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Styrene-Maleimide/Maleic Anhydride Alternating Copolymers: Recent Advances and Future Perspectives

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Alternating sequencing of styrene-maleimide/maleic anhydride (S-MI/MA) in the copolymer chain is known for a long time. But since early 2000, this class of copolymers has been extensively studied using various living/controlled polymerization techniques to design S-MI/MA alternating copolymers with tunable molecular weight, narrow dispersity (*Đ*), and precise chain-end functionality. The widespread diverse applications of this polymeric backbone are due to its ease of synthesis, cheap starting materials, high precision in alternating sequencing, and facile post-polymerization functionalization with simple organic reactions. Recently, S-MI/MA alternating copolymers have been rediscovered as novel polymers with unprecedented emissive behavior. It outperforms the traditional fluorophores with no aggregation caused quenching (ACQ), aqueous solubility, and greater cell viability. Herein, the origin of alternating sequence, synthesis, and recent (2010-Present) developments in applications of these polymers in different fields are elaborately discussed, including the advantages of the unconventional luminogenic property. This review article also highlights the future research directions of the versatile S-MI/MA copolymers.

1. Introduction

An “alternating copolymer” is a special type of copolymer in which the two comonomers (M_1 and M_2) array themselves in a uniformly alternating pattern (....$M_1M_2M_1M_2M_1M_2$...). The alternating copolymers are produced when propagating species favor attaching themselves with the other monomer rather than its own kind of monomer.[1] In 1930, the first paper reporting alternating radical copolymerization of maleic anhydride (MA) and stilbene introduced the research community to the synthesis of these alternating copolymers.[2] Although the discovery was made a long time ago, the cross-propagation mechanism of reactive propagating species leading to alteration in the polymerization is not yet fully understood. Apart from the earliest Mayo–Lewis model, two important models such as the penultimate unit model and complex participation model have been put forward to explain the alternating behavior from a mechanistic point of view.[3] The limited combinations of comonomers, which can form alternating sequences, is the main reason behind its fewer material applications. However, some recent advances in methodologies for controlled synthesis of alternating copolymers have enabled the preparation of well-defined polymers with tunable properties and their implementation for broader applications. The interesting characteristic of the alternating copolymer is the periodicity as well as no sequence distribution. No consecutive sequence of identical units is also a significant feature of alternating copolymers, which makes them unique from corresponding random or gradient copolymers.[4]

It is very much well known that alternating copolymers can be obtained by copolymerization of electron-rich and electron-deficient monomers through the formation of charge-transfer complexes (CTCs). The most extensively investigated systems of this type are styrene (S)-maleimide (MI)/MA. The S-MA alternating copolymerization is one of the earliest studied systems. The studies by Alfrey and Levin showed that this polymer could be prepared at 70–80 °C using typical free-radical initiators.[5] The S-MA copolymers can be synthesized using free radical initiators like benzoyl peroxide (BPO), 2,2′-azobisisobutyronitrile (AIBN), while UV initiation,[6] spontaneous initiation,[7] and other initiators[8] were also reported. However, with conventional free radical copolymerization, the polymerization process is uncontrollable as no more than 50 mol% of MA could be incorporated in the copolymer due to its non-homopolymerizable nature.[5] This may lead to copolymers with compositional drifts[9] where segments with more MA and segments with less MA are statistically distributed along the chain, as evidenced by ^{13}C NMR study.[10]

For the past few years, impressive advancements have been achieved in the area of living/controlled free radical polymerization (FRP) techniques such as nitroxide-mediated polymerization (NMP), atom transfer radical polymerization (ATRP), reverse ATRP, and reversible addition-fragmentation chain transfer (RAFT) polymerization.[11,12] Controlled radical

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polymerization[13] provides better control over the alternating monomer sequence at an imbalanced infeed ratio.[14] Both NMP and RAFT are applicable for the synthesis of S-MA copolymers.[15] The ATRP seems incompatible for the preparation of S-MA copolymers which could be due to the interaction between MA and the copper complex, which is required for ATRP. However, the copolymerization[16] between styrene and *N*-substituted maleimides (RMIs) is possible using ATRP.[17,18] Using ATRP and alternating radical copolymerization, the synthesis of sequence-regulated vinyl copolymers with acidic and basic monomer units was also reported.[19] The synthesis of one-step P(S-*alt*-MA)-*b*-PS copolymers with highly alternating S and MA sequences was made possible with the NMP technique.[20] The RAFT polymerization technique can be employed for the one-pot synthesis of polyhedral oligomeric silsesquioxane (POSS)-containing alternating copolymers.[21]

The incorporation of MA augments the thermal resistance property of polystyrene (PS) proportional to the MA content.[22] The well-defined S-MA copolymers exhibit unique properties such as superior thermal stabilities,[23] fire resistances,[24] photo, X-ray, and electron-beam sensitivities,[25] catalytic and chiroptical activities,[26] and are extremely low bandgap materials.[27] The thermoplastic S-MA has a high glass transition temperature (T_g), high deflection temperature under load, chemical resistance, low melt flow rate, good impact, rigidity, and dimensional stability.[28] Non-chelating resins based on S-MA copolymers found application in removing heavy metal ions from aqueous solutions.[29]

The susceptibility of RMIs to homo- and co-polymerization by a free radical pathway has been known for quite some time. Due to their ability to function as photoinitiators, fire resistance properties, versatility, and high sensitivity in lithographic applications, ion-exchange characteristics, catalytic, and optical activities, a lot of attention have been given to RMIs with different functional groups during the last few years. Sinclair Petrochemicals commercialized it first in the 1960s, and in 1972, the injection molding S-MA resin found its first use in automotive dashboards by Nova (Arco) Chemicals using the trade name Dylark, although it is no longer produced.[30] In the packaging and construction industries, there is widespread usage of molding resin made of copolymers of MI and S. These copolymers are also used in alloys and plastic blends to enhance their mechanical and thermal performance. Apart from commercial and industrial purposes, in the past few years, these copolymers have found many applications in biomedical purposes like drug delivery, metal sensing, pH-responsive smart material, dye separations, etc. Adhesive and water-repellent materials are also produced by functionalizing the pendant hydroxy group of styrenic monomers and RMIs with long alkyl chains.[31] Aqueous foam stabilizer controlling morphologies and their related applications are also obtained from alternating copolymerization of S and *N*-phenylmaleimide (PMI).[32] Maleimide-based macromonomers with suitable functionalization can achieve high T_g, thermal stability, etc.[33] Photoresponsive properties were observed when *o*-nitrobenzyl alcohol-terminated amidoamine dendrons were attached as pendant side groups to S-MA alternating copolymer.[34] Physical gelation of alternating copolymers was observed by incorporating phenol in vinyl monomer and using a long alkyl pendant group in MI unit.[35] Therefore, to demonstrate the vast prospect of alternating copolymerization as a versatile tool for fabricating materials to meet the requirements for new applications under unusual conditions, an in-depth understanding of these alternating copolymers is essential.

In this review, we have highlighted the recent advancements (2010–Present) on the sequence-controlled S-MI/MA alternating copolymers based on their developed pathway of synthesis and how the basic research in this area has translated to diverse applications. We have started with discussing the origin of alternating sequence and relevant mathematical expressions. We also have described the developments in alternating copolymerization techniques leading to the synthesis of polymers with well-defined structures, controlled molecular weights, low dispersity (*Đ*), and precise chain-end. Thereafter, we have focused on the recent applications of these alternating copolymers in the field of drug delivery, dye separation, heavy metal separation, stimuli-responsive polymers, coating materials, etc. Recently, unusual fluorescence was reported from this class of alternating copolymers.[36] Thus, their properties as non-conventional luminogen and possible applications have been discussed in detail in this review. By enlightening the unique properties of these types of alternating copolymers, we hope to present new insights not only into the fundamental research challenges and associated broad and in-depth interdisciplinary questions but also its practical applications and potential future perspectives in biomedical and environmental uses.

2. Origin of Alternating Sequence

When two monomers M_1 and M_2 are mixed together in the presence of an initiator, the monomers may combine in several ways. Among those, the combination in which M_1 and M_2 units are arranged in an alternating sequence throughout the chain will lead to the formation of an alternating copolymer (....$M_1M_2M_1M_2M_1M_2$....). During the propagation step, the propensity of each monomer to add to the chain can be quantified considering a simple sequence of reactions of chain propagation via a radical chain carrier. Du Plessis was the first,[37] who made an assumption that the nature and size of the radical chain do not influence the propagation rate of the polymer chain and the rate is dependent only on the nature of the radical end group and the incoming monomer which is also referred as Mayo–Lewis model or terminal model.[38] The four reactions proposed in the classical "terminal" model are shown in **Figure 1**. Assumption of steady-state conditions for the four elementary reactions leads to an equation where instantaneous copolymer composition (m_1/m_2) relates to the composition of monomers in the reaction mixture ($[M_1]/[M_2]$).[39]

$$\frac{m_1}{m_2} = \frac{[M_1]}{[M_2]}\left(\frac{r_1\,[M_1]+[M_2]}{r_2\,[M_2]+[M_1]}\right)\quad r_1 = \frac{k_{11}}{k_{12}},\ \ r_2 = \frac{k_{22}}{k_{21}} \tag{1}$$

The parameters r_1 and r_2 are monomer reactivity ratios that are the ratio of the rate constant of homopropagation to the rate constant of cross-propagation of each reactive propagating species, which provides the extent of bias a radical possess when reacting with its own kind of monomer compared to the comonomer in the reaction mixture.[4] An alternating copolymer formation is defined as the products of reactivity ratios of two monomers

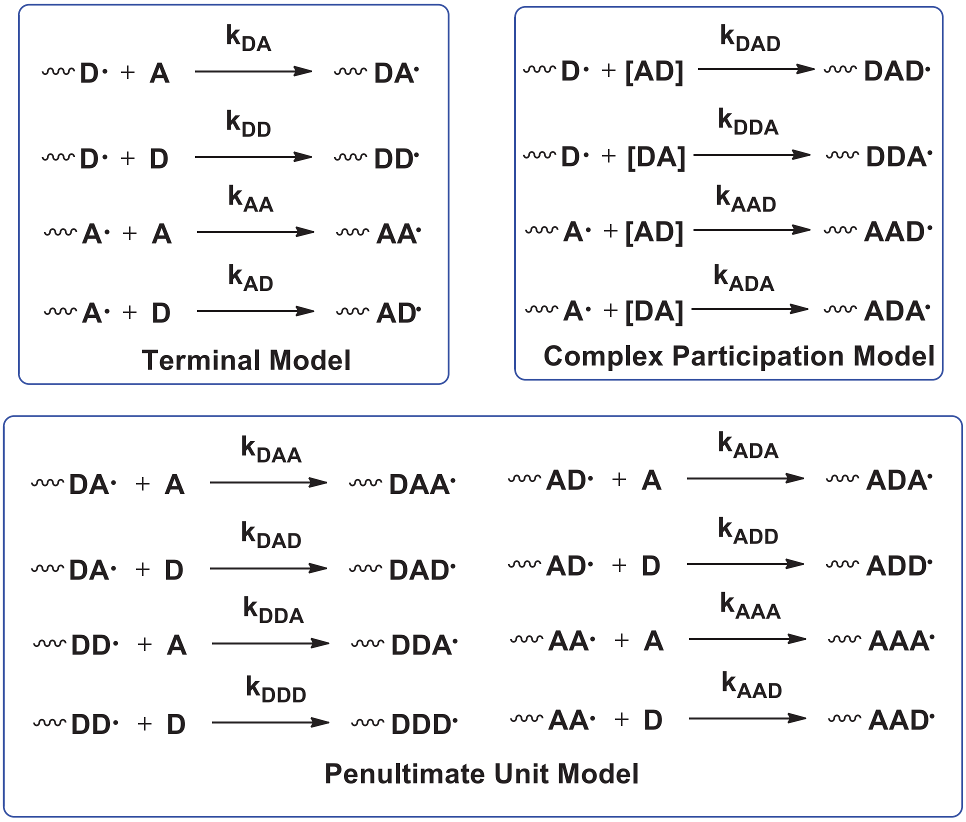


Figure 1. Illustration of three models of the mechanism of alternating copolymerization. A and D represent acceptor and donor monomers, respectively.

$r_1 r_2 = 0$, which means instead of reacting with its own kind of monomer, each propagating species preferably reacts with the other kind of monomer. When r_1 and r_2 are both equal to zero and no dyad or homo-addition are found in the copolymer, perfect alteration is obtained. If the r_1 and r_2 are very small or one r is small and the other r is zero, the copolymer still exhibits an alternating pattern but does not follow the strictly alternating sequence. One drawback of the terminal model is that it cannot explain the relationship between rate constant and monomer feed composition.[40]

Several other models have been proposed to analyze the alternating behavior from a mechanistic point of view. By using the penultimate unit model (Figure 1),[40] this relationship could be explained where the propagation rate of the polymer chain is assumed to be not only dependent on the terminal radical but also the penultimate monomer unit.[41,42] The theoretical calculations give one plausible interpretation that the transition state of the propagation step can be described as three hindered rotors, one rotor being significantly influenced by the penultimate monomer unit.[43]

In the complex participation model (Figure 1), it was proposed that electron-donor and electron-acceptor monomer pairs interacting with each other from the charge-transfer complex, which participates in this copolymerization.[44,45] Although spectroscopic evidence confirms the existence of CTC,[46,47] it still remains unclear whether the proposed CTCs add to the propagating radical species or they dissociate upon polymerization,[48] and only one monomer is added to the propagating chain each time.[49,50] On the whole, argumentation about the exact mechanism behind this alternating behavior is persisting and incessant efforts are being made to study mechanistic steps of alternating copolymerization.

3. Styrene-Maleimide/Maleic Anhydride Alternating Copolymerization Techniques

Some of the alternating copolymer forming comonomer systems are electron donor-acceptor pairs,[51] zwitterion intermediates,[52] metallocene or Ziegler–Natta catalyzed *cis*-olefins and ethylene,[53] complexes formed with Lewis acids,[54] etc. Among these, the systems of particular interest for this paper are electron donor-acceptor pairs where electron acceptor monomers are MA, MI, or RMIs and electron donor monomer is S or substituted S. The copolymerization techniques for synthesizing such alternating copolymers and their developments in recent years are discussed below.

3.1. Free Radical Polymerization

After the earlier investigations by Alfrey et al.[5] verifying the synthesis of S-MA (**Figure 2**A) using a free radical initiator, the S-MA became one of the most widely studied systems. Alternating copolymers with S as electron-rich monomer and MA or RMIs as electron-deficient monomers were mostly prepared using FRP techniques using most commonly used initiators such

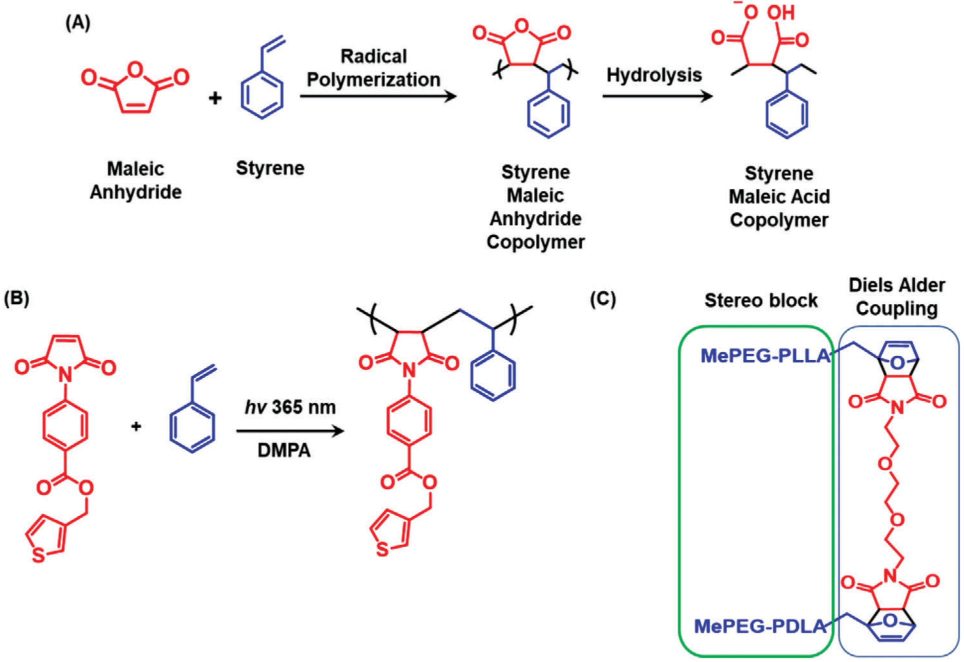


Figure 2. A) Preparation of S-MA via free radical copolymerization. B) Synthesis of S and thiophene-containing PMI-based copolymer via photoinduced radical polymerization. C) Copolymers of RMIs with S derivatives bearing various α-substituents.

as BPO and AIBN. In addition, some other initiators, UV initiation, and spontaneous initiation were also employed for the synthesis of S-MA.[8,10] The *N*-4-carboxybutylmaleimide (NBMI) has been reported to form alternating copolymers with S at 60 °C using AIBN as an initiator and chloroform as solvent via free radical copolymerization with the conversion of 33–83 wt.%.[55] Although FRP and copolymerization of S with RMIs producing nearly alternating copolymer through the formation of CTC have already been reported in many papers, Yilmaz et al. chose photoinduced radical polymerization to prepare the alternating copolymers of thiophene-containing PMI with S at room temperature (Figure 2B).[56] The ω,ω-dimethoxy-ω-phenyl acetophenone (DMPA) was used as the photoinitiator for the synthesis. Photopolymerization pathway is seemingly the promising method for the fabrication of S-MA alternating copolymer due to the following reasons: a) higher temperature leads to a decrease in electron donor-acceptor complex formation (exothermic), b) lower temperature leads to an increase in copolymer stereoregularity by the increasing equilibrium constant for complex formation, and also c) photopolymerization excludes any possibility of competition between thermal Diels–Alder and addition polymerization. Two different solvents (benzene and dichloromethane) were employed for polymerizations (with the same feed ratio of comonomers) to observe the influence of reaction conditions on the characteristics of obtained polymeric materials.

