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Functional Polymer Particles via Thiol-Ene and Thiol-Yne Suspension

“Click” Polymerization

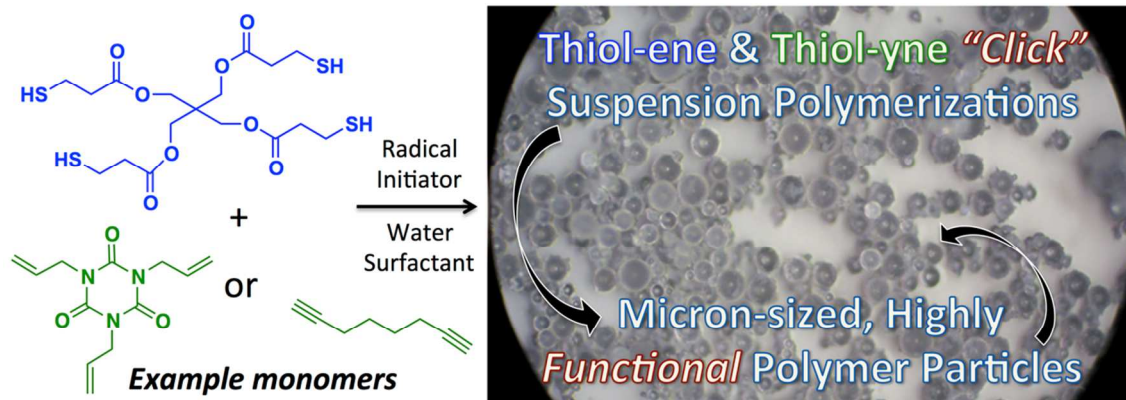
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Abstract

Water-borne thiol-ene and thiol-yne polymer particles were synthesized using several alkene, alkyne, and thiol monomers in suspension thiol-ene and thiol-yne “click” polymerizations. In particular, we show, for the first time, that thiol-yne suspension polymerizations are possible, and that thermal initiation provides similar results as previously reported photoinitiation of thiol-ene monomers. The particles were analyzed in terms of particle size, glass transition temperature (T_g), and ability to undergo chemical functionalization. Composition and crosslink density clearly impacted the glass transition temperatures, with higher crosslink densities leading to higher T_g values. Polymer particles with excess alkene/alkyne or thiol functionality were also synthesized to examine the influence of monomer stoichiometry on particle size and thermal properties of each system. Functionalization of thiol-ene polymer particles was demonstrated using either the inclusion of an ene-functionalized chromophore during the polymerization, or post-polymerization functionalization using thiol-isocyanate chemistry.

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Highly functionalized, water-borne, micron-sized polymer particles were synthesized using thermally or photochemically initiated thiol-ene and thiol-yne “click” suspension polymerizations.

1. Introduction

Polymer particles are widely used in a variety of industrial and biomedical applications including paints and coatings, cosmetics, drug delivery, biomedicine and biotechnology, stimuli-responsive materials, and the development of polymeric composite materials.¹⁻⁷ The method of polymer particle synthesis has an impact on composition, functionality, colloidal stability, and thermo-mechanical properties of the material. Consequently, it is important to choose a method that allows for a facile and affordable means to produce a large quantity of polymer particles with specified physical and chemical properties. In addition, any considered method for polymer particle synthesis should offer control and understanding over the chemical functionality and molecular architecture of the polymer, thus advancing the development of new materials.

Typical heterogeneous methods used to produce polymer particles include suspension, emulsion, and dispersion polymerizations, with these normally using radical chain polymerizations to yield spherical particles composed of linear or crosslinked polymers.¹ Notably, it is only recently that step-growth polymerizations were utilized for the production of particles.^{8, 9} However, we have recently shown¹⁰⁻¹² that thiol-ene “click” chemistry, which has reemerged as is an exemplary approach for the synthesis of versatile and functional polymer materials via a radical-mediated step-growth mechanism,¹³⁻¹⁸ can be applied to the synthesis of micron and sub-micron crosslinked polymer particles. Subsequently, others have used similar approaches to make polymer particles; Tan et al.¹⁹ made porous polymer particles using thiol-ene suspension polymerizations, whereas Jasinski et al.²⁰ developed linear polymer particles using a miniemulsion thiol-ene photopolymerization approach, Wang et al.²¹ synthesized uniform microspheres using base-catalyzed thiol-acrylate Michael polyaddition, and Amato et al.²² showed that sub-100 nm crosslinked particles could be made using thiol-ene miniemulsion

polymerizations. Amato et al.²³ have very recently shown that thiol-yne miniemulsion polymerizations are also possible. Each of these examples take advantage of the thiol-ene/yne “click” chemistry tenets by using multifunctional alkenes, alkynes, and thiols that provide crosslinked polymer particles with well-defined networks at high yields under ambient reaction conditions.^{13-17, 24-26} High reaction rates, multiple modes of initiation (photo-, thermal, and redox), the ease of synthesis in a water-based medium, and the facile compositional tunability afforded by many thiol, ene, and yne monomers and polymers offers numerous opportunities for such materials to be utilized in a variety of fields and applications.^{13-17, 24, 27-32}

In our previous communications outlining the use of thiol-ene suspension polymerizations we focused on a limited set of monomers, used photoinitiation, and examined a range of surfactants and stabilizing agents.¹⁰⁻¹² Here, not only do we expand the range of monomers used in thiol-ene/yne “click” suspension polymerizations, thus providing polymer particles with different compositions, thermo-mechanical properties, and functionality, we also present the first instance of using thiol-yne radical polymerization in suspension polymerizations. We additionally demonstrate that thermal initiation can be used in these systems, which further demonstrates the versatility of this approach for polymer particle synthesis. Furthermore, an attractive feature of thiol-ene and thiol-yne “click” chemistries is the potential for functionalization which, as a result of the step-growth mechanism, can be easily tuned via stoichiometric imbalance of thiol and ene/yne groups.^{14, 16, 32} Consequently, we demonstrate that polymer particles with residual functionality (thiols, enes orynes) can be produced and subsequently used in post-polymerization functionalization reactions.

2. Materials and Methods

2.1 Materials

The following materials were purchased from Sigma-Aldrich unless otherwise noted, and were used as received: 1-hydroxycyclohexyl phenyl ketone, azobisisobutyronitrile (AIBN), 1,7-octadiyne (ODY), 5-hexynoic acid (HYA), 1,3,5-triallyl-1,3,5-triazine-2,4,6(1H,3H,5H)-trione (TTT), trimethylolpropane diallyl ether (TMP), pentaerythritol tetrakis (3-mercaptopropionate) (PETMP), 1,6-hexanedithiol (HDT), 3,6-dioxa-1,8-dithiooctane (EGDT), dichloromethane (DCM), triethylamine (TEA), 4-pentenoyl chloride, 1-naphtyl isocyanate, *N,N*-dimethylformamide (DMF) (Fisher Scientific), methanol (Fisher Scientific), acetone (J. T. Baker), anhydrous diethyl ether (J. T. Baker), dodecyltrimethylammonium bromide (DTAB), Tween 20, toluene (Fisher Scientific), sodium dodecyl sulfate (SDS) (J.T. Baker), and 2-naphthol (Acros Organics).

