Published in final edited form as:

Macromolecules. 2019 January 8; 52(1): 236–248. doi:10.1021/acs.macromol.8b02517.

Guiding the Design of Organic Photocatalyst for PET-RAFT Polymerization: Halogenated Xanthene Dyes

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Abstract

By examining structurally similar halogenated xanthene dyes, this study establishes a guiding principle for resolving structure–property–performance relationships in the photocontrolled PET-RAFT polymerization system (PET-RAFT: photoinduced electron/energy transfer–reversible addition–fragmentation chain transfer). We investigated the effect of the halogen substituents on the photophysical and electrochemical properties of the xanthene dyes acting as photocatalysts and their resultant effect on the performance of PET-RAFT polymerization. Consideration of the structure–property–performance relationships allowed design of a new xanthene photocatalyst, where its photocatalytic activity (oxygen tolerance and polymerization rate) was successfully optimized for PET-RAFT polymerization. We expect that this study will serve as a theoretical framework in broadly guiding the design of high performance photocatalysts for organic photocatalysis.

Graphical Abstract

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The authors declare no competing financial interest.

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.macromol.8b02517.

Experimental details, MALDI-TOF MS, GPC data, NMR, DFT calculation (Figures S1–S14 and Table S1) (PDF)

INTRODUCTION

In 1912, Ciamician proposed that the use of visible light could provide a more sustainable approach for chemical production.¹ Ciamician used plants as an example to illustrate the potential of visible light in mediating complex chemical reactions. Indeed, plants and cyanobacteria have exploited the photosynthesis process to sustain life on earth for the past 3.4 billion years. Throughout this time, plants have evolved to derive a variety of chlorophyll and bacteriochlorophyll compounds capable of harvesting a broad spectrum of visible light under different conditions; this natural catalyst selection has allowed these organisms to thrive on the earth's surface and in oceans. Although visible light was proposed to mediate chemical reactions as early as 1912, it has only become broadly exploited to drive chemical transformations since the turn of this century.^{2–5}

A variety of photocatalysts (PCs) have been discovered and explored since, and in parallel, PCs have been implemented in controlled/living polymerization, which has opened up a new avenue for polymer production and provided temporal/spatial control over polymerization processes.^{6,7} Exemplary visiblelight-catalyzed reversible deactivation radical polymerization (photo-RDRP) systems include photo-atom transfer radical polymerization (photo-ATRP)^{8–12} and photoinduced electron/energy transfer-reversible addition–fragmentation chain transfer (PET-RAFT) polymerization.^{13–17} In these systems, PCs play a central role in converting visible light energy through photoinduced electron/energy transfer (PET) processes to activate/deactivate polymerization and manipulate polymerization kinetics. In early works, metal-based PCs (e.g., iridium,^{8,13} ruthenium,¹⁸ copper,^{12,19–22} iron,¹¹ and zinc¹⁴ based PCs) were recognized in organic synthesis and were thus adopted for photo-RDRP. However, the presence of metalbased PCs usually leads to metal contamination in polymer products, potentially limiting applications. In response, organic analogues were developed, which has paved the way for metalfree photo-RDRP.^{23–30}

Numerous organic PCs have been identified for application in both organic synthetic transformations and photo-RDRP.³¹ In metal-free photo-RDRP, a library of phenothiazine,^{23,24} dihydrophenazine, phenoxazine,²⁹ polycyclic aromatics,^{32,33} eosin Y (EY),²⁵ and others have been identified as efficient PCs. To guide the rational design and optimization of organic PCs that satisfy the specific needs of photo-RDRP and organic synthesis, researchers

recently started to explore the relationships between PC structure and the performance of photocatalyzed systems. For example, structure–property relationships have been established for organic PCs that affect excited state redox potentials,²⁷ charge transfer characters,^{27,34,35} and triplet quantum yields³⁶ based on dihydrophenazine and phenoxazine derivatives in organocatalyzed photo-ATRP (OATRP). Very recently, Kim, Gierschner, and Kwon also generated a library of donor–acceptor PCs and used a computer-aided strategy to elucidate the PC property–performance relationship in O-ATRP.³⁷ Meanwhile, the structure–property relationships of donor–acceptor PCs were recently investigated to perform organic transformations;^{38,39} for instance, Nicewicz's group gained insight into a range of core-modified acridinium-^{40–52} and pyrylium-based^{53,54} PCs for a series of photocatalyzed organic reactions.