Even though well-known organic solvents like *N*,*N*-dimethylformamide (DMF), carbon tetrachloride, tetrahydrofuran (THF), benzene, acetone have been used as media for FRP for the synthesis of S-MA copolymers, supercritical carbon dioxide (CO_2) has proven to be suitable synthesis media for preparing ultrahigh molecular weight S-MA copolymers. Radical copolymerization of S and MA in supercritical CO_2 at 50–80 °C using AIBN has been reported.[57] As the chance of CTC generation of S and MA increases with high pressure, low temperature, and weak polarity, favoring the alternating copolymerization, supercritical CO_2 has proven to be a preferred alternative because of its non-polarity, tunable versatile properties like solvent strength, low dielectric constant, and viscosity.[58] The use of supercritical CO_2 as media for synthesis of S-MA copolymer has outgrown the controlled living radical copolymerization techniques like ATRP, RAFT as they were unable to bring the strictly alternating behavior in the copolymers. Also, because of its large swelling effects and low viscosity supercritical CO_2 enhances the transportation of monomers into polymer particles by increasing the propagation rate. It also decreases the termination rate by restricting the diffusion of active polymer chains due to chain entanglements. As a result, the obtained S-MA copolymer has an alternating sequence and a high molecular weight ($>10^6$ g mol^{-1}).

Free radical copolymerization of MI-based benzoxazine and S at 60 °C in dimethylsulfoxide (DMSO) with AIBN as initiator was reported to give alternating copolymer with high thermal resistance properties.[59] Hisano et al. reported free radical alternating copolymerization of RMIs like *N*-methyl, *n*-butyl, 2-ethylhexyl groups with S derivatives with various α-substituents like methyl, ethyl, *n*-propyl, isopropyl, phenyl in 1,2-dichloroethane at 60 °C using AIBN as an initiator (Figure 2C).[60] The yield and molecular weight of the resulting copolymers were independent of *N*-substituents. But, the yield and molecular weight of the copolymers significantly decreased with the increase in the size of α-substituents of styrene derivatives due to their steric effects rather than electron-donating nature.

3.2. "Living"/Controlled Polymerization

Copolymerization of S with MA or RMIs by conventional FRP produces alternating copolymers under selected conditions, however, it poses some disadvantages. In conventional FRP, rapid chain growth and a short lifetime of chains lead to ambiguity in molecular weight and molecular weight distribution (dispersity, *Đ*). Additionally, it leads to broad and complex chemical-composition distribution unless the composition of the monomer is controlled. The chains formed at the early stages of polymerization have a different composition to those formed later. To achieve similar properties between all chains, ensuring the increment of the lifetimes of chains and their ability to propagate for the total reaction time is essential. To achieve this goal, living radical polymerization techniques have been developed. In recent years, much attention has been given to prepare S-MA or S-RMI copolymers through controlled living radical polymerization techniques, some of which are discussed below.

3.2.1. Reversible Addition-Fragmentation Chain Transfer (RAFT) Polymerization

In alternating copolymerization, RAFT agents play a pivotal role, as they influence the rate of reaction. At the initialization period, the RAFT agent combines with S or MA to form a monomer adduct depending on the electronic structure of the RAFT agent, that is, electron-rich RAFT agent would prefer to combine with MA. This initialization period was found by van den Dungen et al., and the initialization behavior of RAFT-mediated S and MA copolymerization using 2-cyanoprop-2-yl dithiobenzoate (CIPDB) and cumyl dithiobenzoate (CDB) as RAFT agents was investigated at 60 and 70 °C, respectively. CDB predominantly adds one MA unit, whereas the CIPDB mainly forms a monomer adduct with S at the initialization period.[61] De Brouwer et al. copolymerized S and MA via RAFT polymerization resulting in copolymers with predetermined molecular weight and narrow *Đ*, but they were unsuccessful in preparing strictly alternating copolymer.[62] You and co-workers employed the RAFT method for performing copolymerization of S with MA at 22 °C in the presence of dibenzyl trithiocarbonate (DBTTC) and the absence of any initiator.[63] The synthesized copolymers possessed a well-defined alternating structure as evidenced by distortionless enhancement by polarization transfer (DEPT) experiments and mole fraction data obtained from ^{13}C NMR. Zhu et al. reported the copolymerization of MA with S at 80 °C using (*S*)-benzyl dithiobenzoate (BTBA) with AIBN as RAFT initiating system resulting in alternating copolymer S-MA.[64] The same RAFT copolymerization of MA and S with a molar feed of 1:9 at 60 °C produced a well-defined block copolymer poly(S-*alt*-MA)-*b*-poly(S) (PSMA-*b*-PS) indicating that the copolymerization involves simultaneous incorporation of MA and S resulting in the alternating copolymer. Moreover, the consumption of pure S for the continuation of chain propagation happens after the MA has been exhausted. Harrisson et al. have demonstrated one-pot synthesis of AB and ABA block copolymers from MA and S via the RAFT method using a similar synthetic strategy (**Figure 3**A).[65] They have also shown the subsequent formation of micelles and shell-crosslinked nanoparticles from these block copolymers.

In a reported ATRP polymerization of S to form comb-like polymers, the macroinitiator used was prepared via RAFT copolymerization of PMI and *p*-chloromethyl styrene (CMS) using AIBN as initiator and 2-(ethoxycarbonyl)prop-2-yl dithiobenzoate as RAFT agent producing alternating copolymers with controlled molecular weight and narrow *Đ*.[66] Zhang and co-workers reported one-pot synthesis of poly(S-*alt*-maleimide isobutyl POSS) alternating copolymer and poly(S-*alt*-maleimide isobutyl POSS)-*b*-poly(S) block copolymer via RAFT copolymerization at 65 °C with AIBN as initiator and CDB as chain transfer agent using 1,4-dioxane as solvent.[21] Weiss et al. employed the RAFT polymerization method along with ATRP for one-step synthesis of tapered diblock copolymers by copolymerizing an excess of functionalized styrene monomer, (4-vinylbenzyl methoxytetrakis(oxyethylene) ether) with various RMIs, where one block contains the alternating structure of S and MI monomer units.[67]

3.2.2. Atom Transfer Radical Polymerization (ATRP)

Due to the interaction between MA and the copper complex required in ATRP, this copolymerization technique seems incompatible for S-MA synthesis. However, the ATRP method can be used in alternating copolymerization for the electron donor-acceptor comonomer system (S being the electron donor monomer) when the electron-deficient monomer is RMI. Chen et al. successfully carried out controlled living ATRP of S and RMIs with *N*-substituents being 2-acetoxy-ethyl and phenyl using a catalytic system (1-phenylethyl bromide/CuBr/bipyridine) at 80 °C (Figure 3B).[16] Zhao et al. reported ATRP of S and RMIs such as PMI, *N*-butyl maleimide, and *N*-cyclohexyl maleimide.[18] The polymerization was performed in an ionic liquid media 1-butyl-3-methylimidazolium hexafluorophosphate ([bmim][PF$_6$]) using dendritic polyarylether 2-bromoisobutyrates with different generations (Gn-Br, n = 1–3) as macroinitiators and CuBr/pentamethyldiethylenetriamine (PMDTA) as the catalytic system at room temperature with vigorous stirring. The use of ionic liquids prevented contamination of products as it made the catalyst removal process easier and more efficient and also contributed to producing strictly alternating structures in the resulting polymer. Jiang et al. reported ATRP polymerization of CMS with *N*-cyclohexyl maleimide in cyclohexanone and anisole using CuCl/2-2′bipyridine as a catalytic system where CMS acted as both initiator and monomer (inimer) to produce a hyperbranched copolymer.[17] Similar preparation of hyperbranched copolymer was reported by Quiang et al. by ATRP, where the *N*-substituent of RMI was 4-α-bromobutyryloxy phenyl and synthesis media was 1-methyl-2-pyrrolidone, but in this case, the maleimide acted as inimer instead of the styrene.[68]

3.2.3. Nitroxide Mediated Polymerization (NMP)

Nitroxide mediated polymerization (NMP) can be employed for the synthesis of both S-MA and S-RMIs alternating copolymers. Lokaj et al. reported thermal radical copolymerization of S with MI in diglyme at 125 °C in the presence of 2,2,6,6-tetramethylpiperidin-1-yloxyl (TEMPO) radical producing functional copolymers with narrow *Đ*.[69] Lessard et al.

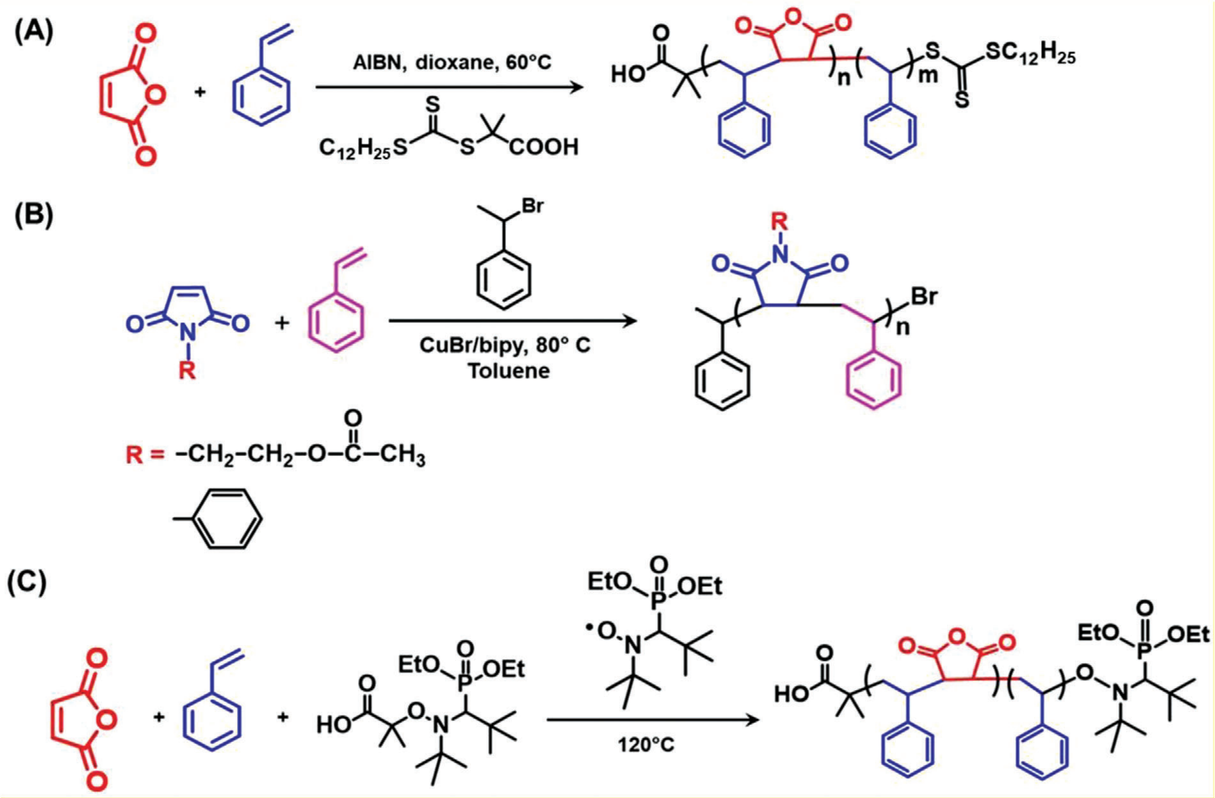


Figure 3. A) Preparation of PSMA-*b*-PS via RAFT polymerization. B) Synthesis of copolymers with S and different RMIs using ATRP. C) PSMA-*b*-PS synthesis via NMP.

demonstrated a synthetic strategy where they showed that performing S-MA copolymerization at 80–110 °C in 50 wt. % 1,4-dioxane using 5 mol % {*tert*-butyl-[1-(diethoxyphosphoryl)-2,2-dimethylpropyl]amino}oxidanyl (SG1) relative to 2-({*tert*-butyl-[1-(diethoxyphosphoryl)-2,2-(dimethylpropyl)amino}oxy)-2-methylpropionic acid (BlocBuilder), one-step synthesis of PSMA-*b*-PS copolymers (Figure 3C) possessing strictly alternating sequence is possible.[20] The BlocBuilder enabled the polymerization of these one-step block copolymers with a strictly alternating S-MA first block by NMP.

3.2.4. Other Techniques

Other controlled polymerization techniques have also been applied for the copolymerization of S with MA or RMIs. Wu et al. reported solution copolymerization of S with MA in THF at room temperature under UV irradiation in the presence of 1-(ethoxycarbonyl)prop-1-yl dithiobenzoate (EPDTB).[7] The polymerization was "living" in nature as evidenced by linear evolution of molecular weight with conversion and production of alternating copolymers with narrow *Đ*. Ishizu et al. synthesized alternating hyperbranched copolymers via controlled radical copolymerization of maleimide with *N*,*N*-diethyldithiocarbamyl)methylstyrene (DTCS), which acted as an inimer under UV light irradiation.[70] Nishimori and co-workers conducted copolymerization of S with *N*-ethyl maleimide via a halogen-free cationic Ruthenium complex-catalyzed living radical polymerization with malonate-based bromine initiator in toluene at 60 °C (**Figure 4**A).[71]

The polymeric iniferter technique as discovered by Otsu[72] is a radical polymerization process where iniferter refers to a class of free radical initiators that can simultaneously undergo chain transfer and polymer radical termination processes. In this type of polymerization, chain transfer to the initiator and primary radical termination are far more crucial than bimolecular termination, which is a predominant step in conventional radical polymerization, for which this can be considered as a repeated insertion of monomer between a disulfide linkage. Suwier et al. reported copolymerization of S with PMI and *N*-methylmaleimide thermally initiated by polytetrahydrofuran (PTHF)-1000-based iniferter, which occurs via an insertion mechanism between disulfide bonds of PTHF iniferter.[73] Soejima and co-workers demonstrated the synthesis of main-chain and side-chain sequence-regulated vinyl copolymers.[19] First of all, they prepared a complete set of maleimide-ended sequence-regulated oligomonomers consisting of trimeric vinyl monomer units of styrene via atom transfer radical additions (ATRAs) by choosing appropriate metal catalysts for side-chain control. Then they radically copolymerized the oligomonomers with styrene in alternating 1:1 AB-fashion for main-chain control (Figure 4B).