2.2 Thiol-Ene and Thiol-Yne Suspension Photopolymerizations

All reactions consisted of 10 ml aqueous solutions with 10 wt. % monomer content relative to water. General thiol-ene and thiol-yne reactions used equimolar ratios of π bond functionality relative to thiol functionality, such that each alkene group (double bond) or thiol moiety behaves as mono-functional, while each alkyne (triple bond) is treated as di-functional. The concentration of surfactant stabilizers was 5 wt. % relative to water. The stabilizers utilized included anionic surfactant SDS, the cationic surfactant DTAB, and the nonionic surfactant Tween 20. The organic phase consisted of two multifunctional monomers (alkene and thiol monomers or alkyne and thiol monomers) and toluene (1:1 volume ratio of toluene to monomers), which were combined with the photoinitiator 1-hydroxycyclohexyl phenyl ketone

(0.15 wt. % relative to amount of monomers). The reactions were homogenized via magnetic stirring (~1000 rpm) in a glass vial (20 ml, O.D. x H 25 mm x 57 mm) and Teflon-coated stir bar (12.7 mm x 3 mm). Once the organic phase was combined with the aqueous phase, the reaction was allowed to mix for 5 minutes and then cured under UV light (365 nm, 11 mW/cm²). Reactions with excess ene, yne, or thiol functionality followed the same procedure other than the mole ratio of ene to thiol or yne to thiol. Ratios examined include 1:2 ene-to-thiol, 1:2 yne-to-thiol, 2:1 ene-to-thiol, and 2:1 yne-to-thiol.

2.3 Thiol-Ene and Thiol-Yne Suspension Thermal Polymerizations

The thermal thiol-ene polymerizations were conducted in a three-neck 250 ml round bottom flask with overhead stirring (166 rpm) using a 7.2 cm blade. For the thermal thiol-yne polymerization, the reaction was homogenized via magnetic stirring in a glass vial (20 ml, 25 mm (o.d.) x 57 mm (h)) and Teflon-coated stir bar (12.7 mm x 3 mm). All organic phases consisted of either alkene or alkyne monomers along with thiol monomers, toluene, and AIBN (1 wt. % relative to monomers). The aqueous phase consisted of 5 wt. % SDS relative to water. After the organic phase was added to the aqueous phase, the reaction mixtures were mixed for 5-10 minutes. After initial mixing, the reaction vessels were placed in an oil bath at 60°C for 3 hours.

2.4 In Situ Particle Functionalization

In situ functionalization was conducted by combining TTT and PETMP monomers with varying amounts of 2-naphthyl-4-pentenoate. Synthesis of 2-naphthyl-4-pentenoate is described and characterized in the Supplemental Information. Two naphthyl loadings were examined, with

the 2-naphthyl-4-pentenoate providing either 5% or 15% of the ene functionality (1:1 mole ratio of ene to thiol was maintained). Both reactions were conducted using ~10 wt. % organics relative to the aqueous phase. For the 5% chromophore reaction, the organic phase consisted of 0.335 ml TTT (0.004678 mol), 0.0557 g 2-naphthyl-4-pentenoate (0.0002462 mol), 0.47 ml PETMP (0.004924 mol), 0.0105 g photoinitiator (1 wt. % relative to monomers and chromophore), and 0.81 ml toluene. This reaction was conducted in 10 ml of 5 wt. % SDS. For the 15% chromophore reaction, the organic phase consisted of 0.185 ml TTT (0.002583 mol), 0.1031 g 2-naphthyl-4-pentenoate (0.0004558 mol), 0.29 ml PETMP (0.003039 mol), 0.0069 g photoinitiator (1 wt. % relative to monomers and chromophore), and 0.5 ml toluene. This reaction was conducted in 5 ml of 5 wt. % SDS. Each reaction mixture was cured under UV-light for 60 minutes while being stirred with a Teflon-coated stir bar (12.7 mm x 3 mm). Each set of product particles were washed twice in DCM for 1 hour. Product particles were analyzed using optical microscopy, fluorescence microscopy, UV-Vis spectroscopy, and fluorescence spectroscopy.

2.5 Post-Polymerization Functionalization

A post-polymerization functionalization of 1:1.5 TTT/PETMP particles and 1:1.5 ODY/PETMP particles was conducted in a thiol-isocyanate reaction with 1-naphthyl isocyanate in the presence of trimethylamine (TEA) as a base catalyst. This procedure was adapted from a procedure reported by Gokmen *et al.*³³ Each reaction used ~50 mg of particles that were synthesized as described in Section 2.2. The isocyanate and TEA were used at approximately three and two times that of the thiol (by moles) available in the polymer particles, respectively. The amount of thiol available for functionalization was taken as the difference between the thiol

and alkene (or alkyne) used in the particle synthesis reaction. The ODY/PETMP functionalization reaction included 50 mg particles, 0.0634 g (0.37 mmol) 1-naphthyl isocyanate, 0.03 ml TEA, and 5 ml of DMF. The TTT/PETMP functionalization reaction included 50 mg particles, 0.0406 g (0.24 mmol) 1-naphthyl isocyanate, 0.02 ml TEA, and 5 ml of DMF. In both the ODY/PETMP and TTT/PETMP reactions, the 1-naphthyl isocyanate was dissolved in 2 ml of DMF in a small vial and this solution was then transferred to a second vial containing 50 mg of particles and 3 ml of DMF. TEA was added to the combined solution. The reactions were stirred for ~8 hours at room temperature. After 8 hours, each reaction was vacuum filtered and washed three times each with 5 ml methanol, 5 ml DCM, 5 ml acetone, and 5 ml anhydrous diethyl ether. The particles were dried thoroughly in a vacuum oven for 2.5 days prior to analyses.

2.6 Characterization

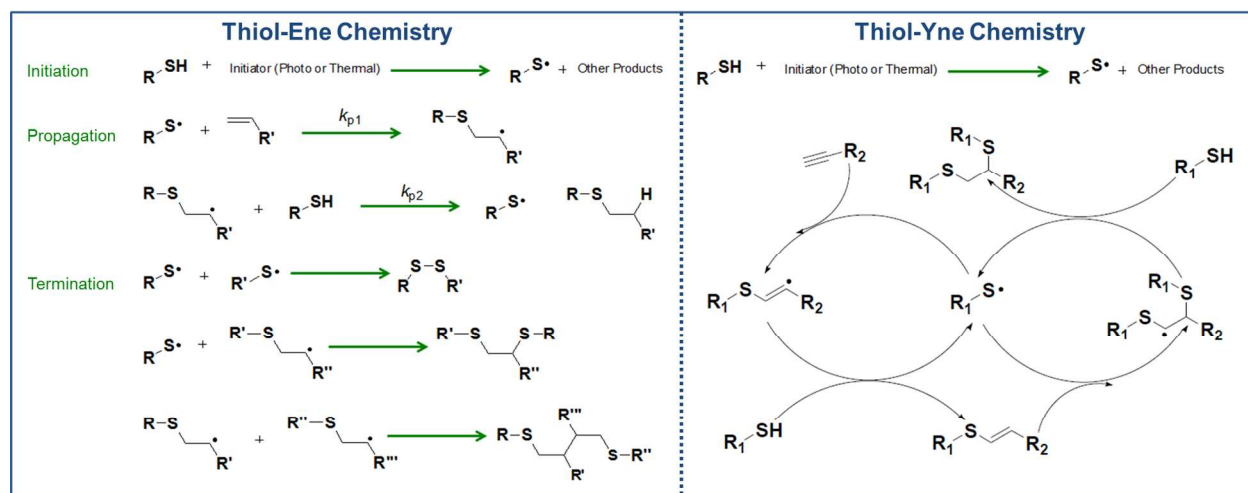
Optical images were obtained on an Olympus optical microscope. Samples were measured in the wet reaction solution or were prepared by simple air-drying on the microscope slide. For additional analyses, product material was filtered and washed with distilled water and ethanol, followed by drying in a vacuum oven. Differential scanning calorimetry (DSC) was performed on a TA Instruments Q100 instrument, with a heating rate of 10°C/min. Ultraviolet-visible (UV-Vis) spectroscopic analysis was done at a fixed wavelength of 275 nm (for analysis with 2-naphthyl-4-pentenoate) or 292 nm (for analysis with 1-naphthyl isocyanate) using an Agilent 8453 Spectrometer with quartz cuvettes. Fluorescence analysis was done using a Perkin Elmer LS 55 Fluorescence Spectrometer ($\lambda_{\text{ex}} = 275$ nm; slit widths: excitation 10 nm, emission 5 nm for analysis with 2-naphthyl-4-pentenoate or $\lambda_{\text{ex}} = 292$ nm; slit widths: excitation 5 nm,

