rizzardo, A. Postma and S. H. Thang, *Macromolecules*, 2003, **36**, 2273–2283.

- 12 Y. K. Chong, J. Krstina, T. P. T. Le, G. Moad, A. Postma, E. Rizzardo and S. H. Thang, *Macromolecules*, 2003, **36**, 2256–2272.
- 13 S. Perrier, *Macromolecules*, 2017, **50**, 7433–7447.
- 14 R. Wei, T. Tiso, J. Bertling, K. O'Connor, L. M. Blank and U. T. Bornscheuer, *Nat. Catal.*, 2020, **3**, 867–871.
- 15 C. Boyer, M. Kamigaito, K. Satoh and G. Moad, *Prog. Polym. Sci.*, 2023, **138**, 101648.
- 16 J. Tanaka, N. E. Archer, M. J. Grant and W. You, *J. Am. Chem. Soc.*, 2021, **143**, 15918–15923.
- 17 N. B. Cramer, S. K. Reddy, A. K. O'Brien and C. N. Bowman, *Macromolecules*, 2003, **36**, 7964–7969.
- 18 K. Satoh, M. Mizutani and M. Kamigaito, *Chem. Commun.*, 2007, 1260–1262, DOI: [10.1039/B616598B](https://doi.org/10.1039/B616598B).
- 19 M. Mizutani, K. Satoh and M. Kamigaito, *Macromolecules*, 2009, **42**, 472–480.
- 20 M. Kamigaito, *Polym. J.*, 2022, **54**, 1391–1405.
- 21 N. E. Archer, P. T. Boeck, Y. Ajirniar, J. Tanaka and W. You, *ACS Macro Lett.*, 2022, **11**, 1079–1084.
- 22 J. Xu, *Macromolecules*, 2019, **52**, 9068–9093.
- 23 S. Houshyar, D. J. Keddie, G. Moad, R. J. Mulder, S. Saubern and J. Tsanaktsidis, *Polym. Chem.*, 2012, **3**, 1879–1889.
- 24 P. Delduc, C. Tailhan and S. Z. Zard, *J. Chem. Soc., Chem. Commun.*, 1988, 308–310.
- 25 B. Quiclet-Sire and S. Z. Zard, *Pure Appl. Chem.*, 2010, **83**, 519–551.
- 26 S. Z. Zard, *Macromolecules*, 2020, **53**, 8144–8159.
- 27 J. B. McLeary, F. M. Calitz, J. M. McKenzie, M. P. Tonge, R. D. Sanderson and B. Klumperman, *Macromolecules*, 2004, **37**, 2383–2394.
- 28 M. Chen, K. P. Ghigino, A. W. H. Mau, E. Rizzardo, W. H. F. Sasse, S. H. Thang and G. J. Wilson, *Macromolecules*, 2004, **37**, 5479–5481.
- 29 J. B. McLeary, J. M. McKenzie, M. P. Tonge, R. D. Sanderson and B. Klumperman, *Chem. Commun.*, 2004, 1950–1951, DOI: [10.1039/B404857A](https://doi.org/10.1039/B404857A).
- 30 G. Pound, J. B. McLeary, J. M. McKenzie, R. F. M. Lange and B. Klumperman, *Macromolecules*, 2006, **39**, 7796–7797.
- 31 J. B. McLeary, F. M. Calitz, J. M. McKenzie, M. P. Tonge, R. D. Sanderson and B. Klumperman, *Macromolecules*, 2005, **38**, 3151–3161.
- 32 M. Chen, M. Häussler, G. Moad and E. Rizzardo, *Org. Biomol. Chem.*, 2011, **9**, 6111–6119.
- 33 J. J. Haven, M. Hendrikx, T. Junkers, P. J. Leenaers, T. Tsompanoglou, C. Boyer, J. Xu, A. Postma and G. Moad, *Reversible Deactivation Radical Polymerization: Mechanisms and Synthetic Methodologies*, American Chemical Society, 2018, vol. 1284, ch. 4, pp. 77–103.
- 34 Y. Zhou, Z. Zhang, C. M. Reese, D. L. Patton, J. Xu, C. Boyer, A. Postma and G. Moad, *Macromol. Rapid Commun.*, 2020, **41**, 1900478.
- 35 A. Aerts, R. W. Lewis, Y. Zhou, N. Malic, G. Moad and A. Postma, *Macromol. Rapid Commun.*, 2018, **39**, e1800240.