Along with the development of the linear S-MA copolymers, researchers have also engineered different types of polymer

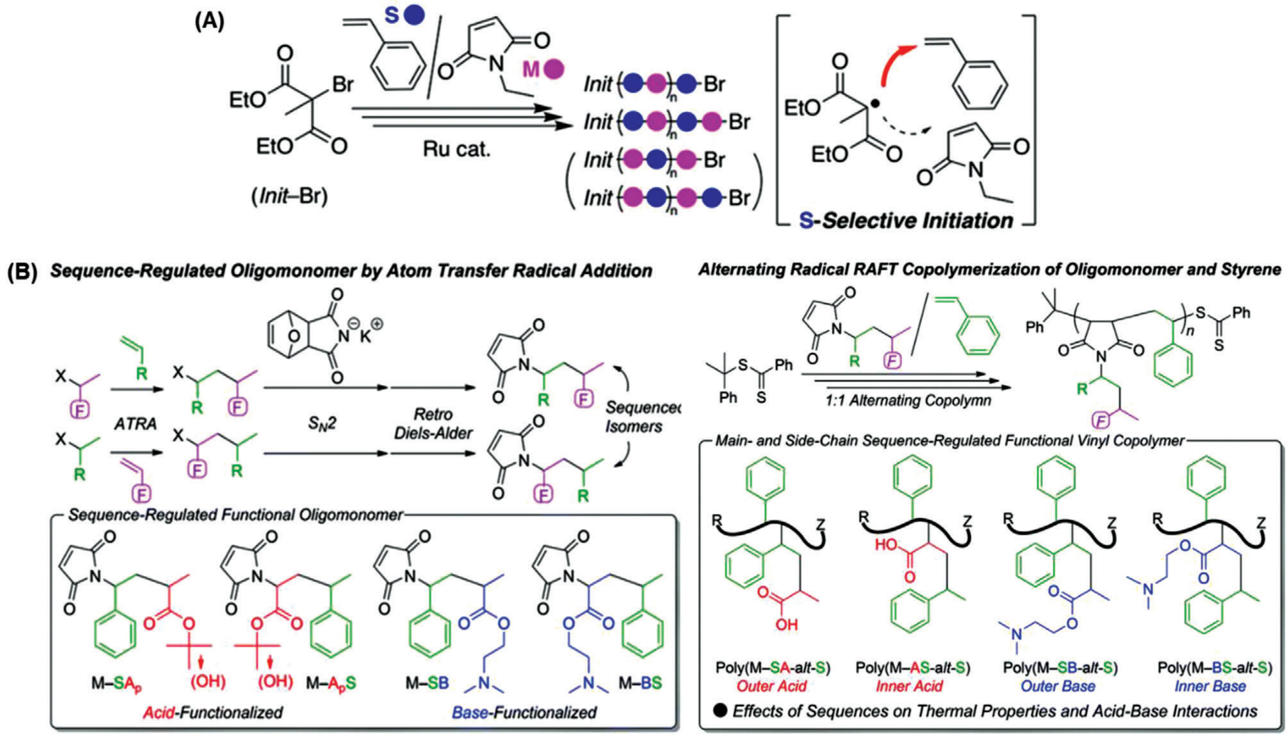


Figure 4. A) Synthetic scheme of copolymerization of S and EMI (M) via ruthenium-catalyzed living radical polymerization with a malonate-based bromine initiator. Reproduced with permission.[71] Copyright 2018, Wiley Periodicals. B) Synthesis of sequence-regulated oligomonomers and their alternating 1:1 and 2:1 radical copolymerization and homopolymerization for main- and side-chain sequence-regulated vinyl copolymers. Reproduced with permission.[19] Copyright 2016, Royal Chemical Society.

brushes where the main backbone was made of S-MA alternating copolymer and the polymeric side-chains were fabricated mainly by incorporating chain-transfer agents of RAFT,[74,75] ATRP initiator,[76,77] ring-opening polymerization (ROP) initiating moiety,[78,79] and covalently attached poly(ethylene glycol) (PEG) chains.[80] A variety of polymeric architectures were developed by these polymeric brushes. Stimuli-responsive hierarchical self-assembly was also achieved.[81]

4. Applications of Alternating Copolymers

Due to their unique structural properties, particular functionalities, optical and catalytic activities, and hydrophobic-hydrophilic content, alternating copolymers of S-MA or S-RMIs find applications in a broad spectrum of fields such as stimuli-responsive polymers, drug delivery, and other biomedical applications, dye separation, heavy metal separation, non-conventional luminogen, etc. (**Figure 5**). In this section, we will review the modification of these alternating copolymers to provide a reactive site upon exposure to various chemical environments. We will also discuss the preparation of several important functionalized polymers using this chemistry and their practical applications.

4.1. Stimuli-Responsive Polymers

Alternating copolymers of S-MA can be modified to produce stimuli-responsive polymers or "smart polymers" that are sensitive to certain external environmental triggers, including temperature, light, chemical environment, electric field, etc. Graft copolymers could be synthesized by reacting methoxy poly(ethylene glycol) (mPEG) lithium alcoholates of contrasting molecular weights onto the alternating copolymers of MA with S and 4-*tert*-butylstyrene.[82] The resulting amphiphilic copolymers (SMA-*g*-PEG350) showed thermoresponsive and pH-responsive properties (**Figure 6**). These graft copolymers exhibited lower critical solution temperature (LCST) in an aqueous medium, which is dependent on the PEG chain length. With increasing PEG chain lengths, the polymers became soluble even under acidic conditions and exhibited an increase in LCSTs and phase transition temperature as the hydrophilicity of the polymer increased. The LCST increased rapidly with the increase in pH of the solution (Figure 6). At high pH, the carboxylic acid is ionized, which disrupts the intra/intermolecular *H*-bonding and suppresses the hydrophobic interactions between S units. The ionization also increases polymer-water interaction. All these factors elevate the phase transition temperature. Overall, these graft copolymer solutions showed LCST in the range of 33.7 to 74.7 °C in response to pH, salinity, additives, and polymer compositions. Therefore, they have potential applications in the field of pH/temperature-responsive hydrogels and surfactants.

The S-MA can be modified by reacting the MA group with primary alkylamines like propylamine, butylamine, and pentylamine to obtain S-MA alkylamide copolymers, which exhibited pH-dependent membrane destabilizing activity.[83] The modified copolymer exhibits pH sensitivity because of having a

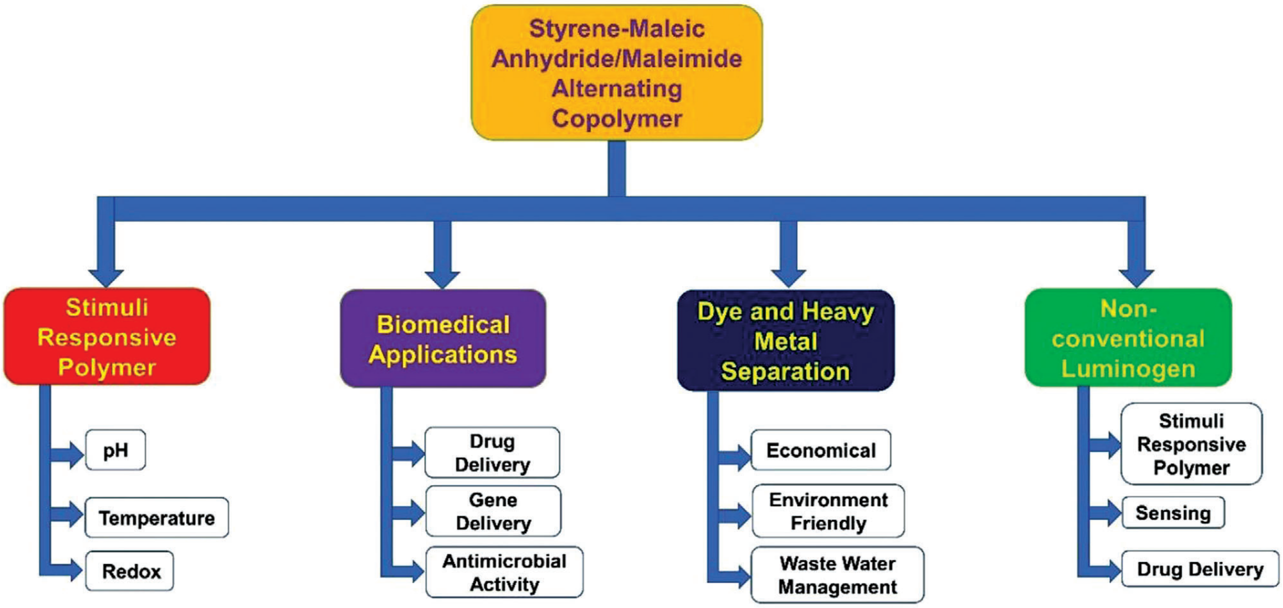


Figure 5. Diverse applications of styrene-maleic anhydride/styrene-maleimide alternating copolymers.

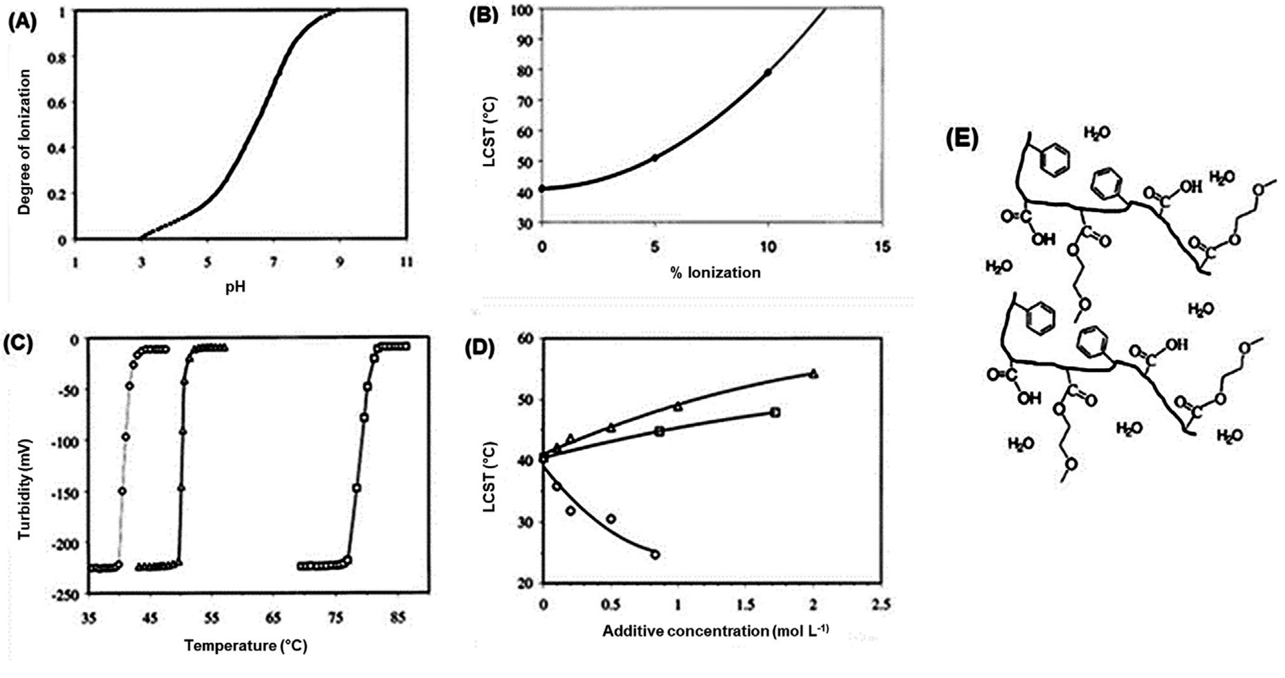


Figure 6. Dependence of the phase transition of pH-sensitive and thermosensitive SMA-*g*-PEG350 copolymers: A) Structure of SMA-*g*-PEG350. B) pH dependence of the degree of ionization of SMA-*g*-PEG350. C) Dependence of the LCST of SMA-*g*-PEG350 on the degree of ionization. D) Dependence of the phase transition of SMA-*g*-PEG350 solution on pH: (○) pH 3.0, (Δ) pH 3.5, (□) pH 4.5. E) Effects of additives on the phase transition temperature of SMA-*g*-PEG350 in aqueous solution at pH 3.0. Trend lines are second-order polynomials: (○) NaCl; (□) EtOH; (Δ) urea. Reproduced with permission.[82] Copyright 2002, American Chemical Society.

carboxylic acid group and alkylamide linkage. Thus, the copolymers are hydrophilic and membrane-inactive at physiological pH, but become hydrophobic and membrane-disruptive in response to endosomal pH. By varying the length of alkylamine groups, the molecular weight of the S-MA backbone, degree of modification; the membrane-disrupting activity of these copolymer derivatives can be engineered to act within specific pH ranges.

A smart, electro-active polymer actuator was prepared by using an ionic crosslinking membrane of poly(S-*alt*-MI) (PSMI)-conjugated with poly(vinylidene fluoride) (PVDF) to enhance the mechanical and electrical efficiency of artificial muscles

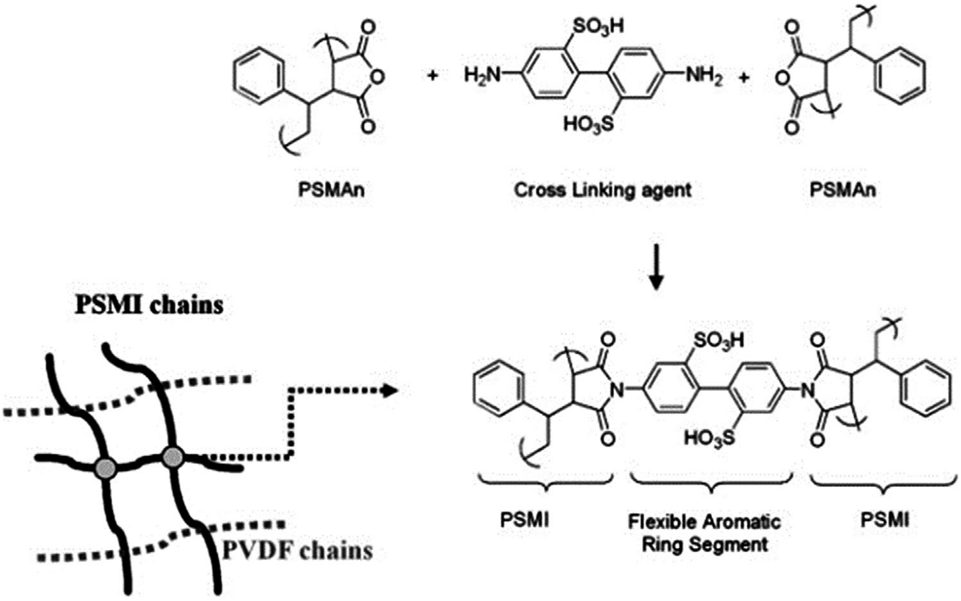


Figure 7. Schematic illustration and chemical structures of the ionic membrane network used to develop an electro-active polymer actuator composed of PSMI and a flexible aromatic ring segment of sulfuric acid groups. Reproduced with permission.[84] Copyright 2008, Wiley-VCH GmbH.

(**Figure 7**).[84] The membrane retained important characteristics of Nafion such as thermal, mechanical, chemical stability due to the presence of the PVDF component. Moreover, compared with Nafion, the cost of the final membrane was reduced with the introduction of the MI unit. The MI unit was also responsible for increasing the thermo-oxidative stability of the copolymer. In addition, due to the lower content of fluorine in the copolymer compared to Nafion, the copolymer is more environment-friendly. The PSMI copolymer chains could be used for cross-linking (flexible sulfonated aromatic diamine was used as crosslinking agent), which along with mechanical stiffness could result in hierarchical and striated structures of real muscles in the membrane. Due to the inherent large ionic exchange capacity and the unique hydrophilic nanochannels of ionic networking membrane, the present actuator overcame the drawbacks faced by previous ionic polymer-metal composite actuators like straightening-back and relaxation under the constant voltage excitation. This actuator also exhibited much larger tip displacement than that of Nafion-based actuators.

Dendronized polymers were prepared by conjugating butylamide terminated poly(amidoamine) dendrimers to the MA of S-MA alternating copolymer and modified polymers showed dual thermo- and pH-responsive properties (**Figure 8**).[85] All the dendronized polymers exhibited LCSTs. Moreover, with the increasing generation of dendrons, although the degree of coverage decreased, the number of amide moieties per dendrimers enhanced, which increased hydrophilicity of the polymer by forming *H*-bond interactions with water molecules. This resulted in an increase in LCST and decreasingly sensitive phase transition temperature. The thermo-responsive properties of these polymers were also dependent on the ionic strength and concentration of salt. The zwitterionic dendronized copolymers showed sensitivity to pH changes due to the presence of the tertiary amino groups in the pendant dendrimer and carboxylic acid groups in the main chain. Overall, due to the reversible character of the thermo-responsive behavior and the tunability of LCSTs by changing the generation and coverage degree of the dendrimer or by altering the concentration of the polymer solutions or adding salt and varying pH; these stimuli-responsive dendronized polymers can be potential candidates for sensors, separation materials, drug delivery, etc.

Polymerizing 4-vinylbenzyl methoxytetra(oxyethylene) ether with various RMIs, various alternating polymers were prepared. By changing the length of the side-chain, the phase transition temperature could be tailored while maintaining a well-defined chemical structure.[86] The changes in phase transition temperature cannot be explained by following the trend of increasing or decreasing hydrophobic-hydrophilic balance. In this regard, the distribution of hydrophobic and hydrophilic segments in the polymer chain also plays a crucial role. Interestingly, alternating copolymers derived from the copolymerization of 4-vinylbenzyl methoxytetra(oxyethylene) ether and hydrophobic motif-containing RMIs exhibited macroscopic phase separation in an aqueous medium and above the cloud point temperature. Moreover, the polymers formed mesoglobules above their phase transition temperature when the hydrophobicity was increased in the pendant side-chains.