emission 2.5 nm for analysis with 1-naphthyl isocyanate). Analysis using UV-Vis and fluorescence spectroscopy was done for thiol-ene and thiol-yne particles (blank or loaded with chromophore) suspended in dichloromethane. Fluorescence microscope images were taken using a Nikon TE200 inverted epifluorescence microscope with a Hamamatsu Photonic camera. Polymer particles (blank and particle containing chromophore) were dispersed in ethanol and then placed on a microscope slide with dual wells. After air drying, samples were covered with cover slips and analyzed. Fluorescence was detected using a mercury arch lamp with its respective DAPI fluorescence filters. Samples were examined using UV light with an excitation wavelength of 350 nm and an emission wavelength of 510 nm. Nuclear magnetic resonance (NMR) analysis was conducted using a Bruker Avance DMX-400 instrument.

3. Results and Discussion

Our recently demonstrated¹⁰⁻¹² approach of thiol-ene suspension polymerizations to yield polymer particles via photoinitiation has several major benefits including reaction times that are a matter of minutes, essentially 100% conversion and yield, and well-defined crosslinked network structures, all features that are common of the “click” chemistries when applied to polymerizations. Such advantages stem from the fact that mechanistically the thiol-ene and thiol-yne polymerizations occur in a step-growth manner yet use radical intermediates. This unique combination provides access to the range of benefits listed above, many of which are not attainable through radical chain growth polymerizations (of acrylics, for example) or condensation step-growth polymerizations. As illustrated in Scheme 1, thiol-ene and thiol-yne polymerizations require radical generation via thermal, photo- or redox processes, and propagation occurs through a sequence of steps wherein thiyl radicals add to alkene or alkyne

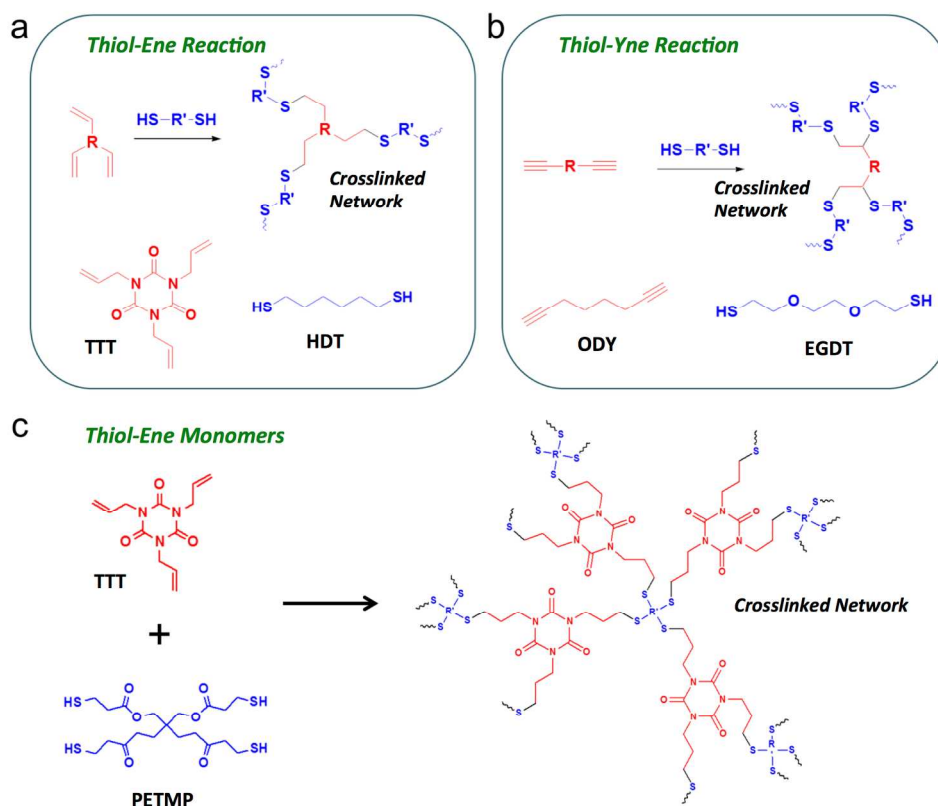
groups, forming carbon-center radicals that then abstract a hydrogen atom, completing the addition process and reproducing a thiyl radical. The propagation reactions have been shown to be extremely fast, and thus these polymerizations occur very quickly.^{15, 28} Interestingly, this is even the case in the photoinitiated suspension polymerizations we have investigated; as shown in the Supplemental Information (Figure SI-2), these non-transparent polymerizations (at least in the small scale reaction vials used here) are complete within 4 minutes, indicating that fast thiol-ene (or yne) reactions can be efficiently conducted even with minimal light penetration into the well-dispersed reaction mixture. As in all radical polymerizations, termination steps, such as the combination reactions shown in Scheme 1, are unavoidable.



Scheme 1. General reaction mechanisms for thiol-ene and thiol-yne chemistry.

Furthermore, one of the primary benefits of the step-growth mechanism of thiol-ene (and thiol-yne) polymerizations is that strict control over functionality can be obtained through judicious choice of monomer stoichiometry, which in turn allows for potential *in situ* and post-polymerization functionalization.^{14, 34-39} In the work presented here, we describe the first application of both thiol-ene and thiol-yne chemistry for the production of polymer particles via

photo- and thermal initiated suspension polymerizations, and demonstrate their potential for *in situ* particle functionalization. Example monomers used and the general reaction for thiol-ene and thiol-yne synthesis are provided in Scheme 2.



Scheme 2. Structures of monomers used for (a) thiol-ene and (b) thiol-yne suspension polymerizations. (c) An example of a crosslinked polymeric network for a thiol-ene polymerization with TTT and PETMP.

3.1 ODY and PETMP Thiol-Yne Photopolymerization

One advantage of thiol-yne polymerizations have over their thiol-ene analogues is that they typically produce networks with greater crosslink density, as well as materials with higher sulfur content.¹⁷ While thiol-yne chemistry has been employed in bulk polymer synthesis,^{13, 16, 17,}

^{24, 38, 40, 41} it has not been reported in heterogeneous (e.g., miniemulsion, dispersion, suspension) polymerizations. To demonstrate the use of thiol-yne chemistry in a suspension polymerization, we initially used the dialkyne ODY and the tetrathiol PETMP with three different stabilizers. Optical microscope images for each reaction are shown in Figure 1. We observe polymer particles from alkyne-thiol monomers that are similar to the particle synthesis in the thiol-ene systems in that both approaches yield spherical crosslinked particles with a variety of sizes, as normally seen in conventional (radical chain growth) suspension polymerizations. The particle size and size distributions varied depending upon the surfactant species used for particle stabilization during synthesis. In general, smaller polymer particles were obtained when reactions were stabilized by ionic surfactant species (Figures 1(a) and 1(b)). Larger particles were obtained when the thiol-yne particles were stabilized with the nonionic surfactant species Tween 20 (Figure 1(c)). These observations are comparable to what has been observed for thiol-ene systems stabilized by different surfactant species.¹¹ Additional thiol-yne systems were also examined (*vide infra*) and similar results were obtained. Thus the extension to include thiol-yne chemistry in suspension polymerizations allows access to an extensive selection of commercially available monomers.

