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Polymer-supported, photo-redox catalysts prepared from unimolecular photo-redox catalyst/initiator systems

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ABSTRACT

Unimolecular, photo-redox catalyst/initiator systems can effectively synthezise their own polymer-support that can then be used to affect recovery and reuse of the resulting supported catalyst. We show that α-bromo ester-containing Ru(bpy)$_3$- and phenothiazine-derivatives (common photo-redox catalysts) can undergo visible light-facilitated radical polymerizations to form polymer-supported photo-redox catalysts that can facilitate photo-redox [2+2] cycloadditions and metal-free borylations in a recyclable manner.

Introduction

The invention of techniques that affect catalyst recovery and reuse play an important role in implementing the green chemistry principles in academia as well as industry. There are many ways to do this, but the use of polymer supports is especially common [1–6]. Both soluble and insoluble polymer supports can be used to affect catalyst and product separations (as either solids or solutions) which leads to catalyst reuse. While insoluble supports offer benefits of simple separations, soluble polymer supports have been shown to exhibit reactivity virtually identical to their low molecular weight counterparts, making them attractive handles for carrying out homogeneous catalysis [7]. Early examples described the use of linear polystyrene (a soluble analogue to Merrifield resins [8]) as well as polyethylene glycol (PEG), poly(ethyleneimine) (PEI), and poly(vinylpyrrolidinone) [9,10]. In the nearly-half-century since, many other supports have been developed, including (but not limited to) polystyrene derivatives [11], poly(*N*-alkylacrylamide)s [12], polyethylene (PE) [13], and polyisobutylene (PIB) [14].

The development of controlled ("living") metal-catalysed/initiated polymerizations [15] has opened the door for the preparation of new, designer macromolecules with exquisite control over molecular weights, morphologies, and end group identity (recent reports detailing the utilization of visible light to facilitate these reactions are incredibly interesting and promising with respect to green chemistry [16]).

In particular, ring opening metathesis polymerization (ROMP [17]) and atom transfer radical polymerization (ATRP [18]) are among the most widely reported techniques, both of which have been utilized to prepare polymer-supported catalysts by our group [19,20] and others [21,22]. However, their use in this regard may amount to nothing more than an academic curiosity since the catalyst required to synthesize the polymer support is (i) often more valuable than the support (and the species being supported) and (ii) is almost always discarded after a single polymerization. This renders the recovery and reuse of the less-precious supported catalyst inconsequential.

Greener alternatives have been developed. For instance, encapsulation strategies and the use of "self-supported" metal catalysts have been reported [23–25]. Both use a metal species to prepare a polymer that retains and uses this same metal for other chemistries. Additionally, Parthiban *et al.* described the use of *unimolecular ligand/initiator systems* (ULIS [26]) for carrying out more atom-economical ATRP reactions. Upon polymerization, a macromolecule composed of all four ATRP constituents (ligand, initiator, catalyst, and monomer) can be isolated (Fig. 1).

Although incredibly intriguing, this report has essentially been ignored. This is surprising considering the obvious potential for such systems to serve as supported catalysts for sequential, tandem, pseudo-tandem, or sequential processes [27]. Realizing this idea would involve merging the principles of the self-supporting/encapsulation strategies with those of a ULIS: designing a catalyst that is able to build its own polymeric scaffold (in a controlled

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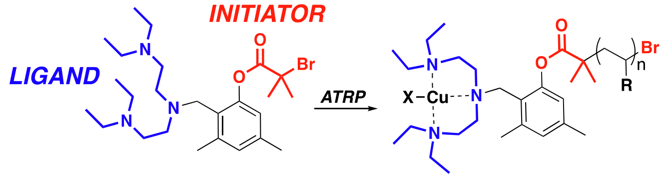


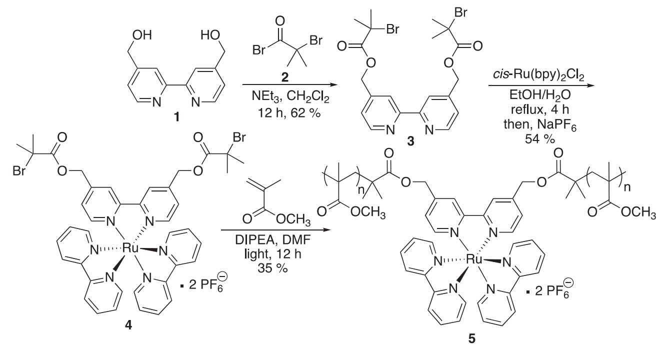
Fig. 1. ULIS-facilitated ATRP to prepare a metal-containing polymer from Ref. [26].

manner) that can then be used to support the catalyst and affect its recovery and reuse in other transformations. This would represent a greener alternative to traditional polymer-supported catalysts, especially those prepared using transition metal catalysts/initiators. The development of such a system is the premise of our current communication.