A series of dendronized copolymers were synthesized by grafting *o*-nitrobenzyl-terminated amidoamine dendrons with amine groups at the focal point onto the backbone of S-MA via a ring-opening reaction.[34] Since UV light (300–365 nm) cleaves the *o*-nitrobenzyl groups, this inducing the photoisomerization of *o*-nitrobenzyl alcohol derivatives to *o*-nitrosobenzaldehyde, all the polymers being jacketed by those *o*-nitrobenzyl group decorated amidoamine dendrons, exhibited photolabile properties. The dendronized polymer with better hydrophobic-hydrophilic balance in its architecture would form aggregates more easily and these aggregates could be disintegrated and become loose

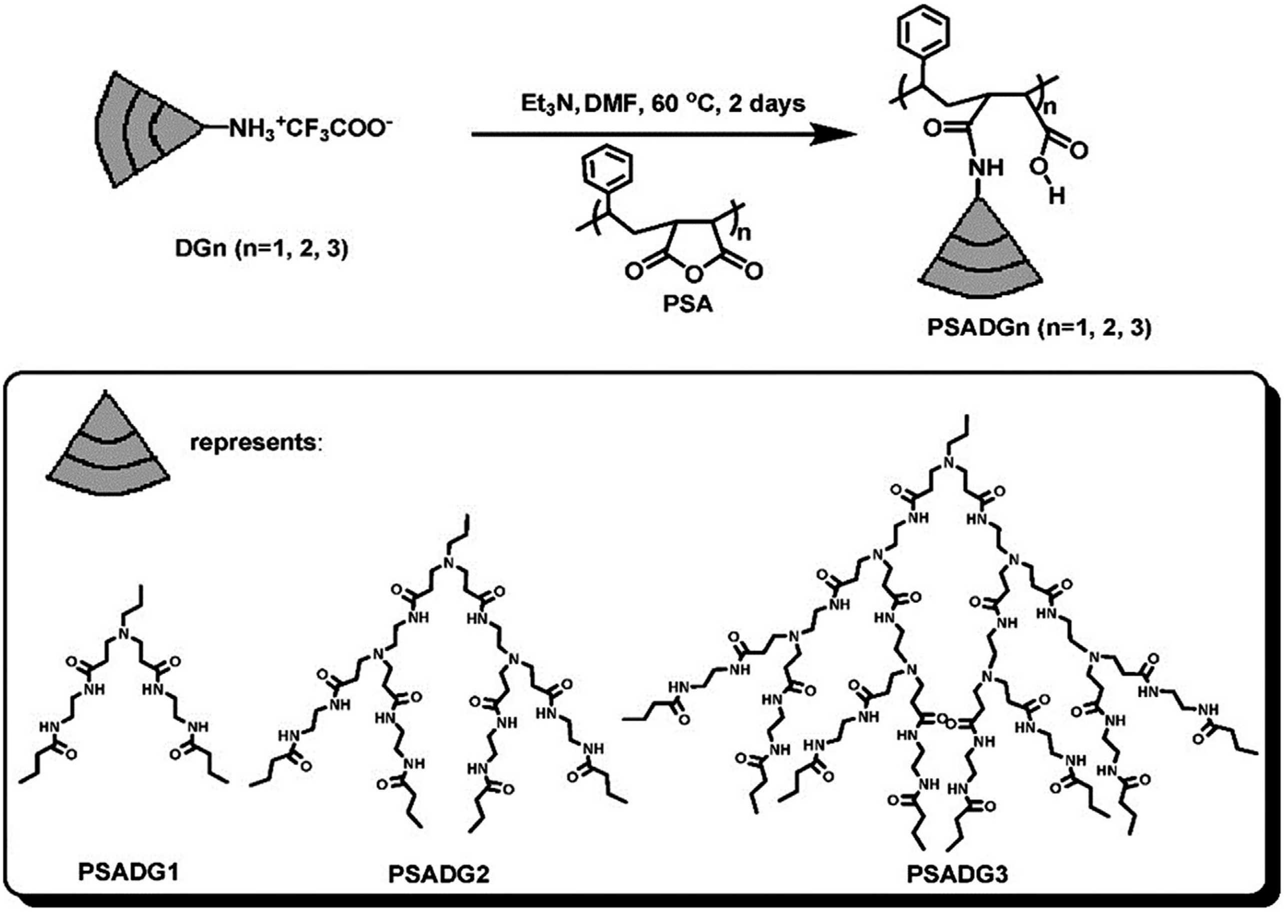


Figure 8. Synthesis and structures of S-MA dendrimers. Reproduced with permission.[85] Copyright 2009, American Chemical Society.

under UV-light irradiation. These properties led to the investigation of guest encapsulation and release properties of these polymers. From these studies, stable encapsulation in the absence of UV-light and release of payload upon UV-light irradiation via disintegration of the aggregates were observed. All these interesting features made the photoresponsive dendronized copolymers potential candidates for drug delivery systems.

4.2. Drug Delivery and Other Biomedical Applications

The S-MA alternating copolymers have shown great promise in biomedical science either by being suitable prefabricated polymer systems for the drugs to be attached or polymerizing drug-containing monomers. The S-MA has the convenience of being used for the preparation of multi-functional polymers, as hydroxy or amino groups containing active agents can react with the MA unit via ring-opening reaction. For example, the S-MA was reacted with 4-aminophenol (AP) to obtain MA-AP conjugate containing carboxyl and amide groups.[87] The AP was chosen as an active agent for phenols as they are known for their antimicrobial properties, and as expected, the SMA-AP conjugate exhibited strong bactericidal activities against both gram-negative (*E. coli*) and gram-positive (*S. aureus*) bacteria, though no inhibition zone was found. The bactericidal activity of SMA-AP is suspected to arise from phenylic hydroxyl groups and is expected to be retained for quite a long period of time as the polymer conjugate does not undergo hydrolysis in similar conditions.

A series of poly(S-*co*-(S-*alt*-MA)) and S-MA derivatives (**Figure 9**) were synthesized by hydrolysis and amidation reaction to investigate their anti-HIV microbicidal activity.[88] Hydrolysis of S-MA with sodium hydroxide produced poly(S-*alt*-(maleic acid, sodium salt)), termed as poly(S-*alt*-MAA) (Figure 9) which exist as negatively charged linear polymers in aqueous solution. On the contrary, poly(S-*co*-(S-*alt*-(maleic acid, sodium salt))), designated as PS-COONa (Figure 9) acquired from poly(S-*co*-(S-*alt*-MA)) is an amphiphilic diblock copolymer. It can self-assemble to form hairy micellar nanostructures in an aqueous medium. The shell of the nanostructure is composed of multimeric hydrophilic linear poly(S-*alt*-MAA) chains and the core contains the PS blocks. Amidation of poly(S-*co*-(S-*alt*-MA)) was done by reacting it with aminoethyl derivatives of mannopyranoside and glucopyranoside separately which also resulted in the formation of micellar nanoparticles. All the derivatives showed low cell toxicity and effectively inhibited HIV-1 infections in an in vitro cellular model, out of which poly(S-*alt*-MAA) was most suitable and has higher effectivity than most microbicides. Although the inhibition efficiency of PS-mannose was comparable with PS-COONa, PS-mannose can be used as a contraceptive microbicide because they tend to bind and aggregate the human sperm.

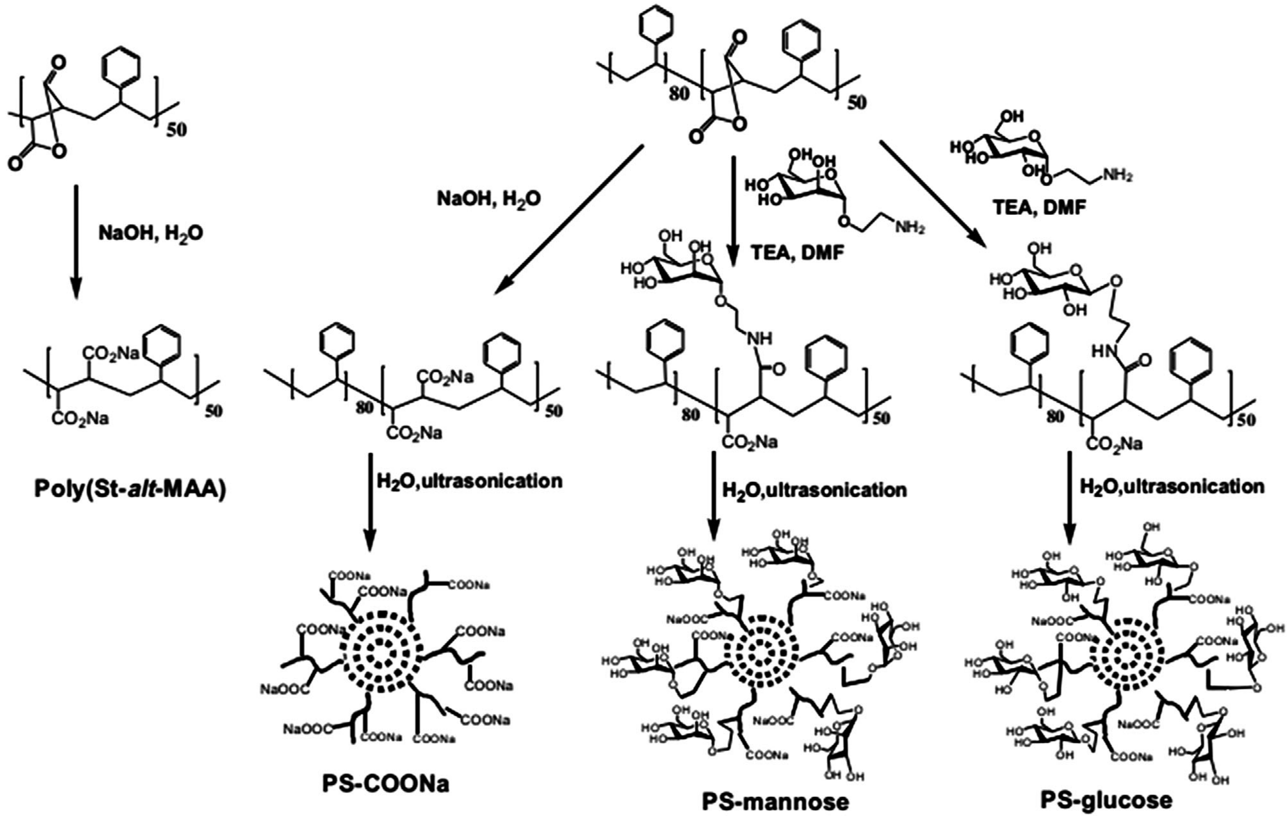


Figure 9. Synthetic routes and morphologies of S-MA derivatives as potent anti-HIV microbicide candidates. Reproduced with permission.[88] Copyright 2009, Elsevier.

Cylindrically shaped and defect-free microfibers were prepared by electrospinning of mixed solutions of S-MA alternating copolymers.[89] On these electrospun mats, poly(propylene glycol) monoamine (Jeffamine M-600), 5-amino-8-hydroxyquinoline ($5NH_28Q$), and a chlorhexidine (CHX) were grafted separately. Moreover, Jeffamine-grafted microfibrous mats were treated with iodine vapor or iodine solutions to obtain iodine complexes of Jeffamine-grafted mats. All these modified mats exhibited antimicrobial and antimycotic activities against *S. aureus, E. coli,* and *C. albicans* due to the covalently bonded biocidal agents like CHX, $5NH_28Q$, and iodine complex of Jeffamine. They also inhibited the adhesion of pathogenic bacteria *S. aureus* and hence showed potential for a variety of applications, including medical devices, protective clothing, antimicrobial filters, and bandages.

In another study, two systems were developed to compare the controlled release of antibiotic ceftriaxone.[90] One of which loaded ceftriaxone by reacting the antibiotic with MA units of the S-MA copolymer. Another system was prepared by physical loading of ceftriaxone on the amine-modified S-MA hydrogels obtained by amidation of MA groups of S-MA by reacting with isopropyl amine resulting in copolymers having alkyl amide linkage and carboxylic acid group conferring to its pH sensitivity. In vitro release profile showed that aside from higher dependence of both copolymer-drug systems on the pH of the release medium, the release efficacy is higher in chemical loading than physical loading. In fact, in the case of chemical loading, the cleavable amide bond controls the delivery of the drug in various mediums. The polymers are not affected by the acidic pH, such as the low pH of the stomach, which has made it a favorite copolymeric platform for delivering the targeted drugs to specific locations like the small intestine.

Five novel-types of polymer-drug conjugates were prepared by covalent grafting of well-known amino medicinal compounds, such as amantadine (antiviral and anti-Parkinson), amlodipine (anti-hypertensive), gabapentin (treatment of epilepsy), zonisamide (anti-convulsant), and mesalamine (anti-inflammatory) onto the backbone of S-MA.[91] Since all these drugs are oral, in vitro hydrolysis investigation was performed in an acidic medium ($pH = 1.3$) at 37 °C, which is simulated gastric juice condition of the human body. Another study was performed in simulated intestine media at higher pH (such as 5.0, 6.0, and 7.4). It was observed that in gastric juice conditions, the hydrolysis of drug-loaded S-MA copolymer was completed gradually, indicating a more controlled and permanent release of drugs from their polymeric backbone. However, in the small intestine conditions, the drug was released more rapidly by the degradation of the polymeric backbone.

Nanocarrier systems were prepared from the amphiphilic diblock copolymers PSMA-*b*-PS, and poly(S-*alt*-MA)-*b*-poly(butyl acrylate) (PSMA-*b*-PBA). The diblock copolymers were synthesized using the RAFT method to achieve control in overall molecular weight and compositions of hydrophilic PSMA blocks and hydrophobic PS or PBA segments (**Figure 10**A).[92] These diblock copolymers reproducibly undergo self-assembly to form

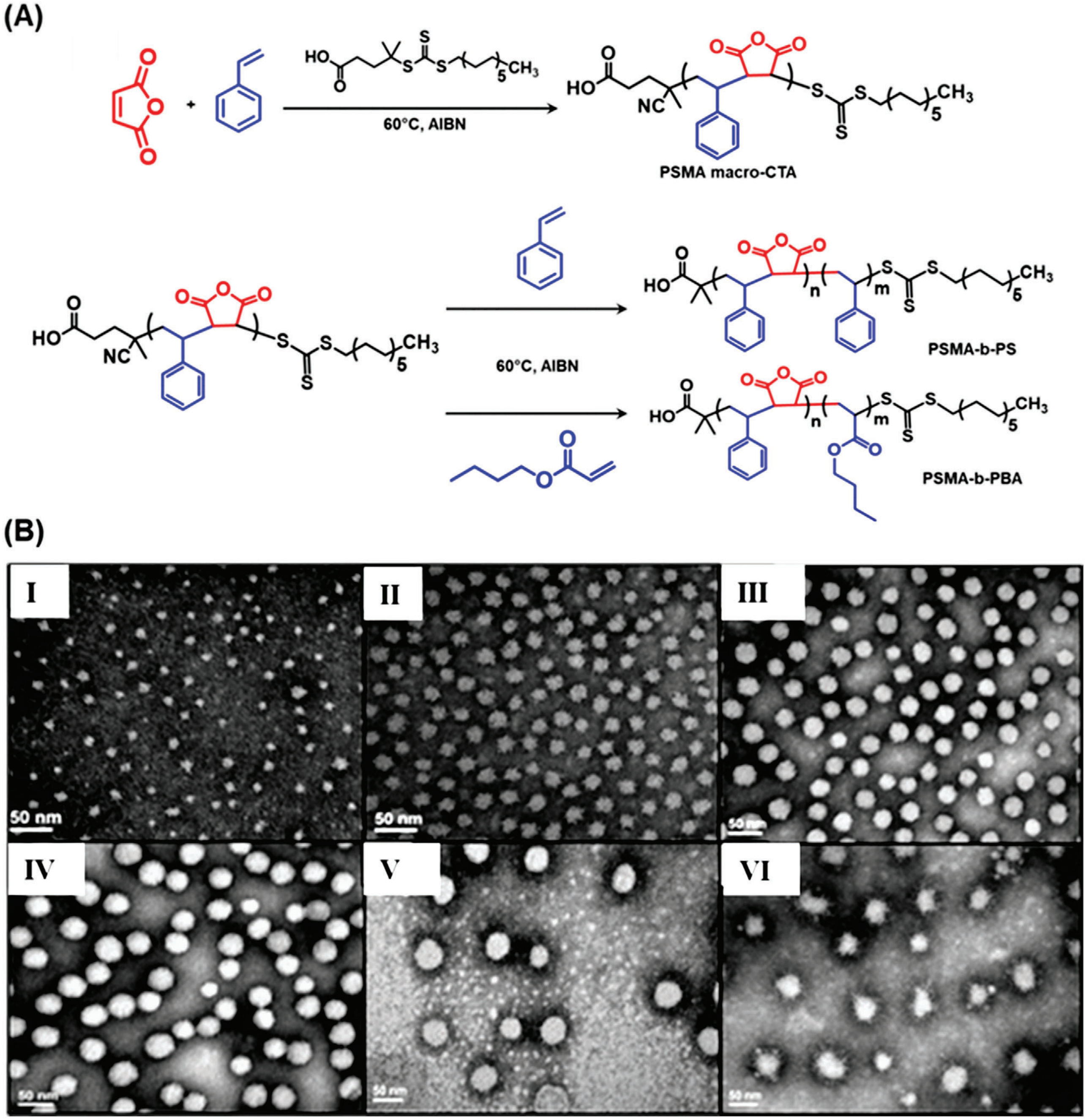


Figure 10. A) Synthesis of PSMA-*b*-PS and PSMA-*b*-PBA. B) The transmission electron microscopy (TEM) images of the self-assembled polymer micelles; I) $PSMA_{63}$-*b*-PS_{10}, II) $PSMA_{59}$-*b*-PS_{63}, III) $PSMA_{100}$-*b*-PS_{258}, IV) $PSMA_{114}$-*b*-PS_{308}, V) $PSMA_{114}$-*b*-PBA_{118}, and VI) $PSMA_{186}$-*b*-PBA_{107}. The scale bar is 50 nm. Reproduced with permission.[92] Copyright 2014, American Chemical Society.