Herein, we systematically establish structure–property–performance relationships among xanthene-based PCs mediating PET-RAFT polymerization (Scheme 1A). In this regard, we chose to examine a series of halogenated xanthene dyes, including EY, erythrosin B (EB), phloxine B (PB), and Rose Bengal (RB, Scheme 1B). Notably, this class of halogenated xanthene derivatives has found vast applications in the food industry as a colorant,^{55–57} in biostaining,^{58–60} and in photodynamic therapy.⁶⁰ By investigating the photophysical and electrochemical properties of EB, EY, RB, and PB, and subsequently correlating these properties to measured apparent propagation rate (k_p^{app}) and other performance parameters during PET-RAFT polymerization under identical conditions, we elucidated the structure–property–performance relationships.^{61–63} Based on the established principles, a new halogenated xanthene dye was designed and synthesized for oxygen-tolerant PET-RAFT polymerization.

RESULTS AND DISCUSSION

Kinetics and Oxygen Tolerance Studies.

Table 1 and Figure 1 show the photophysical properties of four xanthene dyes selected for this study. The respective λ_{max} and ϵ_{max} values of the xanthene dyes are EB (548 nm, 95000 M⁻¹ cm⁻¹), EY (540 nm, 87800 M⁻¹ cm⁻¹), RB (563 nm, 97300 M⁻¹ cm⁻¹), and PB (555 nm, 93800 M⁻¹ cm⁻¹) with all differences <8%; λ_{max} is the maximum wavelength of absorption, and ϵ_{max} is the molar absorptivity at λ_{max} . As λ_{max} of EB, PB, and RB are close to the yellow LED light emission (nominal wavelength: 560 nm), while that of EY is close to the green LED light emission (nominal wavelength: 530 nm), we selected the respective LED light sources corresponding to their maximum absorptions. A light intensity of 2 mW/cm² was employed for both yellow and green lights. The photon flux for 2 mW/cm² green (530 nm, photon flux of 5.34×10^{15} s⁻¹ cm⁻²) and that for 2 mW/cm² yellow (560 nm, photon flux of 5.64×10^{15} s⁻¹ cm⁻²) light irradiation are almost indistinguishable (difference <6%), and the effect of different wavelengths in this process can therefore be considered negligible. To demonstrate this, a control experiment was performed to compare polymerization mediated by EB under 2 mW/cm² 530 nm and 2 mW/cm² 560 nm irradiation (experimental details indicated *vide infra*). Indeed, as shown in the Supporting Information (Figure S1), the difference in polymerization rate is minimal (<5%).

We monitored the kinetics of PET-RAFT polymerization (k_p^{app} , apparent rate constant) in the presence of EB, EY, RB, and PB as PCs, using online Fourier transform near-infrared (FTNIR) spectroscopy. *N,N'*-Dimethylacrylamide (DMA) and 2-(*n*-butyltrithiocarbonate) propionic acid (BTPA) were selected as the model monomer and RAFT agent (see Scheme 1C) at a fixed molar ratio of [DMA]:[BTPA]:[PC] = 200:1:0.004, corresponding to a PC concentration of 20 ppm relative to monomer. As expected, we observed that k_p^{app} appeared to be dependent on the PCs employed for polymerization, where the EB-catalyzed system exhibited the highest k_p^{app} (0.023 min⁻¹), followed by EY (0.014 min⁻¹), RB (0.010 min⁻¹), and finally PB (0.007 min⁻¹) (Figure 2A–D). Linear plots of number-average molecular weights (M_n) versus monomer conversions and good agreements between theoretical and experimental molecular weights confirmed a controlled polymerization character (Figure 2E–H). Furthermore, symmetric and narrow molecular weight distributions ($M_w/M_n < 1.1$) were observed by gel permeation chromatography (GPC, Figure 2I–L). Finally, for all the four dyes, the polymerization immediately ceased after switching off the light, which demonstrated good temporal control.