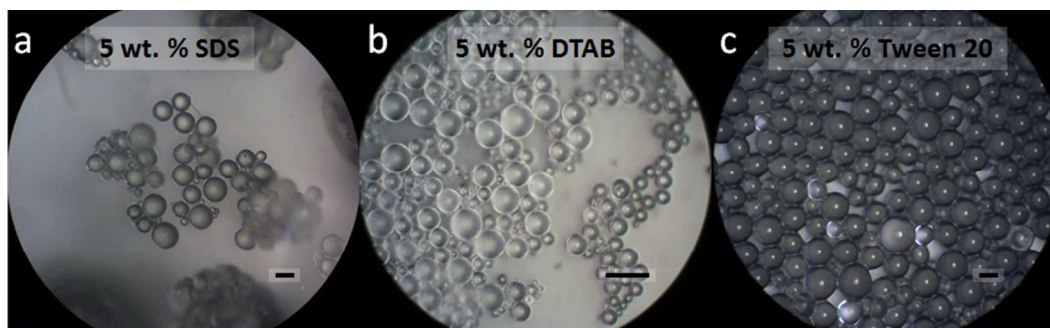


Figure 1. Optical microscope images of product particles from ODY/PETMP.

photopolymerizations using different surfactant stabilizers including (a) SDS, (b) DTAB, and (c) Tween 20. The scale bar in each case is 100 μm .

3.2 Various Monomers in Thiol-Ene and Thiol-Yne Photoinitiation Systems

Since monomer composition in thiol-ene and thiol-yne polymerizations can largely influence incorporated functionality, crosslink density, and thermo-mechanical properties, we evaluated such properties of a variety of polymer particles made using commercially available alkenes, alkynes, and thiol monomer species.^{14, 42-44} These properties in turn may impact particle size and size distribution, as particle size can be influenced by the degree of crosslinking and flexibility of the polymer chain. In addition, different monomer species will influence the solution viscosity and its impact on comminution efficiency, the final polymer molecular weight, and the polymerization efficiency in terms of reactivity of the monomer species.^{7, 14, 42-45} Consequently, the use of thiol-ene and thiol-yne step-growth polymerization will help lead to the production of polymer particles with diverse composition, thermo-mechanical properties, and functionality for a variety of applications. We therefore examined four different polymer compositions for both thiol-ene polymer particles (Figure 2) and thiol-yne polymer particles (Figure 3). The thiol-ene polymer compositions examined include TTT/PETMP, TTT/EGDT, TTT/HDT, and TMP/PETMP. The thiol-yne polymer compositions examined include

ODY/PETMP, ODY/EGDT, ODY/HDT, and HYA/PETMP. All reactions were conducted with equimolar ratios of π bonds (in the alkene or alkyne) to thiol functionality. In addition, each reaction was conducted in 5 wt. % SDS under identical conditions. Based on the images in Figures 2 and 3, it can be seen that all water-borne thiol-ene polymerizations yield spherical polymer particles and that the reaction systems of TTT/EGDT (Figure 2(b)) and TTT/HDT (Figure 2(c)) yielded the smallest polymer particles. Particles obtained in these thiol-ene and thiol-yne reactions have particle diameters in the range of 5-200 μm . The largest polymer particles were obtained in the most densely crosslinked system of TTT/PETMP (Figure 2(a)), although other factors (such as monomer viscosity) might be contributing to such particle size variations. Similar trends were observed in the thiol-yne polymerizations (Figure 3). Data for the range of particle sizes observed in visual analyses as well as the glass transition temperature (T_g) of each polymer composition are provided for each reaction system in Table 1. Due to the variation in particle size attributed to suspension polymerizations, the ranges of particle sizes presented are based on estimation via visual analysis, where the smallest and largest particle sizes were used as the inclusive range. Numerous optical microscope images were evaluated for each set of polymer particles. For these water-based systems, the most densely crosslinked networks yielded the highest glass transition temperatures. The highest T_g values observed were for the highly crosslinked systems of TTT/PETMP and ODY/PETMP.

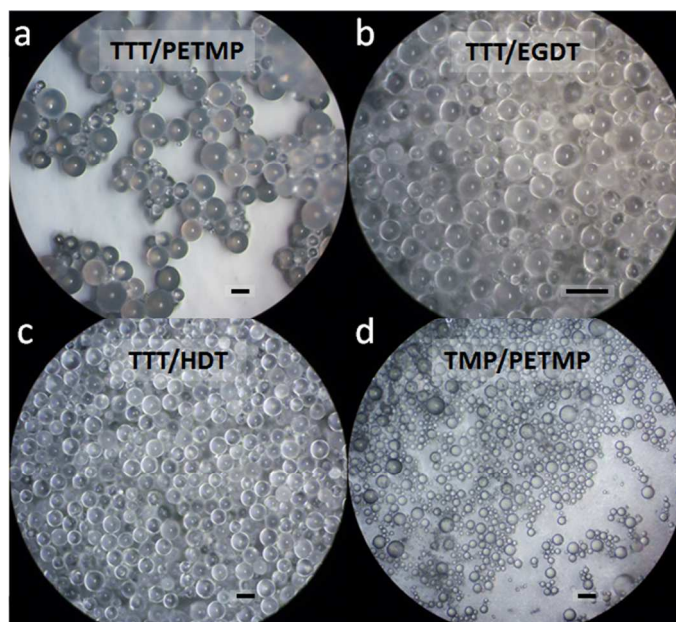


Figure 2. Optical microscope images of various thiol-ene polymer particles stabilized by 5 wt. % SDS. Each scale bar represents 100 μm .

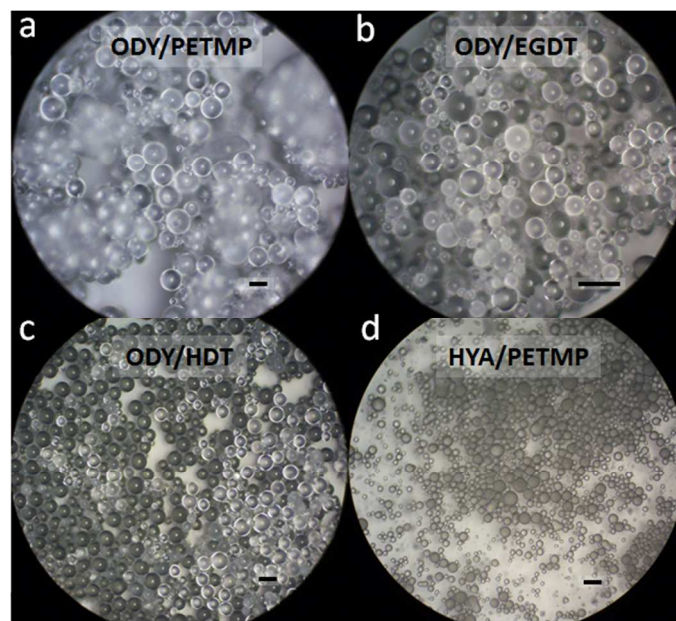


Figure 3. Optical microscope images of various thiol-yne polymer particles stabilized by 5 wt. % SDS. Each scale bar represents 100 μm .