aqueous-soluble micellar nanoparticles. Moreover, their stability, morphology (Figure 10B), size, drug loading, and release characteristics were systematically assessed. The use of PBA blocks gave the chance to investigate the effect of alternative core compositions with more amorphous physical properties, and the comparison between the two types of nanoparticles was more practical since all the micelles were prepared under identical conditions. When a hydrophobic anti-cancer drug, parthenolide (PTL), was encapsulated in the $PSMA_{100}$-*b*-PS_{258} micelles, which had the most ordered hydrophobic environments for more favorable core-drug interactions, it exhibited the highest loading and prolonged release. PTL released more rapidly from the $PSMA_{100}$-*b*-PS_{258} micelles when compared with the release of doxorubicin (DOX), a clinically approved chemotherapeutic drug or nile red and IR-780, two hydrophobic fluorescent probes. It indicates that apart from strong drug-core interactions, other factors like hindrance due to less favorable solvent-drug interactions, localization of drug in the nanoparticle, and/or insolubility

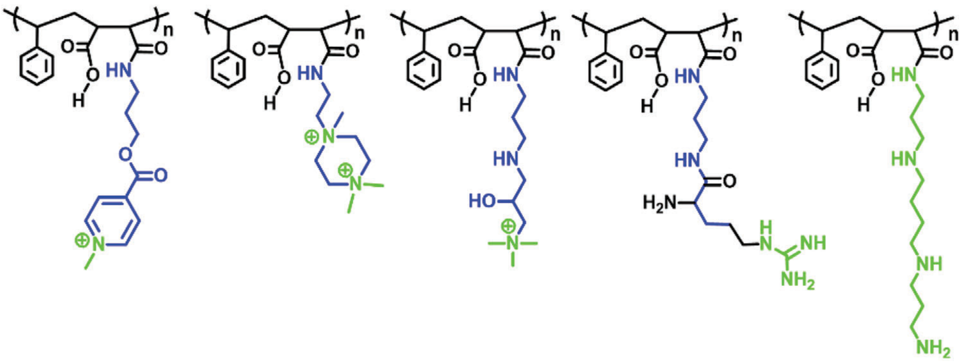


Figure 11. Various polymeric S-MA derivatives for intracellular gene delivery properties.

in micelle come into play, affecting loading and release behavior. Despite negative surface charges, the multi-drug resistant (MDR) ovarian cancer cells could uptake the PSMA$_{100}$-*b*-PS$_{258}$ micelles. Greater cytotoxicity of DOX-loaded micelles than free DOX was observed, as the DOX-loaded nanoparticles overcome the MDR mechanism and higher intracellular retention. These nanoparticle drug carrier systems provide therapeutic superiority to DOX-loaded micelles over free drugs towards MDR cancer cells. They also have the potential of becoming nanoparticle drug carriers for required drug candidates like PTL, which has diminished effect in vivo because of the poor bioavailability and aqueous solubility. The tunability of chemical architectures and drug encapsulation properties show multiple advantages of these copolymers that can be employed for drug delivery applications.

Low molecular weight S-MA-based graft copolymers were prepared by embedding different cationic moieties to the polymer backbone to explore various possibilities for efficient gene delivery (**Figure 11**).[93] Due to their amphiphilic characteristics, these polymeric derivatives can self-assemble into stable core-shell type nanoparticles in an aqueous medium. Embedding the polymer with aromatic quaternary ammonium cation like isonicotinic acid, a highly biocompatible aromatic compound, produced nanoparticles that showed effective endosomal rupturing properties because of having hydrophobic aromatic moieties in pendant side-chains and their ability to effectively conjugate plasmid DNA (pDNA) at lower polymer/DNA weight ratios. While embedding with aliphatic quaternary ammonium cation like glycidyl trimethylammonium chloride, a well-established DNA complexing agent, resulted in nanoparticles that exhibited the ability to surpass the degradation of DNase at lower weight ratios, though having dose-dependent cytotoxicity as their disadvantage. Additionally, the S-MA copolymers were conjugated with spermine and $_{\text{L}}$-arginine (Figure 11), two endogenous molecules capable of complexing and condensing genetic materials through electrostatic interaction present in the physiological system. The conjugation resulted in graft copolymers that exhibited strong binding and condensation of pDNA molecules, endosomal escape properties, efficient protection against DNase I, and excellent transfection.

The hydrolyzed forms of S-MA copolymers (under basic conditions) find a vast range of applications in biomedical science. The polymer is suitable to deliver hydrophobic drugs such as DOX,[77,94] and zinc protoporphyrin IX (ZnPP)[95] (**Figure 12**) at the tumor site. It exploits enhanced permeability and retention (EPR) effect by forming therapeutically advantageous high molecular weight S-MA micelle-drug conjugate. Moreover, it also utilizes the EPR effect by noncovalently binding to albumin, one of the most biocompatible macromolecules, and enabling it to serve as the second drug carrier.[96] The polymer also has potential in the research area of membrane proteins as it is now considered an efficient choice for membrane solubilization due to its ability to form discoidal particles spontaneously[97,98] and at the same time preserving the bilayer integrity of the protein and lipid functions.[99,100]

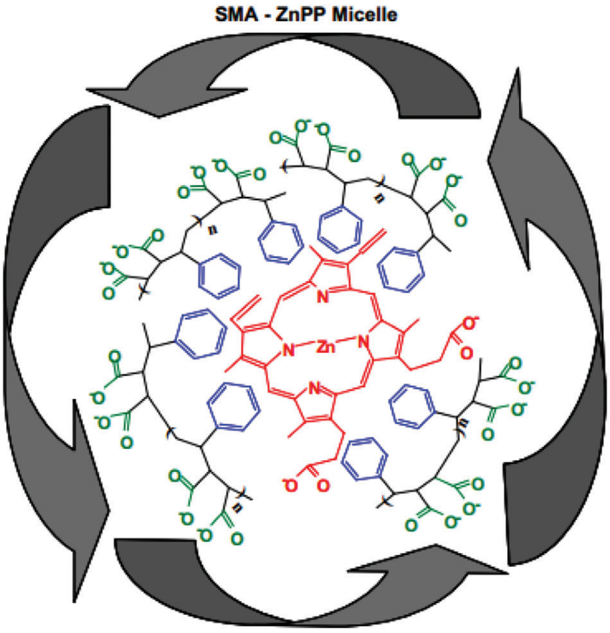


Figure 12. The ZnPP encapsulation by the hydrolyzed S-MA micelles. Reproduced with permission.[95] Copyright 2007, Elsevier.

4.3. Dye Separation

The removal of organic dyes from industrial wastewater has now become one of the major important environmental concerns of this era that needs our attention. In this regard, S-MA is an

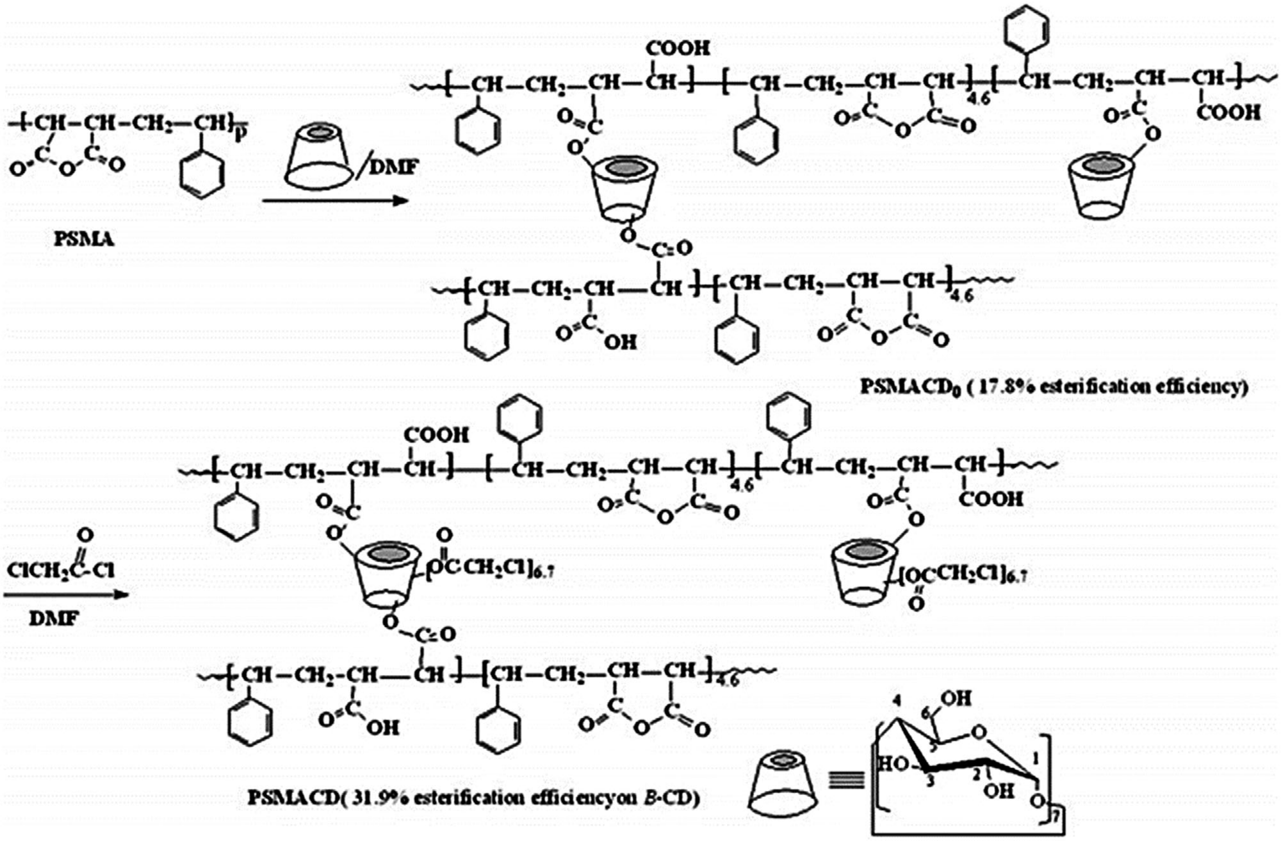


Figure 13. Synthesis of β-CD functionalized S-MA for adsorption of basic dyes. Reproduced with permission.[101] Copyright 2015, Taylor & Francis Group.

inexpensive commercially available copolymer. It acts as an adsorbent without causing secondary pollution after the removal of dyes from aqueous solutions, offering a promising solution for this issue. A water-insoluble β-cyclodextrin (β-CD) modified S-MA material PSMACD was synthesized first by grafting β-CD onto the S-MA backbone and then acylation of hydroxyl groups by chloroacetyl chloride (**Figure 13**). The PSMACD acted as a very efficient adsorbent for the removal of basic dyes such as methylene blue (MB) and basic fuchsin (BF).[101] The adsorbing capacity of PSMACD was enhanced ten-fold from S-MA as there are several binding sites, including the inclusion of β-CD cavities, non-inclusion cavities formed by polymer framework, and carboxyl groups in the polymeric backbone. The adsorption capacity of PSMACD for BF and MB was assessed under different adsorption conditions such as initial concentration, pH, contact time, and temperature.

In another study, two sets of adsorbents were synthesized, one was S-MA microspheres prepared from the precipitation polymerization method, and another was those microspheres coated with the sulfonic acid group via sulfonation by using sulfuric acid as a surface modification agent. The MB and rhodamine B (RhB) were selected as two typical cationic dyes, while methyl orange (MO) and congo red (CR) were selected as anionic dyes.[102] Adsorption studies revealed that the adsorbents could efficiently remove the cationic dyes from aqueous solutions, as in the sulfuric acid-treated S-MA (i.e., SSMA), negative charges were introduced on the surface of microspheres due to the formation of bisulfite ion (HSO_3^-). The surface-modified sulfonated polymer microsphere SSMA exhibited excellent theoretical maximum adsorption capacity and has the ability to become an environment-friendly and economical bio-adsorbent for the removal of cationic dyes from wastewater. In another study, calcium alginate hydrogel was anchored to S-MA polymer to effectively remove methyl violet 6B, a cationic dye, from aqueous solution. The adsorbent efficiency of native hydrogel and grafted hydrogel were measured using dynamic light scattering (DLS), Fourier transform infrared (FT-IR) spectroscopy, thermogravimetric analysis (TGA), and differential scanning calorimetry (DSC). It was found that the adsorbent efficiency of the calcium alginate grafted polymer is more than the native hydrogel by 30%, measured at 40 °C, pH range of 5–11, and at lower ionic strength. This polymer grafted material has the potential to stand out as a low-cost material for cationic dye removal from aqueous solution. The adsorption-desorption cycle can be continued for a minimum of five cycles without any hysteresis.[103]

4.4. Heavy Metal Separation

The use of metal ions as catalysts in industry and as a semiconductor in electric and electronic devices has caused an uprise in metal toxicity and contamination of water resources by industrial effluents, making it a serious environmental problem worldwide. Many separation methods have been developed to

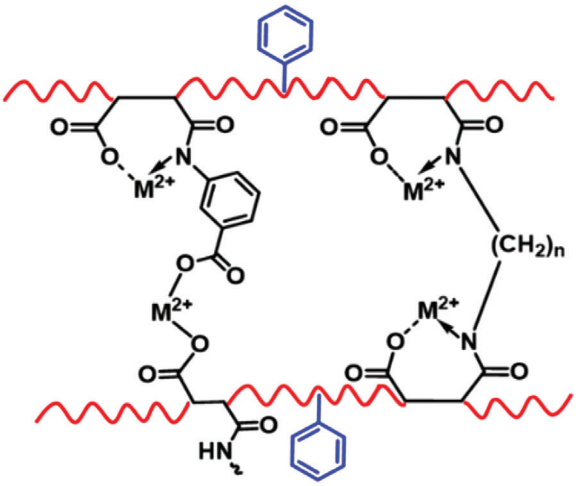


Figure 14. Structural presentation of S-MA copolymer derived resin forming metal-resin chelating complex through amide and carboxylate functional groups.

remove heavy metal ions from aqueous solutions, among which adsorptive removal is one of the most effective methods due to its cost-effectiveness, simplicity, and ease of operation. A new type of reactive nano chelating resin SMA-AB was synthesized by the modification of linear alternating copolymer S-MA with 3-aminobenzoic acid (AB) (**Figure 14**).[104] Next, the resin reacted further with 1,2-diaminoethane and 1,3-diaminopropane by ultra-sonification to obtain 3D porous chelating resin beads CSMA-AB1 and CSMA-AB2, respectively. The adsorption behavior of Fe(II), Cu(II), Zn(II), and Pb(II) ions was studied by all the already prepared chelating resins at different pH. CSMA-AB1 and CSMA-AB2 exhibited a higher selective affinity towards a few specific metal ions as compared to SMA-AB. The adsorption of all the metal ions was moderate in a completely acidic medium and favorable at a pH value of 6–7. Similar results were obtained using 2-aminopyridine instead of AB while preparing the chelating resin by reacting with an S-MA copolymer.[29]

Novel polypyrrole-based conducting nanocomposite with 4-aminobenzenesulfonic acid and modified S-MA (PSMA-*g*-4ABSA) was synthesized via emulsion polymerization.[105] The nanocomposite showed a good tendency for removal of heavy metal ions (e.g., Cu(II), Cd(II), Pb(II)) from aqueous solutions. The carboxylic acid and the amide functional groups, present in the main chain of PSMA-*g*-4ABSA, can form a strong complex with metal ions and thereby enhancing the adsorbing capacity for heavy metal ions. The S-MA copolymer was reacted with two alkyl diamines, ethylene diamine, and hexamethylene diamine, to give modified S-MA copolymers, which were used for the adsorption of Cd(II), Cu(II), and Pb(II) ions from aqueous media.[106] The results indicated that the adsorption is affected by pH, initial concentration of the metal ions, and contact time. Formation of thermally stable products by reaction of S-MA with diamines, and the existence of carboxylic groups in the same polymer with diamine groups providing the copolymer with the high hydrophilicity are needed for the fast kinetics of metal ions uptake. The S-MA was chemically modified by reacting with amino thiophene derivatives, ethyl 2-amino 4,5,6,7-tetrahydrobenzo thiophene-3-carboxylate (EATTC), and 2-amino 4,5,6,7-tetrahydrobenzo thiophene-3-cabonitrile (ATTCN).[107] Apart from the capacity of chelating with metal ions, thiophene moiety itself contains cyano or ester group which can impart interesting properties to the final polymer regarding uptake of metal ions. The metal ion is chelated by NH and either the CN or the ester carboxylic group and is surrounded by water molecules in possibly an octahedral structure in the polymer-metal ion adsorption complex. Comparative study of modified S-MA copolymers has evidenced better adsorption of Cu(II) ion compared to Cd(II) ion.