- 36 R. Liu, L. Zhang, Z. Huang and J. Xu, *Polym. Chem.*, 2020, **11**, 4557–4567.
- 37 S. Lin, L. Zhang, Z. Huang, P. V. Kumar and J. Xu, *Macromolecules*, 2019, **52**, 7157–7166.
- 38 Z. Huang, N. Corrigan, S. Lin, C. Boyer and J. Xu, *J. Polym. Sci., Part A: Polym. Chem.*, 2019, **57**, 1947–1955.
- 39 C. Fu, Z. Huang, C. J. Hawker, G. Moad, J. Xu and C. Boyer, *Polym. Chem.*, 2017, **8**, 4637–4643.
- 40 J. Xu, C. Fu, S. Shanmugam, C. J. Hawker, G. Moad and C. Boyer, *Angew. Chem., Int. Ed.*, 2017, **56**, 8376–8383.
- 41 J. J. Haven, J. Vandenbergh, R. Kurita, J. Gruber and T. Junkers, *Polym. Chem.*, 2015, **6**, 5752–5765.
- 42 J. Vandenbergh, G. Reekmans, P. Adriaenssens and T. Junkers, *Chem. Commun.*, 2013, **49**, 10358–10360.
- 43 D. J. Keddie, *Chem. Soc. Rev.*, 2014, **43**, 496–505.
- 44 G. Odian, *Principles of Polymerization*, 2004, ch. 2, pp. 39–197, DOI: [10.1002/047147875X](https://doi.org/10.1002/047147875X).
- 45 M. Gavrilov and M. J. Monteiro, *Eur. Polym. J.*, 2015, **65**, 191–196.
- 46 D. T. Gentekos, R. J. Sifri and B. P. Fors, *Nat. Rev. Mater.*, 2019, **4**, 761–774.
- 47 P. J. Flory, *J. Am. Chem. Soc.*, 1936, **58**, 1877–1885.
- 48 J. Rosselgong and S. P. Armes, *Macromolecules*, 2012, **45**, 2731–2737.
- 49 S. M. Clouthier, J. Tanaka and W. You, *Polym. Chem.*, 2022, **13**, 6114–6119.
- 50 F. W. P. C. Corporation, https://www.wako-chem.co.jp/kaseihin_en/oilazo/AIBN.htm.
- 51 G. Moad, *Prog. Polym. Sci.*, 2019, **88**, 130–188.
- 52 P. Boeck, N. Archer, J. Tanaka and W. You, *Polym. Chem.*, 2022, **13**, 2589–2594.
- 53 Y. Lu, L. An and Z.-G. Wang, *Macromolecules*, 2013, **46**, 5731–5740.
- 54 K. G. E. Bradford, L. M. Petit, R. Whitfield, A. Anastasaki, C. Barner-Kowollik and D. Konkolewicz, *J. Am. Chem. Soc.*, 2021, **143**, 17769–17777.
- 55 Z. Li, J. Li, X. Pan, Z. Zhang and J. Zhu, *ACS Macro Lett.*, 2022, **11**, 230–235.
- 56 Z. Li, J. Li, B. Zhao, X. Pan, X. Pan and J. Zhu, *Chin. J. Chem.*, 2023, **41**, 503–508.
- 57 J. Phommalsack-Lovan, Y. Chu, C. Boyer and J. Xu, *Chem. Commun.*, 2018, **54**, 6591–6606.
- 58 T. Otsu, M. Yoshida and T. Tazaki, *Die Makromolekulare Chemie, Rapid Communications*, 1982, **3**, 133–140.
- 59 J. F. Quinn, L. Barner, C. Barner-Kowollik, E. Rizzardo and T. P. Davis, *Macromolecules*, 2002, **35**, 7620–7627.
- 60 C.-Y. Hong, Y.-Z. You, R.-K. Bai, C.-Y. Pan and G. Borjihan, *J. Polym. Sci., Part A: Polym. Chem.*, 2001, **39**, 3934–3939.
- 61 J. Xu, S. Shanmugam, N. A. Corrigan and C. Boyer, *ACS Symp. Ser.*, 2015, **1187**, 247–267.
- 62 S. Shanmugam, J. Cuthbert, J. Flum, M. Fantin, C. Boyer, T. Kowalewski and K. Matyjaszewski, *Polym. Chem.*, 2019, **10**, 2477–2483.