Table 1. Particle Properties from Thiol-Ene and Thiol-Yne Polymers.

Composition ^a	Ene or Yne ^b Functionality	Thiol Functionality	T _g (°C)	Particle Size ^c (μm)
TTT/PETMP	3	4	26	15-200
TTT/EGDT	3	2	-16	5-85
TTT/HDT	3	2	4	15-120
TMP/PETMP	2	4	-19	5-130
ODY/PETMP	4	4	8	10-160
ODY/EGDT	4	2	-28	10-70
ODY/HDT	4	2	-9	15-110
HYA/PETMP	2	4	-16	5-95

a) Monomers: 1,7-octadiyne (ODY) and 5-hexynoic acid (HYA), 1,3,5-triallyl-1,3,5-triazine-2,4,6(1H,3H,5H)-trione (TTT), trimethylolpropane diallyl ether (TMP), pentaerythritol tetrakis (3-mercaptopropionate) (PETMP), 1,6-hexanedithiol (HDT), and 3,6-dioxa-1,8-dithiooctane (EGDT).

b) Each alkyne moiety is treated as di-functional.

c) Particle size range estimated visually from microscope images (Figures 2 and 3).

3.3 Variation in Ene/Yne : Thiol Ratio

Several thiol-ene and thiol-yne reactions were conducted to examine the impact of introducing excess functionality from one monomer species into the polymer network during particle synthesis. Three different compositions were examined for both thiol-ene and thiol-yne systems: TTT/PETMP, TTT/EGDT, and TMP/PETMP, and ODY/PETMP, ODY/EGDT, and HYA/PETMP, all with compositions based on 1:1, 1:2, and 2:1 mole ratios of alkene (or alkyne) to thiol functionality. For the thiol-yne work, each alkyne moiety was treated as di-functional. Optical microscope images comparing polymer particles obtained from reactions with excess functionality are provided for the three thiol-ene systems (Figure 4) and for the three thiol-yne systems (Figure 5). Note that some samples provided much better images when still wet and

some polymer compositions formed films when dried to the point that the individual particles were no longer distinguishable. These observations may be attributed to the thermo-mechanical properties of the particular polymer structure, particularly low T_g values. We generally observe that particle sizes might decrease slightly when particles are dried, indicating that the particles being slightly swollen in the aqueous media. The range of particle sizes observed in visual analyses and the glass transition temperatures (T_g) of each polymer composition are given in Table 2.

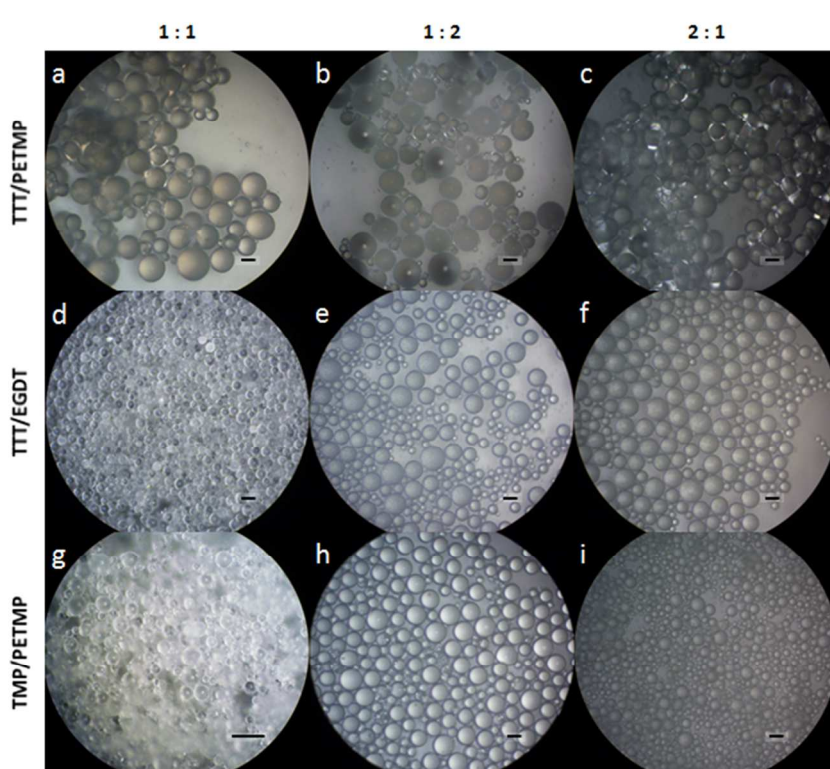


Figure 4. Optical microscope images from different thiol-ene photopolymerization systems that examined the variation of alkene and thiol functionality. Each reaction system was examined at 1:1, 1:2, and 2:1 ene to thiol functionality. Scale bars are 100 μm .

Each reaction was conducted under identical conditions and stabilized by 5 wt. % SDS. The presence of excess functionality affects the particle size and range of particle sizes for each thiol-ene polymer composition. Excess functionality in the polymer network may impact the comminution of monomer droplets due to changes in reaction viscosity. Limited control over the dynamic equilibrium between comminution and coalescence of the monomer droplets during polymerization will result in various polymer particle sizes. All reactions comparing excess functionality yielded spherical polymer particles in a comparable size range as seen in reaction with equimolar functionality. The TTT/PETMP system appears to give particles that have the greatest variance in size in the presence of excess thiol functionality (Figure 4(b)). The TTT/PETMP reaction with excess alkene functionality appears to yield particles that are smaller in size (Figure 4(c)). This observation is also true for the TMP/PETMP reaction with excess alkene functionality (Figure 4(i)). The TTT/EGDT reaction system with equimolar functionality yielded the smallest polymer particles obtained for all thiol-ene systems examined in this particular study (Figure 4(d)). Excess thiol functionality for the TTT/EGDT and TMP/PETMP systems yielded much larger particles with broad variation in particle size as compared to the equimolar reactions (Figures 4(e) and 4(h)).

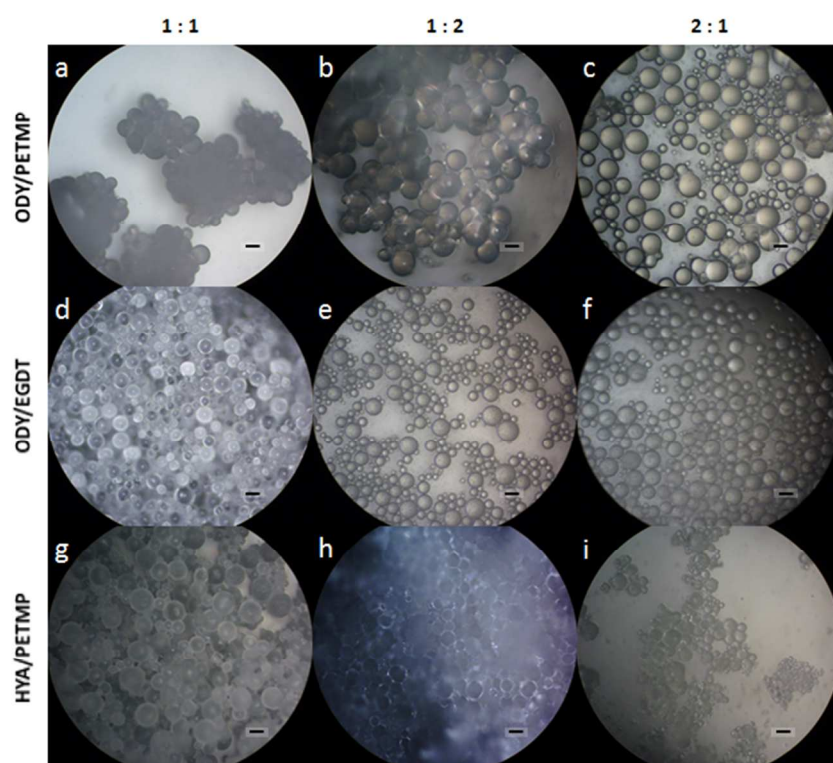


Figure 5. Optical microscope images from different thiol-yne photopolymerization systems that examined the variation of alkyne and thiol functionality. Each reaction system was examined at 1:1, 1:2, and 2:1 yne to thiol functionality. Scale bars are 100 μm .