4.5. Other Applications

Different nanostructures and hierarchical structures have been reported using S-MA alternating copolymers. Dynamic-covalent nanostructure has been formed utilizing Diels–Alder reaction leading to the formation of thermo-reversible core. Size exclusion chromatography (SEC) and DLS analysis further confirmed the reversibility of the concerned polymer.[108] Ping et al. developed a hierarchically self-assembled nanostructure with PSMI alternating copolymer backbone.[109] The hydrophilic shell is made of PEG pendant styrene and cholesterol functionalized methacrylate vinyl monomer, appended from maleimide-based ATRP macroinitiator, formed the hydrophobic core. The tendency of cholesterol to generate higher-order structures is responsible for the formation of this self-assembled nanostructure. A simple, reproducible, high yield, an inexpensive method was established to produce silver nanowire arrays from silver nitrate ($AgNO_3$) and S-MA copolymers. The method takes advantage of the structural property of S-MA copolymer of self-assembling and forming nanotubes in aqueous media to guide silver cyanide (AgCN) growth into a very high aspect ratio nanowire (**Figure 15**A).[110] AgCN is believed to form along the length of the nanotube and its reduction to metallic silver may be supported by the polymer scaffold of the S-MA template. The length of the AgCN-S-MA nanocomposites can be tuned by changing the molecular weight of the polymer and by sonication to prevent stacking between the S-MA-nanotubes. To produce these similar S-MA nano-templates, another novel preparation method was attempted which involves the formation of stable sheets of S-MA polymers from sideways association through π-stacking of linear polymers (occurred at 50% protonation pH), and finally, these sheets curve upon themselves to form tubular structures to minimize surface energy.[111] Necessary conditions for the growth of these templates were 50% protonation to achieve an increase in persistence length and the slow association between polymers from dialysis. The nanorod composites having a diameter between 4–10 nm were used as templates to polymerize pyrrole, reduce $AgNO_3$ to silver metal, and more successfully, to template the growth of micrometer long AgCN-polymer nanowires. They were also used for growing other metal-cyanides and other crystals (e.g., $CdCl_2$ or CdS). Poly(S-*alt*-dimethyl-*N*,*N*-propylamide) is soluble in acidic aqueous solutions and is expected to self-assemble since styrenic monomer is responsible for S-MA-nanotube formation via π-stacking interaction is still present and the MA unit is only functionalized to MI (Figure 15B).[112]

Apart from bioactive groups, a vast variety of functional groups could be attached to the S or MA/MI monomers. This will impart

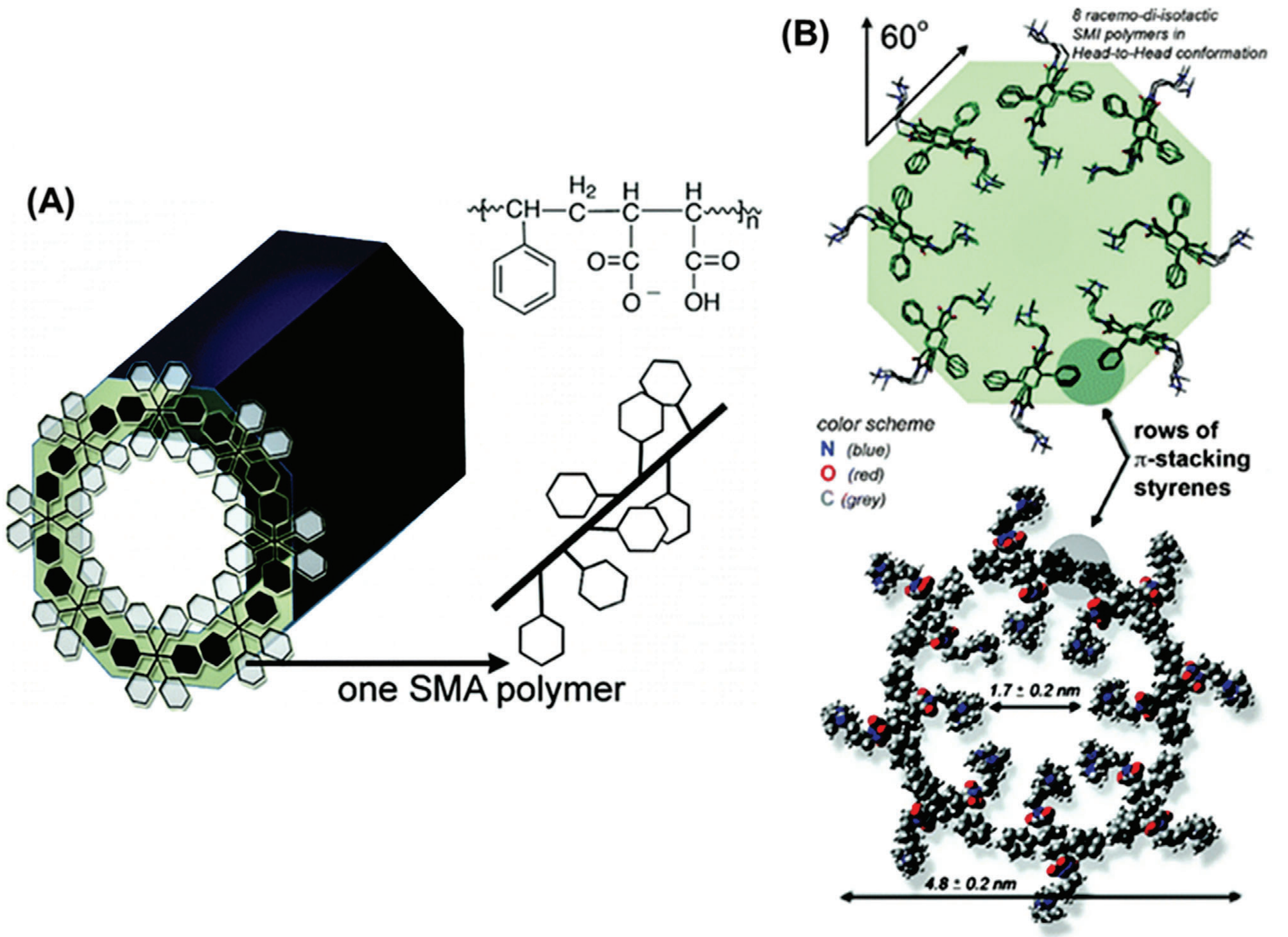


Figure 15. A) Schematic representation of the polymer nanotube where eight S-MA polymer chains are sideways self-assembled by π-stacking of the styrene rings. Reproduced with permission.[110] Copyright 2009, American Chemical Society. B) PSMI nanotube (cross-section, perpendicular to association plane): (top) the nanotube has an octagonal shape, made from eight racemic-di-isotactic PSMI polymers in the head-to-head conformation; (bottom) PSMI nanotube shown with van der Waals radii. Reproduced with permission.[112] Copyright 2008, American Chemical Society.

various physical and chemical properties to the polymer, which could bring interesting applications. Our group reported a series of sequence-controlled crystalline alternating copolymers based on fatty acid tethered to MI and mPEG containing styrenic monomer through RAFT polymerization. A well-ordered lamellar pattern was formed consisting of alternate layers of fatty acid alkyl segments and mPEG, where a regular increase of the interlamellar spacing was only due to increasing of the mPEG chain lengths. This was determined by a small-angle X-ray scattering (SAXS) analysis.[113] Moriceau et al. synthesized S-MA alternating copolymer with different architectural characteristics.[114] They hydrolyzed the MA in post-polymerization modification and functionalized both the newly formed carboxylic acid with long-chain alcohol ($C_{22}H_{45}OH$). The effect of different architecture of the polymer, composition, and long alkyl chain addition to the polymeric backbone was studied in solution by SEC, while the thermal properties were determined by TGA and DSC. The pendant long alkyl chain density and its distribution did not impact the solution conformation of the polymer but affected its size and structural density. The long aliphatic chain grafted to the side-chain of hydrolyzed S-MA made the polymer semicrystalline. The low density of alkyl side-chain resulted in low crystallization temperature ($T_c \approx 8$ °C), while the higher density of the same exhibited high T_c (≈80 °C).

Alternating terpolymers, si-PPMSs were synthesized from S, PSMI, and PMI containing sulphonamide acid groups. The si-PPMS was synthesized to prepare proton-conducting polymer electrolyte membranes for polymer electrolyte fuel cell (PEFC) applications (**Figure 16**).[115] The ion exchange capacity (IEC) values of si-PPMSs could be easily modulated by changing the feed ratio of PMI and sulphonamide containing comonomers of styrene. These si-PPMS membranes exhibited comparatively better thermal and chemical stabilities than sulfonated hydrocarbon polymers. They also showed excellent properties for application as polymer electrolytes for PEFCs with excellent proton conductivity values.

The MA or RMIs of these alternating copolymers can also be modified purposefully to generate certain surface properties. Modified alternating copolymers of S of MI were synthesized based on the PSMI main chain with two different side chains

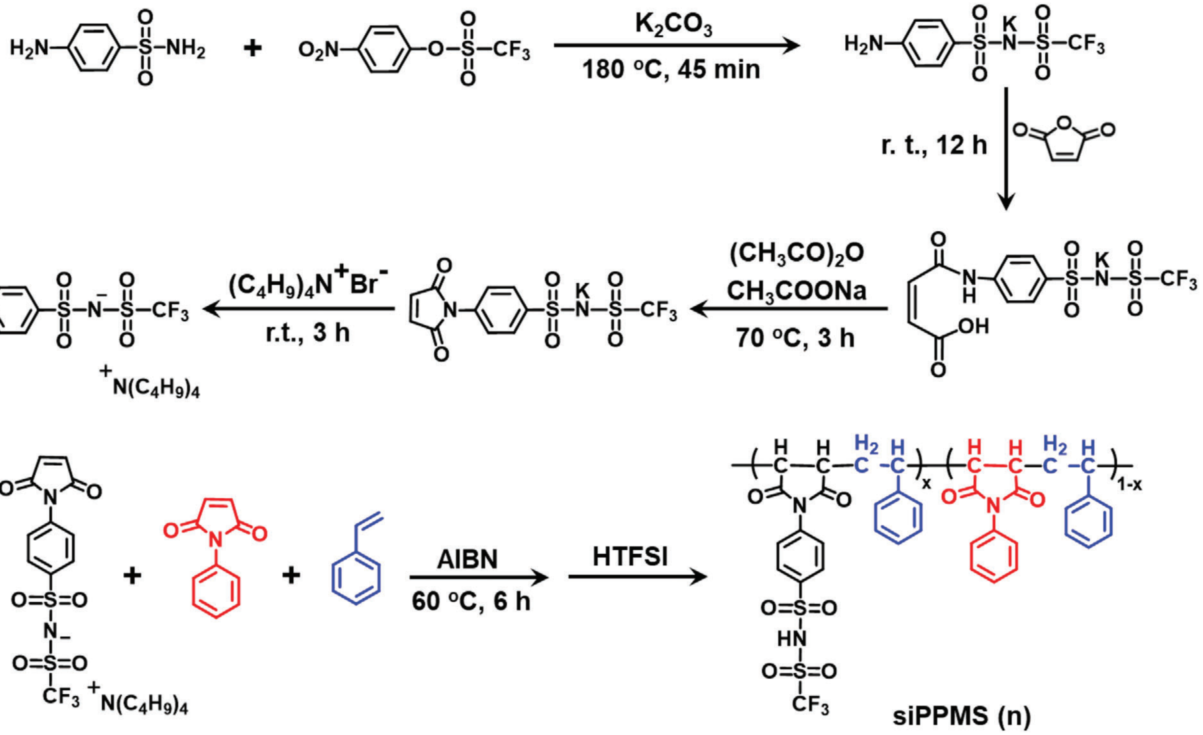


Figure 16. Synthesis of alternating terpolymers, for the PEFC applications.

(4-(*N*-perfluoroheptylcarbonyl)aminobutyl and *n*-dodecyl).[116] The alternating copolymers were used to realize that CH_3 and CF_3 groups are exposed on the top of the surface. This gave a chance to compare, especially, the influence of changing backbones on the surface properties of copolymers with aliphatic and fluorinated side chains. Low hydrophobicity and high surface tension were observed because of the existence of phenyl substituents and sparsely packed side chains. No melting of side-chains for the copolymers with aliphatic side-chains and no phase transition from ordered to disordered for polymer containing fluorinated side-chains were observed from the thermal analysis. By reacting anhydride groups of S-MA with γ-aminopropyltriethoxysilane (APTS), superhydrophilic S-MA/silica organic-inorganic hybrid surfaces have been fabricated on blend membranes of PVDF and S-MA (**Figure 17**).[117] Alongside the superhydrophilic surface, micro-nano hierarchical structures have been formed and the generated hybrid surface is suitable for the entire pH range and has good environmental stability.

A series of alternating copolymers of S or hydrophilic styrene derivatives (vinyl catechol (VC) and vinyl phenol (VP)) with hydrophobic RMIs derivatives with alkyl substituents such as ethyl, trifluoroethyl, dodecyl, and octadodecyl were synthesized to study their adhesive property on glass plates, water repellence, and surface coating properties.[31] The copolymers of VC or VP and *N*-alkyl maleimide (where the alkyl chain is long) exhibited high adhesion on glass plates due to the presence of hydrophilic styrene derivatives capable of forming *H*-bonds. They also showed high water repellences, which can be attributed to the long alkyl chains suppressing the migration of hydrophilic units under static conditions. Additionally, the hydroxyl groups attached to VC or VP influenced the solubilities through *H*-bonding and were also responsible for exhibiting upper critical solution temperature (UCST)-type thermo-responsive property in alcoholic solvents.

Some of the modified alternating copolymers of S-MA or PSMI exhibited distinguishable thermal and mechanical properties compared to unmodified S-MA or PSMI copolymers. Poly(*N*-phenylmaleimide-*alt*-styrene) (P(PMI-*alt*-S)) and poly(*N*-(4-carboxyphenyl)maleimide-*alt*-styrene) (P(CPMI-*alt*-S)) were designed and synthesized via FRP to investigate the introduction of 4-carboxyl onto P(PMI-*alt*-S) and its effect on the heat deflection temperature (HDT) of nylon 6 (PA6).[118] The HDT values of both the PA6/P(PMI-*alt*-S) and PA6/P(CPMI-*alt*-S) blends immensely exceeded that of PA6, while the HDT value of the PA6/P(CPMI-*alt*-S) blend was greater than that of the PA6/P(PMI-*alt*-S) blend. Introduction of 4-carboxyl onto P(PMI-*alt*-S) induced the transformation of crystal type, promoted the crystallinity of PA6 as evident from DSC analysis, and also enhanced the friction between P(CPMI-*alt*-S) and PA6, rendering it to be a promising candidate for the polarity-substituted heat-resistant agent. A series of alternating copolymers of RMIs carrying alkyl chain substituents and VP were synthesized to study the self-assembly of alternating copolymers and investigate the hypothesis that alternating copolymer chains of totally different properties (affinity, polarity, interaction, etc.) can effectively undergo cohesion or self-assembly.[35] Copolymers carrying long alkyl pendant chains on the MI unit showed a UCST-type thermal response in aromatic solvents. Moreover, organogels were specifically formed upon cooling of the fluid solution prepared at higher temperatures due to *H*-bonding between regularly aligned phenol pendant groups.