Results and discussion

2,2′-Bipyridine (bpy) derivatives have exhibited wide applicability as ligands for various transition metals. $[Ru(bpy)_3]^{2+}$ complexes are of particular interest because of their photo-redox properties and have been shown to act as competent catalysts for a number of photo-redox transformations [28,29]. Because of this, various polymer-supported derivatives have already been prepared [30–36]. Additionally, $[Ru(bpy)_3]^{2+}$ complexes have been shown to facilitate visible light-mediated, free radical, ATRP-like polymerizations of methacrylic esters (seemingly the only monomers that undergo polymerizations under these conditions [37]). So, our initial foray into this work involved the preparation of a new, *unimolecular photo-redox catalyst/initiator system* based on a Ru(II)bpy$_3$ derivative **4**. Although Ru(II)bpy$_3$ derivatives bearing ATRP initiators have been prepared before, traditional Cu-catalysed ATRP reactions were used for the polymerizations and their subsequent use as supported catalysts was not even explored [30,32]. Our synthesis involved the esterification of diol **1** (prepared according to literature procedures [38]) with α-bromoisobutyryl bromide **2** to provide diester **3** in 62% yield (Scheme 1). Product formation was confirmed by ^1H NMR spectroscopy by the shift of the singlet at 4.83 ppm (ArCH_2OH) to 5.46 ppm ($ArCH_2CO_2C(CH_3)_2$-Br) as well as the appearance of a carbonyl signal at 165.2 ppm in the ^{13}C NMR spectrum.

The preparation of **4** was carried out by subjecting **3** to reaction with *cis*-Ru(bpy)$_2$Cl$_2$ in a mixture of ethanol and water (1:1), followed by counter anion metathesis with NaPF$_6$. Upon the addition of which, **4** precipitated as a brilliant red/orange solid and was isolated in 54% yield. Product formation was confirmed by ^1H NMR spectroscopy by the appearance of multiple signals between 8.85 and 8.7, 8.19–8.14, 7.80–7.69, and 7.54–7.50 ppm (Ar-*H*) and five new signals between 160 and 120 ppm in the ^{13}C NMR spectrum.



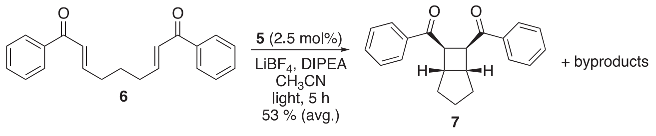
Scheme 1. Synthesis of **3**, **4**, and **5**.

UV–vis analysis showed **4** to exhibit a λ_{max} of 456 nm (similar to the value exhibited by Ru(bpy)$_3$Cl$_2$ of 451 nm (Supplementary Data)). **4** was then subjected to reaction with methyl methacrylate in the presence of Hünig's base (acting as a sacrificial electron donor) in DMF under irradiation with a 30-watt frosted incandescent lamp. After 12 h, polymer **5** was isolated in 35% yield as a red/orange solid via precipitation into methanol. UV–vis analysis showed **5** to exhibit a λ_{max} of 454 nm. Disappointingly, gel permeation chromatography (GPC) analysis revealed that this polymerization occurred with little control, exhibiting a bimodal curve with M_n and $Đ$ values of 15,000 Da and 2.38, respectively (Supplementary Data). Although, this was not completely surprising considering that similar values were disclosed in the original report [37].

Yoon's laboratory showed that Ru(bpy)$_3$Cl$_2$ can serve as useful catalyst for [2+2] enone cycloadditions under visible light irradiation [39]. Polymer-supported complex **5** was competent at facilitating such reactions too. These experiments were carried out by subjecting enone **6** to reaction with **5** in the presence of Hünig's base and LiBF$_4$ in acetonitrile under irradiation (30-W, incandescent lamp) for 5 h (Scheme 2). ^1H NMR analysis showed complete consumption of **6** to provide a product mixture that contained a ratio of ca. 1:1 of **7** to isomeric byproducts (Table 1), similar to those observed in earlier studies (Supplementary Data) [35,40]. Despite this, recovery and reuse of complex **5** was achieved via solvent precipitation into methanol. However, isolated yields of the product mixture were modest (53% average yield through 5 cycles), as the separation of product away from **5** was troublesome due to their similar solubilities. The ratio of **7**:byprd was ca. 1.4:1 (averaged over 5 cycles). Unfortunately, UV–vis analysis revealed a substantial decrease in Ru concentration in **5** after these catalytic cycles (Supplementary Data). The reasoning behind this is, presently, unclear.

Since the disclosure that $[Ru(bpy)_3]^{2+}$ photo-redox complexes can facilitate free radical polymerizations, a plethora of examples describing the use of other photo-redox catalysts for the same purpose have been reported [41–49]. Hawker's laboratory [50] was the first to describe a completely transition-metal free ATRP reaction, which was facilitated by phenothiazine-based photo-redox catalysts. Polymeric products could be obtained with excellent control over molecular weight and end group identity (in contrast to the $[Ru(bpy)_3]^{2+}$ systems). Since this initial report, both soluble and insoluble polymeric or polymer-supported phenothiazines have been developed and used for: facilitating photo-redox transformations [51–53], oxygen sensing [54], battery [55,56] applications, and CO$_2$ capture [57]. Interestingly, phenothiazines bearing ATRP initiators have also been used in "self-catalysed photo-mediated polymerization" reactions to form polymeric nanoparticles, but were not used as polymer-supported catalysts [58]. With this in mind, we set out to develop a new photo-redox catalyst/initiator system based on phenothiazine.