Thiol-yne reactions with various stoichiometries also exhibit the formation of spherical polymer particles. Each reaction was conducted under identical conditions and stabilized by 5 wt. % SDS. For the reaction system of ODY/PETMP, the most consistent particle size ranges were obtained in the cases of equimolar or excess thiol functionality (Figures 5(a) and 5(b)). The equimolar and excess alkyne reactions of ODY/EGDT (Figures 5(d) and 5(f)) yield the narrowest variation in particle size for the thiol-yne reaction systems. Although the reaction systems were significantly polydisperse in particle size, the smallest polymer particles obtained were observed in the systems of HYA/PETMP and ODY/PETMP.

Table 2. Comparison of Particle Properties from Thiol-Ene and Thiol-Yne Polymers with Variations in Akene/Alkyne to Thiol Functionality Ratios.

Composition ^a	Ene/Yne : Thiol ^b	T _g (°C)	Particle Size ^c (μm)
TTT/PETMP	1 : 2	23	10-220
	1 : 1	26	15-230
	2 : 1	22	25-170
TTT/EGDT	1 : 2 ^d	-47	15-195
	1 : 1	-16	12-85
	2 : 1	-33	15-180
TMP/PETMP	1 : 2	-36	25-175
	1 : 1	-19	5-70
	2 : 1	-36	12-115
ODY/PETMP	1 : 2	-8	25-200
	1 : 1	8	15-180
	2 : 1	26	17-190
ODY/EGDT	1 : 2	-58	20-150
	1 : 1	-28	25-125
	2 : 1 ^d	-50	25-120
HYA/PETMP	1 : 2 ^d	-51	17-140
	1 : 1	-16	15-160
	2 : 1	-1	30-155

a) Monomers are 1,7-octadiyne (ODY) and 5-hexynoic acid (HYA), 1,3,5-triallyl-1,3,5-triazine-2,4,6(1H,3H,5H)-trione (TTT), trimethylolpropane diallyl ether (TMP), pentaerythritol tetrakis (3-mercaptopropionate) (PETMP), 1,6-hexanedithiol (HDT), and 3,6-dioxa-1,8-dithiooctane (EGDT)

b) Each alkyne moiety is treated as di-functional.

c) Particle size range estimated visually from microscope images (Figures 4 and 5).

d) Forms a film when dry.

Particles obtained in these thiol-ene and thiol-yne reactions have particle diameters in the range of ~5-230 μm. The polymer compositions with higher glass transition temperatures include

TTT/PETMP and ODY/PETMP, which can be attributed to the rigidity and branching in the crosslinked networks. Several polymer compositions achieved higher T_g values at equimolar or excess alkene/alkyne functionality, while some polymers exhibited high T_g values with excess thiol functionality. The ODY/PETMP and TTT/PETMP polymers exhibited the highest T_g values of all polymers analyzed. This observation can be attributed to the high crosslinking density achieved using tri-functional and tetra-functional monomers. One unsurprising observation that can be made is that the structure of the monomers, as well as degree of functionality within them, impact thermal properties of the resulting polymer network. Specifically, polymer compositions with higher ene/yne or thiol functionality in the starting monomer yield polymers with higher glass transition temperatures. Furthermore, thiol-yne systems may offer the potential to possess higher T_g values compared to similar thiol-ene systems, as demonstrated previously.⁴⁰ Another factor that affects the T_g is the presence of water or diluents, which results in the lowering of the T_g due to the plasticizing effect of solvents⁴⁶⁻⁴⁸ on the polymer network.

3.4 Thermal Thiol-Ene and Thiol-Yne Suspension Polymerizations

The majority of our work presented so far has used photoinitiation, but the use of thermal initiation, a more traditional method in other heterogeneous polymerizations, may allow use of existing infrastructure and processing methods. Thus thermally initiated reactions were conducted using 1 wt.% AIBN as the initiator at 60°C for 3 hours. The reactions took place in a round-bottom flask with an overhead stirrer. Optical microscope images were obtained comparing particles from the thiol-ene system of TTT/PETMP and the thiol-yne system of ODY/PETMP (Figure 6). Both reaction systems yield spherical, crosslinked polymer particles with diameters in the range of 5-110 μm . The thiol-yne system yielded overall smaller polymer

particles (Figure 6(b)). This range of particle sizes is smaller than particles obtained during photoinitiation of these particular polymer compositions. Smaller polymer particles may be attributed to the longer stirring duration of reactions during thermal initiation. The use of thermal initiation can accommodate for the incorporation of additional alkene, alkyne, and thiol species that react more efficiently at higher temperatures or over longer reaction durations.

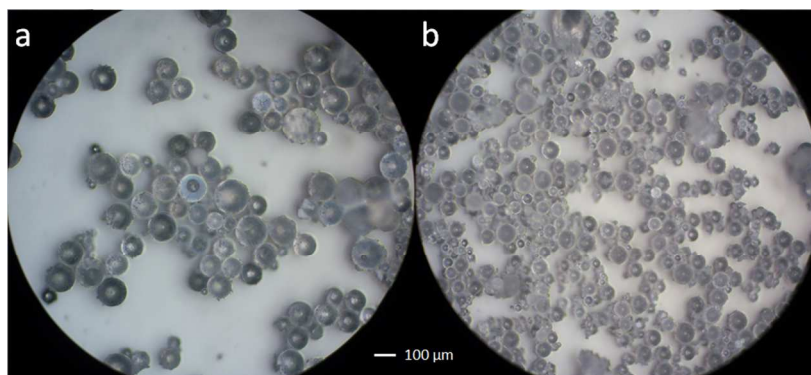
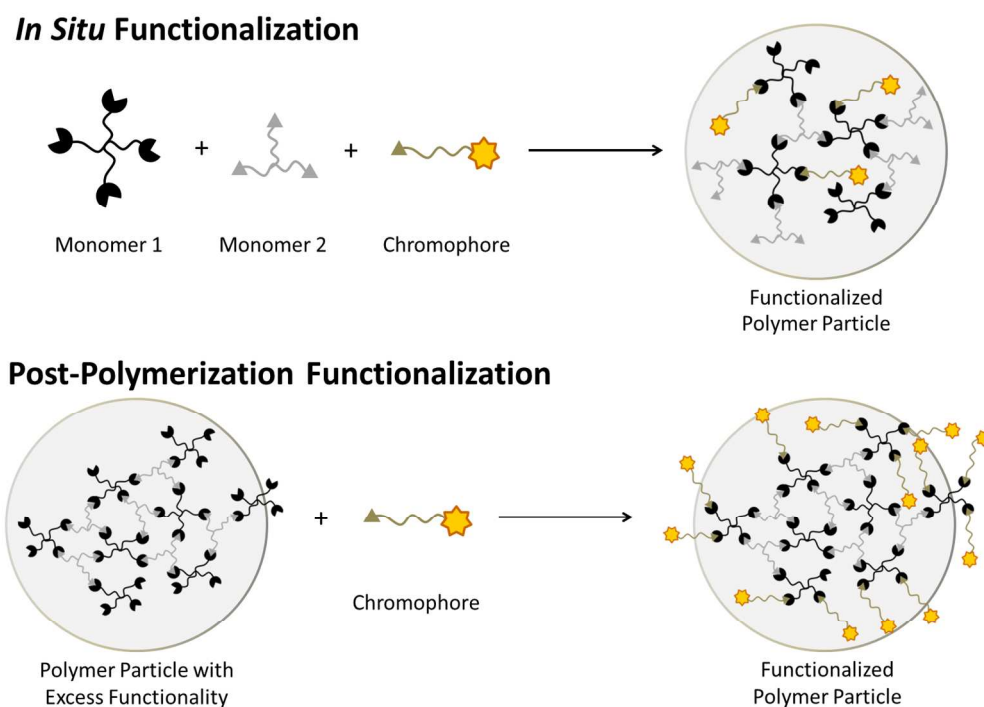