Modification of PSMI or S-MA copolymers can also be used to generate polymers with special architectures. Grafting

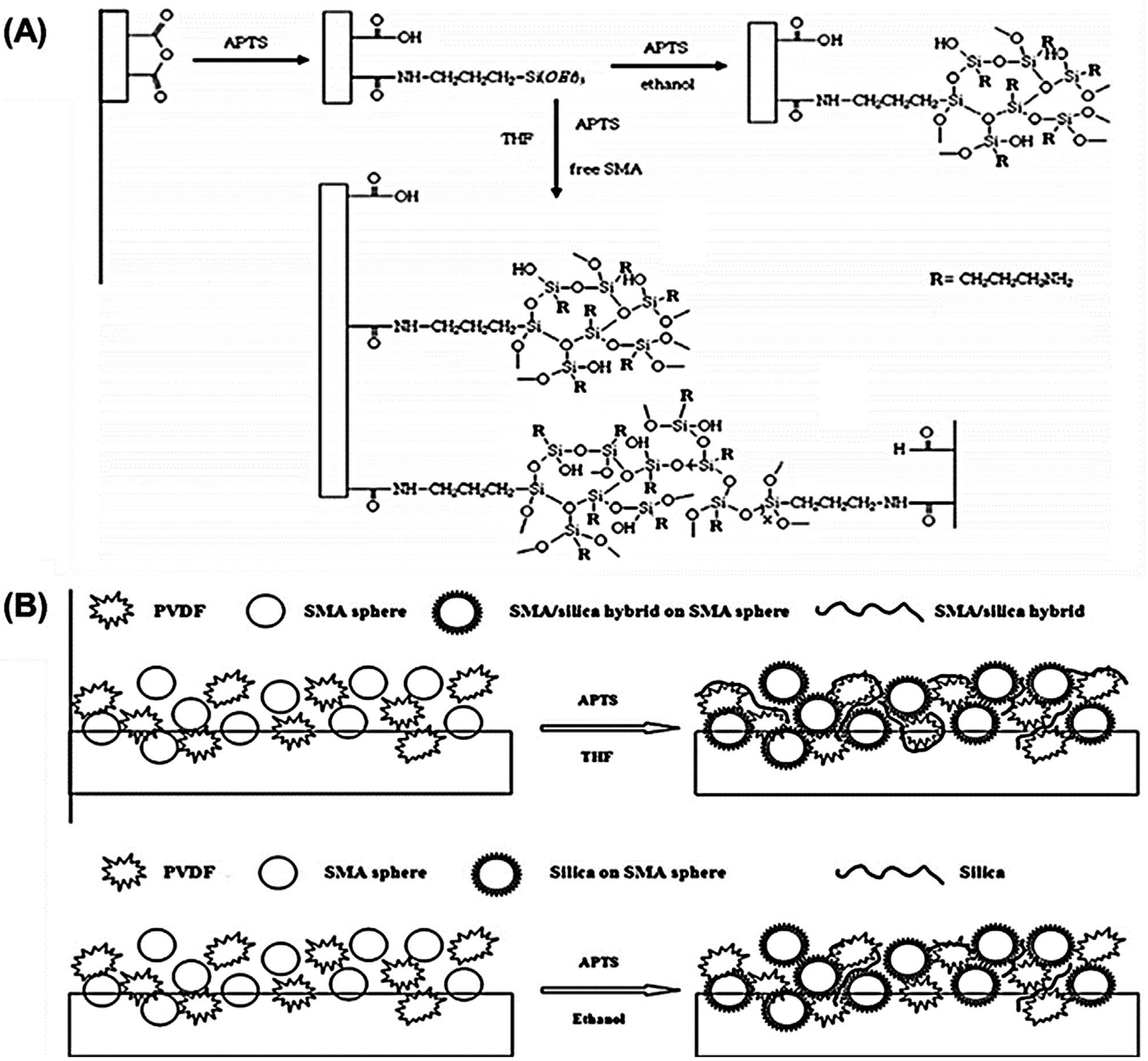


Figure 17. A) Fabrication of superhydrophilic S-MA/silica hybrid surface on PVDF membrane, and B) their mechanism of different wetting behavior. Reproduced with permission.[117] Copyright 2011, Elsevier.

mPEG onto the ultrahigh molecular weight S-MA backbone prepared using supercritical CO_2 as a reaction media, was done via esterification of anhydride groups with hydroxyl groups to obtain an amphiphilic graft copolymer having comb-like architecture.[119] It was used as additives in polyethersulphone (PES) casting solutions to prepare PES/S-MA-*g*-MPEG blend membranes to enhance the surface hydrophilicity and protein adsorption resistance of membranes. They can be well preserved in membrane near-surface and not lost during membrane washing because of their high molecular weight and comb-like architecture. Using RAFT miniemulsion polymerization, a series of well-defined tetra block copolymers poly(S-*alt*-(MA)]-*b*-poly(S)-*b*-poly(*n*-butyl acrylate)-*b*-poly(S) (SMA-PS-PnBA-PS) were synthesized.[120] Their tensile tests and TEM observations revealed that increasing fractions of S-MA in the tetra block copolymers led to wormlike morphology in the elastomeric matrix and higher T_g. It also resulted in a simultaneous increase in the ultimate tensile strength and lowering of the elongation at break, and thereby making it a potential candidate for toughness modification. Alternating copolymerization of styrene-terminated poly(ethylene oxide) (S-PEO) and maleimide-terminated poly(2,5-bis((4-methoxyphenyl)-oxycarbonyl)styrene) (MI-PMPCS), macromonomers via grafting-through strategy produced an amphiphilic alternating copolymer brush (**Figure 18**).[121] After being doped with a lithium salt, the copolymer can form lamellar structures, microphase separation, and can serve as a solid electrolyte for lithium-ion transportation. The ionic conductivity of the same copolymer brush can be increased

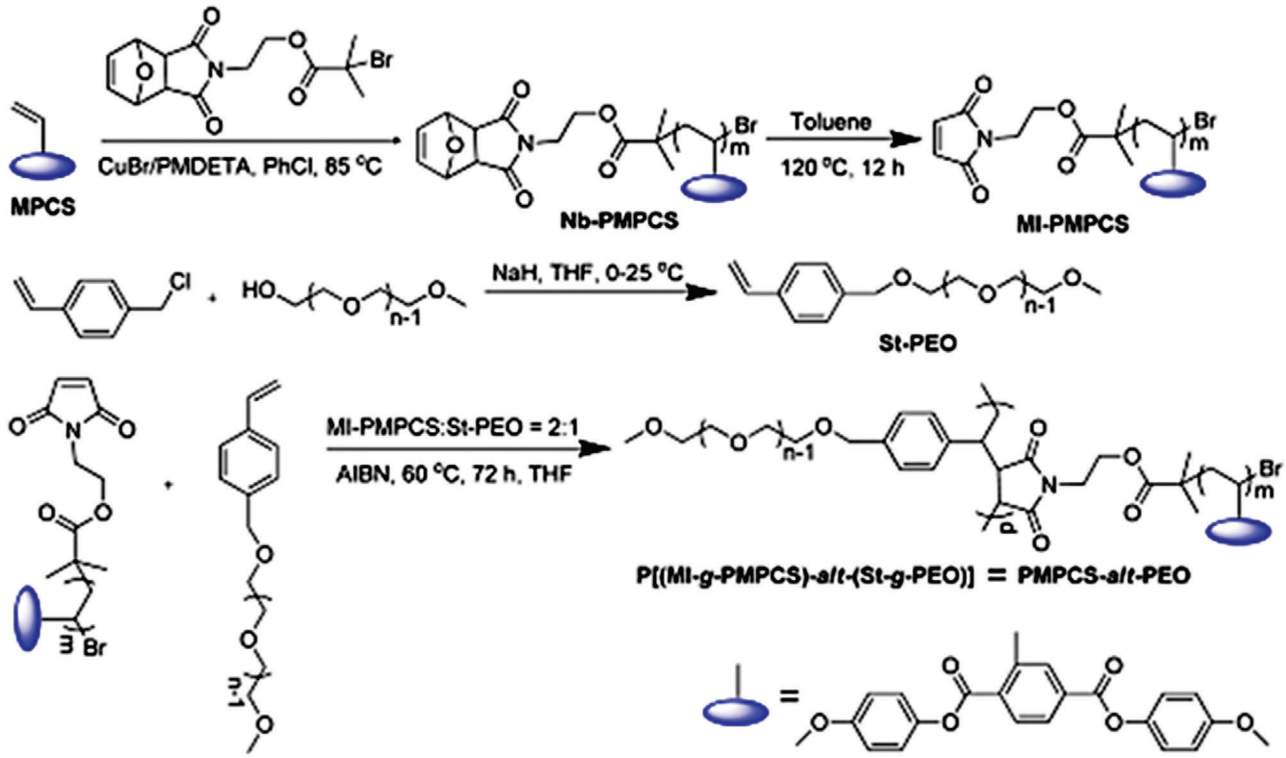


Figure 18. Synthesis of amphiphilic alternating copolymer brushes. Reproduced with permission.[121] Copyright 2015, American Chemical Society.

by increasing the doping ratio. Moreover, the ionic conductivity of different copolymer brushes can also increase by decreasing the length of PMPCS side-chains with the same doping ratios.

Using direct chemical self-assembly of S-MA copolymer induced by aminolysis of S-MA with 3-aminopropyltriethoxysilane (APTES) and in situ polycondensation of APTES under refluxing acetone, nanohybrid particulate emulsifiers having spherical-like morphology with surface activity were generated (**Figure 19**).[122] The nanohybrids were effective particulate emulsifiers when homogenized with various oils (e.g., paraffin oil, silicone oil, etc.) and showed pH-sensitive properties. When the nanohybrids were heavily flocculated by adding HCl, it formed oil-in-water high internal phase emulsions (HIPEs), which were pH-responsive to demulsification with the addition of alkaline solution, and hence showing the potential application in the oil industry. Nonaqueous polymerization-induced self-assembly (PISA) formulation was synthesized via RAFT dispersion alternating copolymerization of S with PMI.[32] The copolymer block forming the core has relatively higher T_g leading to the formation of vesicular morphologies during PISA, as well as forming a more typical sphere and worm phases. Micrometer-sized elliptical particles with internal structure and oligolamellar vesicle morphology were revealed from TEM and SAXS studies. When the PISA synthesis was carried out at a higher temperature for a longer reaction time, then the unilamellar vesicular morphology was generated. The worms were a much more efficient stabilizer of aqueous foam than spherical or oligolamellar elliptical vesicles.

Substituting the S monomer with methoxydiethylene glycol and maleimides with 2-salicylaldehyde-aminoethyl group, the resulting copolymers showed excellent fluorescence “OFF-ON” response to Zn^{2+}. However, the RMIs showed no fluorescence response to Zn^{2+} due to the photoinduced electron transfer (PET) process. The alternating copolymers show fluorescence response by inhibiting the PET effect through copolymerization with a very fast response time and well-defined detection limit.[123] In addition, the alternating copolymers exhibit a remarkable green fluorescence “OFF-ON” switch when the pH changes from 11 to 12, showing their promising application in dual-color detection. A series of alternating copolymers of 4-acetoxy-styrene, 4-hydroxy-styrene with MI containing isobutyl POSS substituent were synthesized along with the synthesis of homopolymer of isobutyl POSS containing MI.[36] Dipole-dipole interactions between C=O groups and *H*-bonding interactions between C=O groups of POSS-containing MI and -OH of hydroxy-styrene units were detected by FT-IR spectra. These polymers exhibited unexpected fluorescence as they are lacking any common fluorescent units. The emission of homopolymer was stronger than alternating copolymers, presumably due to the former’s crystallinity and clustering of locked C=O groups of the POSS units.

The alternating copolymer scaffolds also can be employed to fabricate suitable nitric oxide (NO)-releasing the vehicle. In recent times, NO has gained much attention as they exhibit anti-cancer activity, anti-bacterial activity, wound healing properties, and so on. Recently, our group has developed such polymeric NO carrier by modifying the mPEG containing S-MA copolymer.[124] Various types of diamine compounds were introduced in the S-MA backbone by post-polymerization modification reactions (**Figure 20**). The study implied that the *N*-phenyl ethylenediamine conjugated copolymer (P4NO) exhibited a significant NO

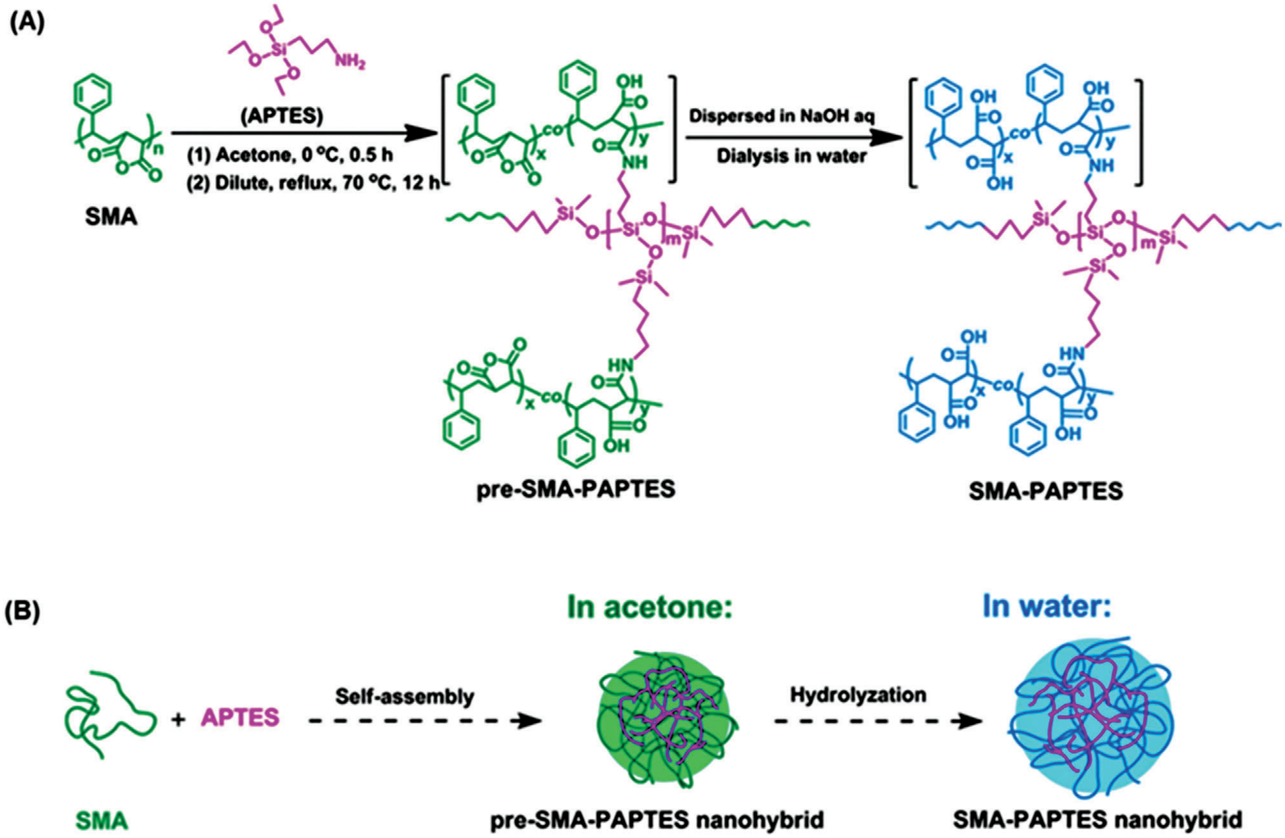


Figure 19. A) Synthesis route and formation of self-assembly by SMA-PAPTES nanohybrids and B) Schematic representation of the self-assembled SMA-PAPTES nanohybrids. Reproduced with permission.[122] Copyright 2014, American Chemical Society.

release in the presence of acidic pH or UV-light (254 nm). The release is also temperature-dependent and the release rate is enhanced with the increase in temperature. The P4NO could store ≈0.2 µmol NO/mg of NO, which is suitable for various biomedical applications.

5. Nonconventional Luminogenic Property of S-MI/MA Copolymers

Although the S-MA or PSMI copolymers were developed a long time ago, their unexpected luminescence behavior was explored recently by Kuo et al. They observed the unexpected fluorescence emission from POSS connected various PSMI backbones in THF.[36] The presence of dipole-dipole interaction between C=O groups in POSS substituted maleimide-based homopolymer and *H*-bonding interaction between C=O group of POSS appended from maleimide and -OH group appended from styrene part were revealed from FT-IR studies. They envisioned that the dipole-dipole interaction between the C=O groups is responsible for the emergence of fluorescence of the POSS substituted maleimide-based homopolymer. Fluorescence emission from different types of MA-derived alternating copolymers with different olefinic comonomers was also explored, and the origin of the unprecedented emissive behavior was investigated by experiments and theoretical calculation.[125] From the theoretical study, it was suggested that the π bond of the styrene acts as a HOMO (highest occupied molecular orbital) and π-π interaction between the C=O groups and benzene ring in the vicinity acts as the lowest unoccupied molecular orbital (LUMO). The most intriguing aspect of this unexpected fluorescent emission is its aggregation-induced behavior. The through space π-π interaction between the maleimide carbonyl group and styrene aromatic ring is responsible for the emissive behavior of the polymer. Because of this fact, the PSMI copolymer is devoid of aggregation-caused quenching (ACQ). Also, these polymers are biocompatible, less toxic, and easy to prepare than most other aggregation-induced emission luminogens (AIEgens). Being empowered with these advantages, S-MA alternating copolymer is used as novel stimuli-responsive polymeric materials,[126,127] for sensing application,[128] for drug delivery,[129] etc.