As oxygen can rapidly trap and terminate propagating radicals via peroxide formation, most RDRP techniques require deoxygenation prior to polymerization. In our previous reports, we have demonstrated that PET-RAFT polymerization could be performed in the presence of air with some specific PCs. The oxygen tolerance mechanism is based on the elimination of oxygen via the generation of singlet oxygen (¹O₂) in the presence of excited PCs such as zinc tetraphenylporphyrin⁶² (ZnTPP) and chlorophyll *a*⁶³ (Chl *a*). Singlet oxygen can be consumed by a variety of reactants, including the solvent DMSO to form dimethyl sulfone (DMSO₂) or organic compounds such as anthracene derivatives (Scheme 1A).⁷⁴ Inspired by some early works in photodynamic therapy using halogenated xanthene dyes,⁷⁵ we decided to test the oxygen tolerance of PET-RAFT polymerization in the presence of these four xanthene PCs (Figure 3). Because of the RAFT preequilibrium, there is usually a brief induction period at the beginning of PET-RAFT polymerization (seen in Figure 2A–D). Meanwhile, PET-RAFT polymerizations in the presence of oxygen (nondegassed) exhibit a longer inhibition period (Figure 3A–D). Therefore, the delay of nondegassed polymerization compared to its degassed counterpart (namely, the oxygen inhibition period) gives an estimation of oxygen tolerance of our systems. Despite different oxygen inhibition periods, each dye-catalyzed nondegassed polymerization exhibited a similar k_p^{app} to its corresponding degassed polymerization (Figure 3A–D). Furthermore, good agreement between the experimental and theoretical molecular weights (Figure 3E–H) as well as low dispersities ($M_w/M_n < 1.1$) confirmed a controlled polymerization behavior (Figure 3I–L).

The high end-group fidelities of polymers prepared via xanthene-dye-catalyzed PET-RAFT polymerizations were confirmed by matrix-assisted laser desorption ionization time-of-flight mass spectrometry (MALDI-TOF MS, Figures S2–S8). For each dye-catalyzed PET-RAFT polymerization, evenly distributed mass peaks (separated by 99 *m/z*) and highly symmetric mass distribution were revealed. Closer inspection of the detailed structure of each mass peak (from 2200 to 2400 *m/z*) enabled the identification of two repetitive signals. We observed a set of main peaks corresponding to poly-DMA (PDMA) containing BTPA chain-end plus Na⁺ as well as a secondary set of peaks corresponding to PDMA with BTPA chain-end plus K⁺. This trend was in excellent agreement with theoretical values and within

instrumental error ($< 1\ m/z$), which demonstrated that there was no evidence for end-group loss. Meanwhile, the polymers synthesized without deoxygenation exhibited highly similar results compared to the polymers prepared after deoxygenation. Nuclear magnetic resonance (NMR) analysis was subsequently performed on the purified polymer synthesized with EB as catalyst in the presence of oxygen (Figure S9A). Characteristic signals of the trithiocarbonate functionality at 5.1 ppm confirmed the retention of end-group. Furthermore, M_n calculated by NMR (15000 g/mol) was in good agreement with the theoretical value (14500 g/mol) and the GPC result ($M_{n,GPC} = 13300\ g/mol$). Finally, chain extension was performed to confirm the high end-group fidelity; GPC traces displayed a complete shift to higher molecular weights from $M_{n,GPC} = 13300\ g/mol$ to $M_{n,GPC} = 32500\ g/mol$ after chain extension, without a significant increase in dispersity (from 1.05 to 1.10) (Figure S9B). All these results confirmed the high retention of the RAFT end-group. Finally, to demonstrate the robustness of this process, polymerizations were performed in various solvents with EB as catalyst, with prior deoxygenation. The DMSO solvated system displayed the fastest rates, while in all other solvents tested, polymerization still proceeded to some extent after 2 h irradiation (Table S1).