Figure 6. Polymer particles obtained via thermal polymerization with 4 wt. % AIBN relative to monomers for a) the thiol-ene system of TTT and PETMP and b) the thiol-yne system of ODY and PETMP.

3.5 Particle Functionalization

Two approaches for the synthesis of functionalized polymer particles were investigated, as depicted in Scheme 3. Firstly, *in situ* particle functionalization was used for the synthesis of thiol-ene polymer particles that contain a chromophore in the polymer network. This approach combined the alkene monomer TTT, the thiol monomer PETMP, and the vinyl-functionalized chromophore 2-naphthyl-4-pentenoate. Secondly, post-polymerization functionalization was demonstrated by reacting both thiol-ene and thiol-yne polymer particles that contain an excess of thiol functionality with an isocyanate chromophore species via a thiol-isocyanate reaction in the

presence of TEA as a base catalyst. Polymer compositions used were TTT/PETMP and ODY/PETMP with a 1:1.5 mole ratio of ene or yne functionality to thiol functionality. Confirmation of residual ene, yne or thiol functionality was made using either the Baeyer's reagent test of unsaturation or titration with silver nitrate (see Supplemental Information, Figures SI-3 and SI-4). Details regarding the synthesis of the ene- and thiol-functionalized chromophores and an outline of the functionalization reactions conducted (*in situ* and post-polymerization functionalization) are provided in the Supplemental Information (Figure SI-5).



Scheme 3. General pathways investigated for the synthesis of functionalized polymer particles.

Polymer particles made via the *in situ* functionalization route consisted of TTT, PETMP and 2-naphthyl-4-pentenoate exhibited a characteristic pale yellow color (Figure 7), even after exhaustive washes in DCM, whereas particles made without the chromophore are white in appearance. The visible color observed is derived from the naphthyl pentenoate, which exhibits a

pale yellow when dissolved in various solvents. Fluorescence spectra also demonstrate the chromophore loading of particles compared to non-functionalized TTT/PETMP particles (Figure 8), as does fluorescence microscopy (Figure 9).

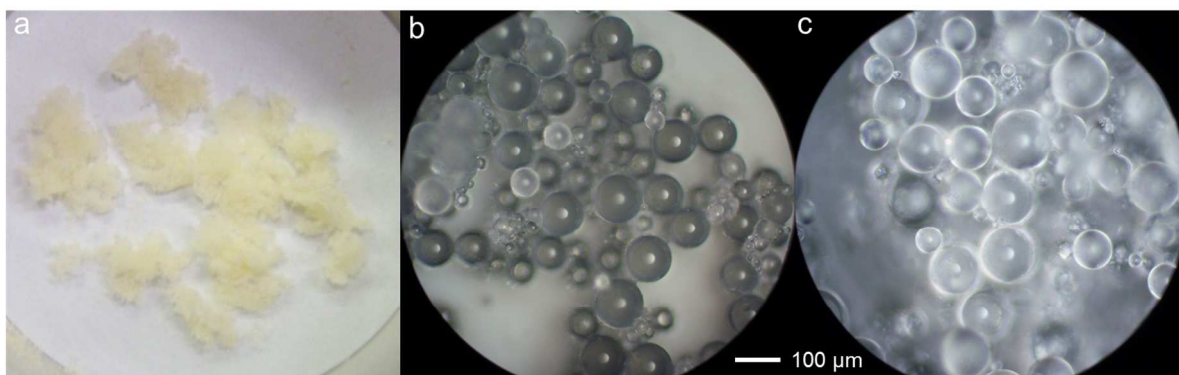


Figure 7. Product material from an a) *in situ* functionalization reaction of TTT and PETMP with 2-naphthyl-4-pentenoate is compared to optical microscope images of b) particles functionalized with 5% ene functionality from 2-naphthyl-4-pentenoate and c) particles functionalized with 15% ene functionality from 2-naphthyl-4-pentenoate.

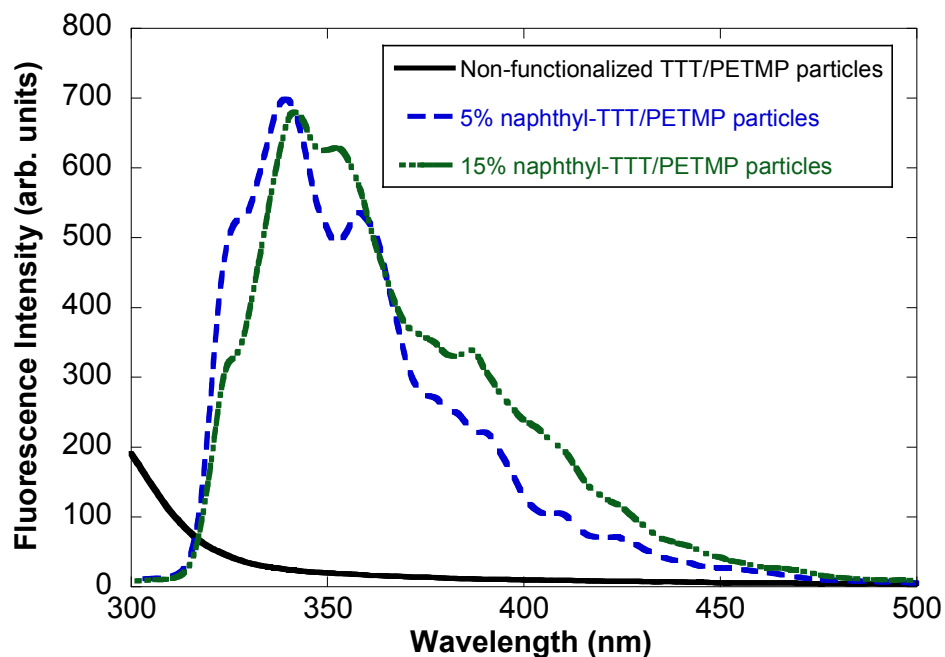


Figure 8. Fluorescence spectra of *in situ* functionalized TTT/PETMP particles with 5% or 15% of ene functionality from 2-naphthyl-4-pentenoate compared to non-functionalized TTT/PETMP polymer particles.