Our group is one of the few research groups that has been exploring since 2016 the nonconventional luminogenic property of these types of alternating copolymers synthesized via RAFT polymerization by functionalizing both the comonomers. From our group, Saha et al. reported for the first time a conventional fluorophore-free polymeric material in which MI was attached with a thermoresponsive group and styrene with a pH-responsive moiety (amino acid) (**Figure 21**). The *tert*-butoxycarbonyl (Boc) protected copolymers exhibited bright blue emission in the organic solvent, and its deprotected version preserved its emission in both organic solvent and water with pH and thermoresponsive tunability.[126] Bauri et al. explored the same polymer as a turn-off fluorescent sensor for nitroaromatic explosives detection in water with excellent selectivity and sensitivity.[128] The solid

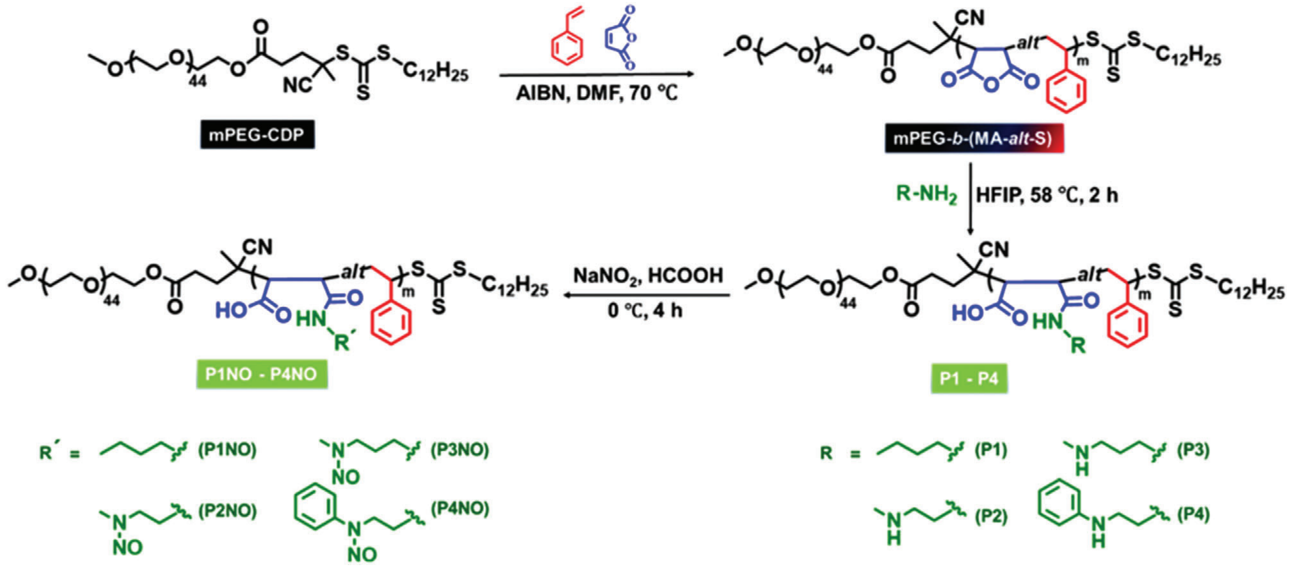
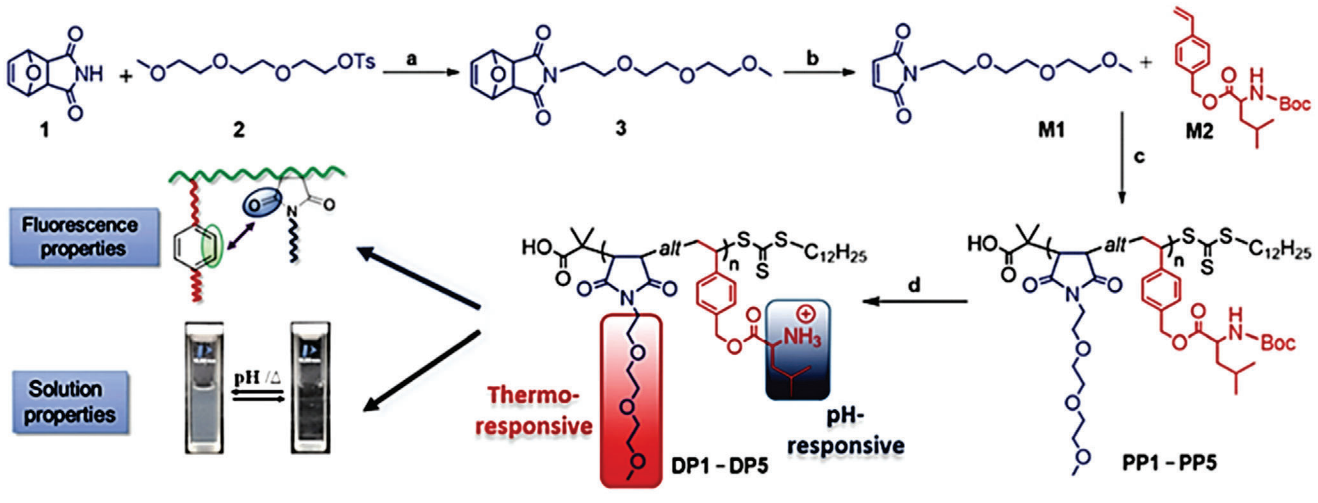


Figure 20. Synthetic scheme for the preparation of various polymeric NO donors. Reproduced with permission.[124] Copyright 2021, American Chemical Society.



(a) Dry CH_3CN, reflux, 50 °C, 48 h; (b) Toluene, 120 °C, 20 h; (c) DMP, AIBN, 1,4-dioxane, 70 °C, 24 h; (d) TFA, DCM, 4 h.

Figure 21. Synthetic pathway of *N*-(methoxy diethylene glycol) maleimide (M1) and its alternating copolymers (PP1-PP5) with the Boc-protected leucine attached styrenic monomer (M2) utilizing RAFT polymerization, followed by Boc group deprotection obtaining deprotected polymers (DP1-DP5). Reproduced with permission.[126] Copyright 2016, Royal Society of Chemistry.

and vapor phase sensing of nitroaromatics were also achieved with this auto-fluorescent polymer (**Figure 22**). The ground state complex of the positively charged amine group (appended from leucine functionalized styrene) with picrate anion (a representative nitroaromatic explosive) is responsible for the quenching mechanism of the sensor.

Amino acid-derived PSMI-based alternating polyampholyte was reported by Saha et al. where both the comonomers were functionalized with leucine.[129] It was observed that the synthesized deprotected polymer becomes charge-neutral at pH 7.0. Further, this polymeric material can selectively sense carbon disulfide (CS_2) in the aqueous and vapor phase (naked-eye colorimetric detection) with great sensitivity. To employ the intrinsically fluorescent property of the alternating copolymer in biomedical applications, an amphiphilic pH-responsive auto-fluorescent drug delivery vehicle was developed.[129] The maleimide comonomer was attached with hydrophobic nitrogen mustard drug chlorambucil (CBL) and the poly(ethylene glycol) (PEG) was appended to styrene to develop amphiphilicity (**Figure 23**). The polymer self-assembled in an aqueous medium to form nanoparticles with hydrophobic drug-based core and PEGylated shell. At endo-lysosomal pH 5.0, the ester linkage between the drug and the polymer gets cleaved, leading to a 90% release of drug from the vehicle. Moreover, the native fluorescence emission of polymer enabled it for intracellular tracking by fluorescence microscopy.

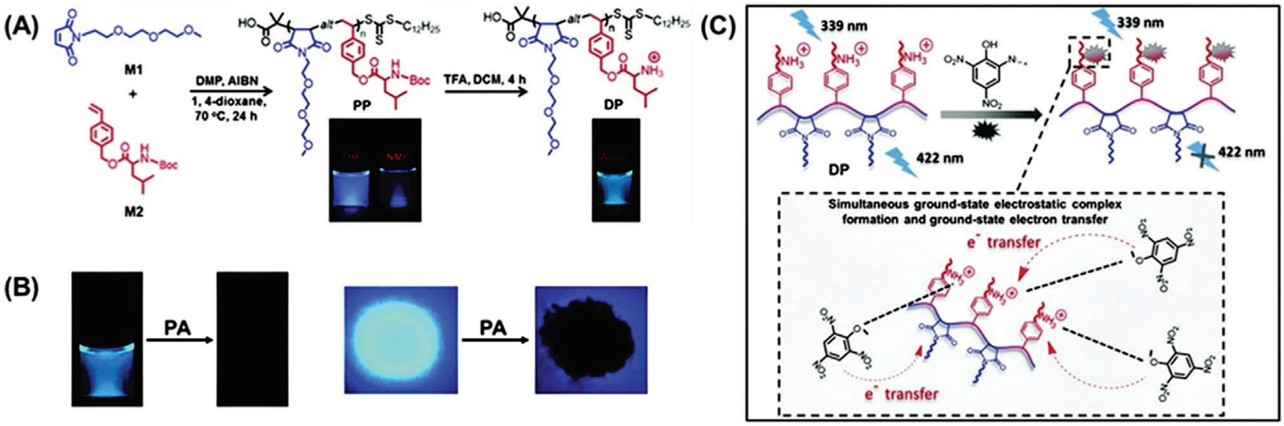


Figure 22. A) Synthetic route of Boc-protected alternating copolymer PP, and its concurrent deprotection under the acidic condition to obtain the target polymeric probe DP. Fluorescence images of PP in THF and *N*-methyl-2-pyrrolidone, and DP in water when UV light of 366 nm was irradiated. B) Naked-eye observation of fluorescence quenching under UV light: I) in solution state upon picric acid (PA) addition to aqueous sensor solution, and II) in solid-state upon adsorption of PA solution on sensor spot on a TLC plate. C) Schematic representation of the mechanism for the selective fluorescence response of sensor DP towards PA. Reproduced with permission.[128] Copyright 2017, Royal Society of Chemistry.

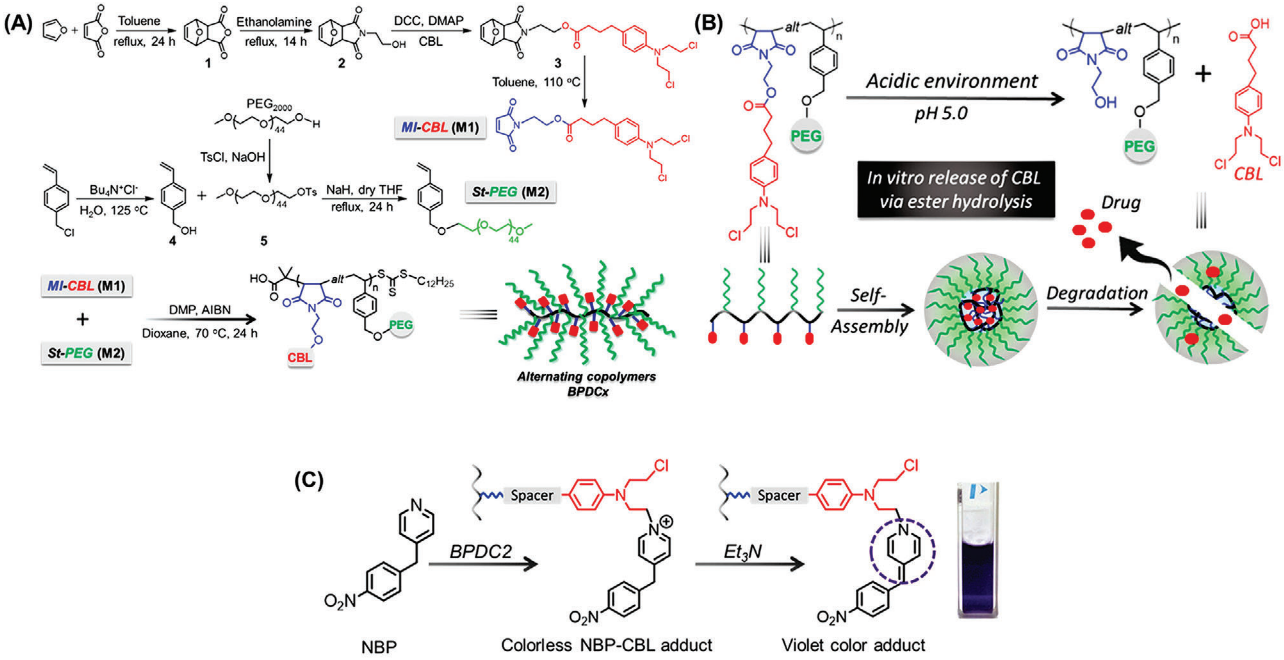


Figure 23. A) Synthetic routes for the preparation of CBL appended maleimide monomer (M1), styrenic macromonomer (M2), and pH-responsive amphiphilic alternating copolymer, BPDCx, via RAFT polymerization. B) Schematic illustration of the pH-triggered release of CBL from BPDCx nanocarrier. C) Schematic depiction of the alkylation of 4-(nitrobenzyl)pyridine (NBP) which is a representative compound of DNA bases and CBL conjugated BPDCx polymer. Reproduced with permission.[129] Copyright 2018, American Chemical Society.

The synthesis via RAFT polymerization of sequenced controlled 1:1 alternating D- and L-alanine containing alternating polymers based on the PSMI backbone has been reported. The PSMI backbone consisted of an RMI monomer having Boc-L-alanine and a styrene conjugated Boc-D-alanine monomer.[130] It is important to mention that these copolymers are fluorescent in different organic solvents and preserved their fluorescent behavior in organic and aqueous solvents even after successful deprotection. Recently, we engineered an alternating copolymer based on two dipeptides alanyl-alanine and glycyl-glycine, where the former is appended from maleimide and the latter one from styrene.[131] Unprecedented luminescent activity was observed in both solution and solid-state. Surprisingly, only blue emissions occurred in the solution, while in the solid-state, blue, green, and red emissions were observed.

6. Conclusions and Future Perspectives

Copolymers of S-MI/MA have attracted significant attention in both academia and industry due to their alternating sequence throughout the main chain, and interesting physical and chemical properties. In this review, we have extensively discussed synthetic strategies of S-MI/MA alternating copolymers. Although this unique type of alternating sequencing was developed long ago, researchers still often use this polymeric backbone due to 1) cheap commercially available monomers, 2) ease of synthesis by both FRP or controlled radical copolymerization techniques, 3) ease to functionalize the monomers and polymers, 4) large scalability, and 5) having strict alternating sequencing, resulting in maintenance of homogeneity along with the polymer irrespective of molecular weight. Thus, the research and development of various types of S-MI/MA alternating copolymers have expanded rapidly in recent years. Therefore, our understanding of their unique structural characteristics, selective reactivity, and underlying mechanisms have also significantly improved.

This special class of alternating copolymers has an interesting ability to produce unique functionalized polymeric structures with precise placements of functional groups throughout the polymer backbone, thus making them a vibrant and productive area in polymer chemistry. Exploiting the reactivity of PSMI or S-MA comonomer systems, a plethora of functionalized copolymers have been synthesized with unique mechanical, optical, solution, and biological properties. Modifying and bringing variation in several synthesis techniques gives us a chance to explore the vast variety of possible architectures of these copolymers. Moreover, knowledge about controlling their morphologies leads to the generation of new classes of synthetic materials, thereby broadening their spectrum of applications. Desired properties in these alternating copolymers can be introduced by functionalization of monomer, attaching pendant side-chains, or grafting different organic moieties to the polymeric backbone according to our needs. Numerous stimuli-responsive polymers prepared from the S-MA backbone find their use in sensing and bio-sensing, artificial muscles, and on-demand drug delivery.[132,133] The S-MA alternating copolymers show unique catalytic activity,[134] and enhanced thermal and mechanical properties. In addition, the copolymers form unique nanostructure morphologies which have applications in the industry[110,111] and in the field of nanotechnology.[120,121] Apart from these, the copolymers are used in biomedical science due to their excellent delivery[90,92] and release systems for drugs and genetic materials.[93,95] The copolymers also produce special architectures which are used in environmental science for toxic metal removal,[106,107] contaminated dye separation,[101,102] and producing new kinds of coating materials.[31,117] Continuous development of these alternating copolymers sets new standards for their promising properties and potential applications in upcoming times.

Recently, conventional fluorophore-free luminescent polymer development has emerged as an exciting field of research. Hence, we believe there is a bright prospect for the S-MI/MA alternating copolymers as non-conventional luminogen. We have contributed significantly so far in extending the applications of unprecedented emissive behavior of S-MI/MA alternating copolymers from developing stimuli-responsive polymeric materials to fabricating drug delivery vehicles. We envisage that the S-MI/MA alternating copolymer has the potential to stand out as a versatile polymeric backbone that can be functionalized easily according to the necessity with the help of facile organic reactions. The auto-fluorescent behavior will not only help to locate the polymer in bioimaging or drug delivery applications but also prevent unwanted hazards generated from the usage of the conventional fluorophores.[135] Also, we strongly believe that the advantages of using S-MI/MA alternating copolymer polymeric skeleton can be further extended to other fields of research like fibril inhibition in various proteins,[136] as antifouling polymer for biomedical applications, and developing novel adhesive materials. Nevertheless, this review will provide the researchers a detailed discussion on the synthesis of the S-MI/MA alternating copolymers, the scope of functionalization on the polymeric backbone, and the future prospects. We envision that in the coming days, the S-MI/MA-based non-conventional luminogenic polymers will emerge as an efficient polymeric skeleton and will be able to provide numerous novel polymeric architectures by effective functionalization on its side-chain. Furthermore, the detailed discussion on conventional fluorophore-free S-MI/MA alternating copolymer and its unprecedented properties and achievements will inspire researchers to develop novel ideas.

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S.B. and S.G. contributed equally to this work. S.B. and S.P. acknowledge the Council of Scientific and Industrial Research (CSIR), Government of India, for their junior research fellowships (JRF).

Conflict of Interest

The authors declare no conflict of interest.

Keywords

alternating copolymers, maleic anhydride, maleimide, non-conventional luminogen, styrene

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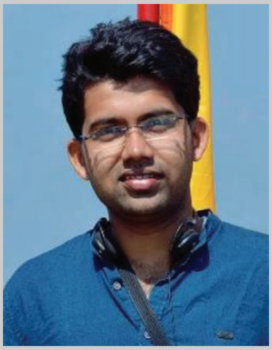

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