Property–Performance Relationship: Correlating PET-RAFT Performance with PC Properties.

The lowest triplet excited state (T_1) for xanthene derivatives typically exhibits a sufficiently long lifetime (0.1–4.0 ms, Table 1) to allow efficient PET processes,^{31,76} in line with our previous observations.^{14,25,77} Therefore, an ideal PET-RAFT PC is preferred to possess a high Φ_T upon irradiation. On the other hand, the oxidative potential of T_1 , $E^0(PC^{*+}/^3PC^*)$, which defines the ability of $^3PC^*$ to reduce a substrate (e.g., RAFT agent in the case of PET-RAFT) through the oxidative quenching pathway, determines the change of Gibbs free energy (G^0) of the corresponding electron transfer reaction (see the Supporting Information, eqs S1–S3). According to Marcus theory,^{78,79} with more negative G^0 (i.e., more negative $E^0(PC^{*+}/^3PC^*)$, eq S3), the electron transfer rate k_{et} increases until entering the inverted Marcus region where k_{et} starts to decrease with more negative G^0 values (eq S4). However, unlike intramolecular PET in which the distance between donor and acceptor is constant, the inverted Marcus region is scarcely observed in intermolecular PET, and more often, a more negative G^0 would lead to an increase in k_{et} up to the diffusion limit where diffusion becomes the rate-determining step for even more negative G^0 values (described as Rehm–Weller behavior,⁸⁰ eq S5). Hence, given the use of the same RAFT agent as an electron acceptor, $E^0(PC^{*+}/^3PC^*)$ largely determines G^0 (eq S3) and thereby controls k_{et} (eq S5) which further determines k_p^{app} of PETRAFT polymerization at a fixed temperature (eq S6).

Overall, with more negative $E^0(PC^{*+}/^3PC^*)$, k_p^{app} should exhibit an increase followed by a plateau, based on the proposed PET mechanism. Despite this, partial or even complete involvement of energy transfer pathways is still possible in these processes, and there is still debate in most cases of PET transformations (including that for PET-RAFT processes).³¹ However, the driving forces for both pathways (i.e., $E^0(PC^{*+}/^3PC^*)$ for electron transfer and T_1 excited state energy (E_T) for energy transfer) are closely related, as the available energy for electron transfer processes from excited state molecules increases with increasing E_T .

($E^0(\text{PC}^{\bullet+}/^3\text{PC}^*) = E^0(\text{PC}^{\bullet+}/\text{PC}) - E_{\text{T}}$). Especially for structurally similar PCs that share similar chromophores, the trends for $E^0(\text{PC}^{\bullet+}/^3\text{PC}^*)$ and E_{T} are in principle the same; i.e., higher T_1 energies correspond to a more reducing (more negative $E^0(\text{PC}^{\bullet+}/^3\text{PC}^*)$) T_1 state. Hence, a more photoactive PC generally tends to exhibit both more negative $E^0(\text{PC}^{\bullet+}/^3\text{PC}^*)$ and more positive E_{T} . Indeed, structurally similar PCs normally share the same chromophore and would thereby exhibit similar ground state electrochemical properties; for example, the commercial halogenated xanthene dyes used in this work were reported to exhibit similar ground state redox potential $E^0(\text{PC}^{\bullet+}/\text{PC})$ within the range 0.92–0.96 V (vs SCE).⁶⁹ As the aim of this work is mainly to propose a guideline for relationships between substitutions of the chromophore and performance of the photocatalyzed system on a qualitative basis, to simplify, herein we only consider the electron transfer pathway. However, a purely energy transfer pathway will also fit well in the context of this work and will not affect the main conclusions. In addition, the back-electron-transfer (BET) process is not discussed in this work on account of three reasons. Firstly, BET solely exists in an electron transfer pathway, and secondly, it should only affect temporal control (does not affect chain transfer process and has a minor contribution to the living character in PET-RAFT polymerization, unlike in photo-ATRP and other techniques). Importantly, accurate redox potential values of the RAFT agent (which are required to study BET) are still in debate despite years of efforts by us and other groups both experimentally and computationally. More importantly, we observed a good temporal control in all experiments, and the BET process is beyond the scope of this study; we decided not to discuss the BET process, and the interested readers are directed to this review.⁸¹