- 63 S. Shanmugam, J. Cuthbert, T. Kowalewski, C. Boyer and K. Matyjaszewski, *Macromolecules*, 2018, **51**, 7776–7784.
- 64 T. G. McKenzie, Q. Fu, M. Uchiyama, K. Satoh, J. Xu, C. Boyer, M. Kamigaito and G. Qiao, *Adv. Sci.*, 2016, **3**, 1500394.
- 65 Z. Li, J. Li, X. Pan, Z. Zhang and J. Zhu, *ACS Macro Lett.*, 2022, **11**, 230–235.
- 66 P. N. Kurek, A. J. Kloster, K. A. Weaver, R. Manahan, M. L. Allegranza, N. De Alwis Watuthanthrige, C. Boyer, J. A. Reeves and D. Konkolewicz, *Ind. Eng. Chem. Res.*, 2018, **57**, 4203–4213.
- 67 M. L. Allegranza and D. Konkolewicz, *ACS Macro Lett.*, 2021, **10**, 433–446.
- 68 J. Xu, K. Jung, A. Atme, S. Shanmugam and C. Boyer, *J. Am. Chem. Soc.*, 2014, **136**, 5508–5519.
- 69 J. Xu, K. Jung, N. A. Corrigan and C. Boyer, *Chem. Sci.*, 2014, **5**, 3568–3575.
- 70 N. Corrigan, J. Xu, C. Boyer and X. Allonas, *ChemPhotoChem*, 2019, **3**, 1193–1199.
- 71 S. Shanmugam, J. Xu and C. Boyer, *J. Am. Chem. Soc.*, 2015, **137**, 9174–9185.
- 72 J. Yeow and C. Boyer, *Adv. Sci.*, 2017, **4**, 1700137.
- 73 J. Xu, S. Shanmugam, H. T. Duong and C. Boyer, *Polym. Chem.*, 2015, **6**, 5615–5624.
- 74 R. N. Carmean, M. B. Sims, C. A. Figg, P. J. Hurst, J. P. Patterson and B. S. Sumerlin, *ACS Macro Lett.*, 2020, **9**, 613–618.
- 75 C. A. Figg, J. D. Hickman, G. M. Scheutz, S. Shanmugam, R. N. Carmean, B. S. Tucker, C. Boyer and B. S. Sumerlin, *Macromolecules*, 2018, **51**, 1370–1376.
- 76 Y. Zhou, Z. Zhang, C. M. Reese, D. L. Patton, J. Xu, C. Boyer, A. Postma and G. Moad, *Macromol. Rapid Commun.*, 2020, **41**, e1900478.
- 77 G. Xie, M. R. Martinez, M. Olszewski, S. S. Sheiko and K. Matyjaszewski, *Biomacromolecules*, 2019, **20**, 27–54.
- 78 S. S. Sheiko and A. V. Dobrynin, *Macromolecules*, 2019, **52**, 7531–7546.
- 79 M. Müllner, *Macromol. Chem. Phys.*, 2016, **217**, 2209–2222.
- 80 D. C. Lee, R. J. Lamm, A. N. Prossnitz, A. J. Boydston and S. H. Pun, *Adv. Healthcare Mater.*, 2019, **8**, 1800861.
- 81 T. T. Hoang Thi, E. H. Pilkington, D. H. Nguyen, J. S. Lee, K. D. Park and N. P. Truong, *Polymers*, 2020, **12**, 298.
- 82 H. Cabral, Y. Matsumoto, K. Mizuno, Q. Chen, M. Murakami, M. Kimura, Y. Terada, M. R. Kano, K. Miyazono, M. Uesaka, N. Nishiyama and K. Kataoka, *Nat. Nanotechnol.*, 2011, **6**, 815.
- 83 S. Kaga, N. P. Truong, L. Esser, D. Senyschyn, A. Sanyal, R. Sanyal, J. F. Quinn, T. P. Davis, L. M. Kaminskas and M. R. Whittaker, *Biomacromolecules*, 2017, **18**, 3963–3970.
- 84 C. H. J. Johnson, T. H. Spurling and G. Moad, *Polymers*, 2022, **14**, 5013.
- 85 Z. Huang, B. B. Noble, N. Corrigan, Y. Chu, K. Satoh, D. S. Thomas, C. J. Hawker, G. Moad, M. Kamigaito, M. L. Coote, C. Boyer and J. Xu, *J. Am. Chem. Soc.*, 2018, **140**, 13392–13406.