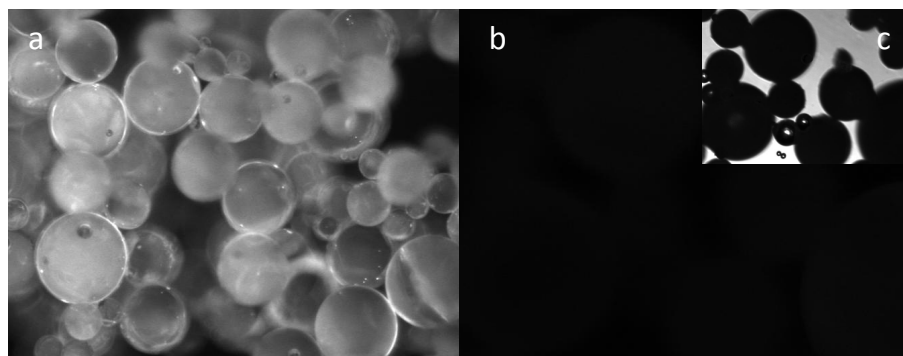


Figure 9. Fluorescence microscope images of a) *in situ* functionalized TTT/PETMP particles using 15% of ene functionality from 2-naphthyl-4-pentenoate and b) non-functionalized TTT/PETMP polymer particles. c) White light image of non-functionalized TTT/PETMP polymer particles.

The post-polymerization functionalization process is illustrated using both thiol-ene and thiol-yne polymer particles with excess thiol moieties that were subjected to the thiol-isocyanate reaction with 1-naphthyl isocyanate. Optical microscopy was conducted to examine polymer particles before and after functionalization (Figure 10). Both sets of functionalized polymer particles were exhaustively washed with methanol, acetone, DCM, and diethyl ether. After washing and drying the polymer particles, fluorescence spectroscopy was conducted to compare the non-functionalized TTT/PETMP and ODY/PETMP particles to particles functionalized with 1-naphthyl isocyanate (Figure 11). While there are no changes to particle size or shape, as demonstrated in Figure 10, there is clearly fluorescence from the functionalized particles (Figure 11), a good indication that the thiol-isocyanate reaction was successful.

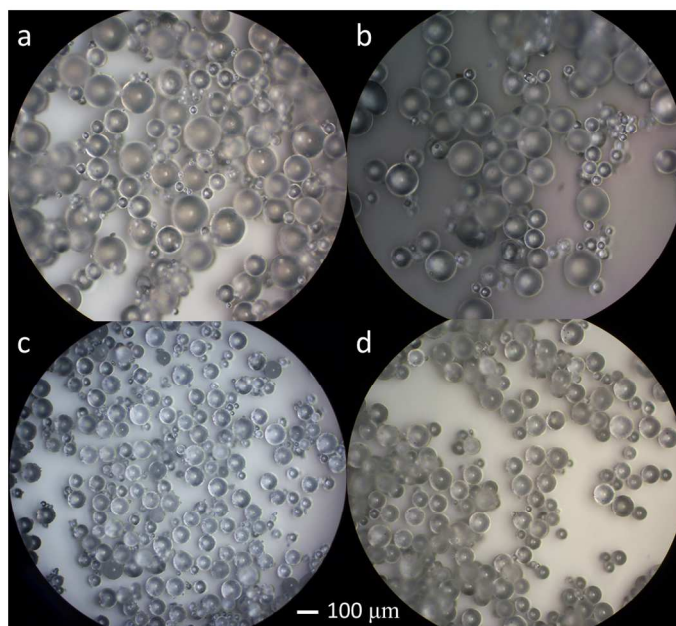


Figure 10. Optical microscope images of a) 1:1.5 TTT/PETMP and c) 1:1.5 ODY/PETMP particles before functionalization are compared to c) functionalized TTT/PETMP and d) functionalized ODY/PETMP particles after the thiol-isocyanate reaction with 1-naphthyl isocyanate.

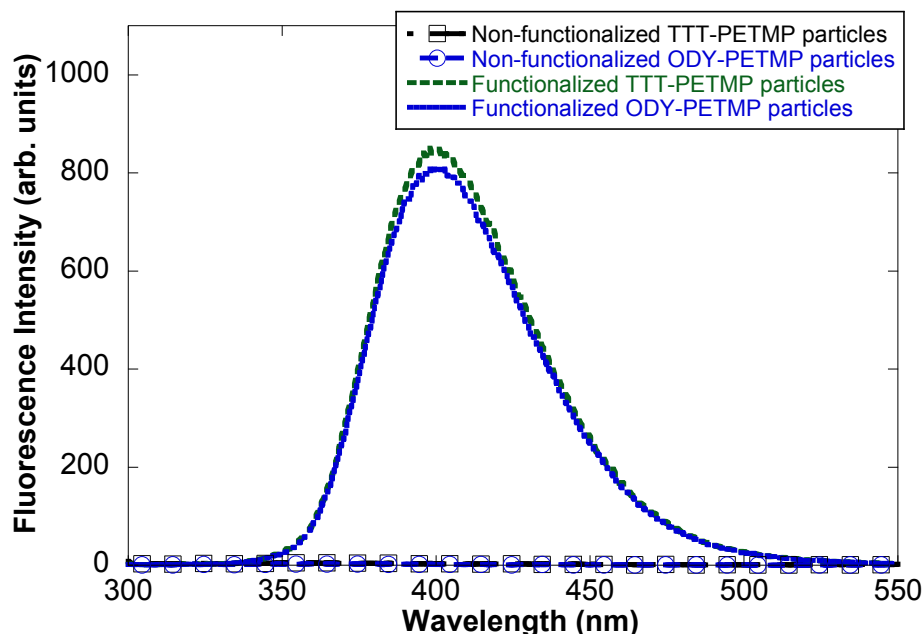


Figure 11. Fluorescence spectra of 1:1.5 TTT/PETMP and 1:1.5 ODY/PETMP particles functionalized with 1-naphthyl isocyanate in a post-polymerization functionalization process compared to non-functionalized 1:1.5 TTT/PETMP and 1:1.5 ODY/PETMP polymer particles.

4. Conclusions

We have reported that suspension thiol-ene and, for the first time, thiol-yne “click” polymerizations can be successfully conducted with various polymer compositions, crosslink density and monomer stoichiometry. All polymer particles obtained were micron-sized particles with variation in particle size, as is commonly seen in conventional suspension polymerizations. Based on our analyses, monomer selection, and thus parameters such as crosslink density, impacts particle size and size distribution only slightly. It was also found that thiol-yne suspension polymerizations parallel our previous work on thiol-ene polymer particles in terms of parameters that affect particle size and distribution.

We also have demonstrated the synthesis of polymer particles with excess alkene, alkyne, or thiol functionality. The presence of excess functionality may allow for the post-polymerization functionalization of the product thiol-ene and thiol-yne particles through a variety of orthogonal chemical reactions. We also show that thiol-ene (and thiol-yne) suspension polymerizations can easily incorporate specific functional groups into the polymer particles simply through using vinyl- or thiol-containing monomers that contain the desired functional group(s). These advances enhance the opportunities of these and other ‘click’ chemistries to be used in the production of highly functionalized polymer colloids, along with offering an efficient means for the synthesis of water-borne polymer particles.

Electronic Supplemental Information

Electronic Supplemental Information is available (experimental details, additional data, and spectra). See DOI: 10.1039/.....

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