Our work commenced with the preparation of **8** from commercially-available 10H-phenothiazine following literature procedures (Scheme 3) [59]. Reduction of **8** with NaBH$_4$ led to alcohol **9** in 73% yield. Formation of this product was ascertained by the appearance of a singlet at 4.82 ppm (ArCH_2OH) and the disappearance of, both, the singlet at 9.83 ppm (Ar-C*H*O) in the ^1H NMR spectrum and the carbonyl signal at 190.7 ppm in the ^{13}C NMR spectrum. Subjecting

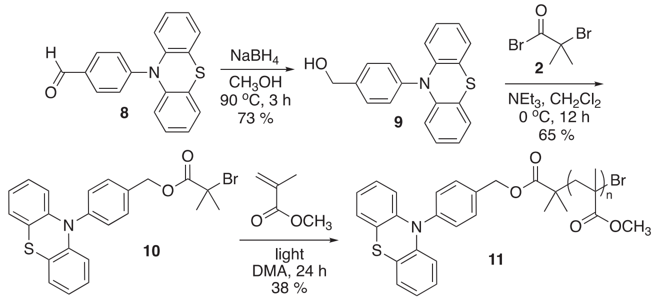


Scheme 2. [2+2] cycloaddition of **6** facilitated by polymer-supported **5**.

Table 1
Recycling data for the [2+2] cycloaddition reaction of **6** using supported catalyst **5**.

Cycle	Yield (%)[a]	**7**:byprd[b]
1	32	1:1.1
2	40	1:1
3	51	1.7:1
4	76	2.4:1
5	64	1.3:1

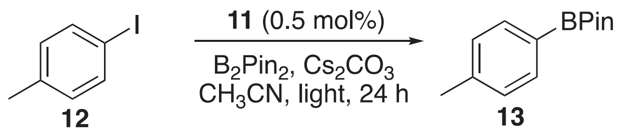
[a] Isolated yield of product mixture.
[b] Determined by ^{1}H NMR spectroscopy.



Scheme 3. Synthesis of **8**, **9**, **10**, and **11**.

alcohol **9** to esterification with **2** led to the formation of **10** in 69% yield. Its formation was confirmed by a shift of the signal at 4.82–5.31 ppm (ArC*H*$_2$OCOC(CH$_3$)$_2$Br) and the appearance of a carbonyl signal at 171.6 ppm in the ^{13}C NMR spectrum. The use of **10** to facilitate the polymerization of MMA under irradiation with a 23-watt, compact fluorescent bulb led to the formation of polymer-supported phenothiazine **11** in 38% yield. (The polymerization of MMA was chosen because of the apparent limited monomer scope of these polymerizations [60]. A control experiment using methyl acrylate instead of MMA provided no observable polymerization by ^{1}H NMR (Supplementary Data).) GPC analysis of **11** revealed higher levels of control than that of **5**, exhibiting a much narrower and monomodal GPC curve, with M_n and *Đ* values of 11,600 Da ($M_{n,theor.}$ = 13,219 Da) and 1.42, respectively.

Larionov et al. recently showed that phenothiazine derivatives could be utilized to facilitate metal-free borylation reactions, a synthetically-important transformation [61]. As proof of concept, we decided to test the ability of **11** to act as a recoverable and reusable photo-redox catalyst for this reaction. Subjecting 4-iodotoluene **12** to reaction with bis(pinacolato)diboron (B_2Pin_2) in the presence of **11** and Cs_2CO_3, under irradiation (using the same 23-watt, compact fluorescent bulb), led to borylated product **13** after 24 h (Scheme 4). Recovery and reuse of **11** was accomplished by evaporation of excess solvent, followed by precipitation into methanol and vacuum filtration. Evaporation of excess solvent from the filtrate led to isolation of product **13**. The recovered catalyst could successfully be reused 5 times, providing product in 80% total yield (after combining and purifying the products from 5 cycles), similar to yields reported by Larionov [61] utilizing phenothiazine as a photo-redox catalyst.



Scheme 4. Metal-free borylation of **12** carried out by polymer-supported **11**.

Conclusions

In conclusion, we have shown that photo-redox catalysts can be designed in which an ATRP initiating site is covalently linked. This allows for the photo-active catalyst to facilitate the synthesis of its own macromolecular scaffold, resulting in a polymer-supported, photo-redox catalyst that can be used to facilitate other chemistries in a recyclable manner. This offers a synthetic advantage over existing systems in the form of atom economy and green chemistry. Our future plans involve the extension of this chemistry toward the polymerization of other monomers and using the resulting polymer-supported species as catalysts for other photo-redox transformations (i.e. polymerizations).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data (experimental procedures, spectroscopic data and GPC traces) to this article can be found online at https://doi.org/10.1016/j.tetlet.2020.152759.

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