Density functional theory (DFT) calculations were performed to compute $E^0(\text{PC}^{\bullet+}/^3\text{PC}^*)$ for each PC, which were correlated to the reported values within experimental/ computational error (Table 2). By comparing EB and EY and considering their comparable $E^0(\text{PC}^{\bullet+}/^3\text{PC}^*)$, we naturally attributed the higher catalytic efficiency of EB (higher $k_{\text{p}}^{\text{app}}$) to the much higher Φ_{T} (EB: 0.62–0.69 and EY: 0.28–0.32; Table 2, entries 1 and 2). On the other hand, as EB and RB have similar Φ_{T} values (EB: 0.62–0.69 and RB: 0.76–0.86; Table 2, entries 1 and 3), the better catalytic efficiency of EB is due to its more negative $E^0(\text{PC}^{\bullet+}/^3\text{PC}^*)$ compared to RB (EB: –1.34 V and RB: –1.00 V vs SCE; Table 2, entries 1 and 3). This general trend can be extended to the full list of Table 2, where higher Φ_{T} and more negative $E^0(\text{PC}^{\bullet+}/^3\text{PC}^*)$ lead to higher $k_{\text{p}}^{\text{app}}$ in PET-RAFT polymerization.

The oxygen inhibition period observed in nondegassed PET-RAFT polymerization is often explained through two different possible mechanisms. One possible mechanism is that the triplet–triplet annihilation (TTA) process between oxygen and $^3\text{PC}^*$ competes with the PET process (between the RAFT agent and $^3\text{PC}^*$), resulting in this short inhibition. Another explanation is that the oxygen is consumed by the presence of radicals (through polymerization). As mentioned previously, polymers produced in the presence of oxygen display excellent end-group fidelity; moreover, with polymerization targeting higher M_{n} , we were still able to observe a good correlation between experimental and theoretical values ($M_{\text{n, GPC}} = 61000$ g/mol, $M_{\text{n, theoretical}} = 76000$ g/mol; for detailed discussion of the ~20% mismatch see Figure S10 and relevant discussion), acceptable dispersities ($M_{\text{w}}/M_{\text{n}} = 1.18$), and a symmetrical GPC profile (Figure S10). Therefore, we can exclude the second potential mechanism in this work. Subsequently, we decided to examine the first mechanism (TTA

between oxygen and $^3\text{PC}^*$). Given the short $^1\text{O}_2$ lifetime of only 20–70 μs in common polar solvents,⁸⁴ the quenching of $^1\text{O}_2$ by DMSO should also be rapid, since we have experimentally observed this process previously.⁶² Consequently, $^1\text{O}_2$ generation should be the rate-determining step for oxygen elimination in these systems. We then investigated the oxygen tolerance for these four PCs using FTNIR spectroscopy. As expected, we observed that the length of the oxygen inhibition period (calculated by the delay of the nondegassed polymerization compared to its degassed counterpart) was correlated to the $^1\text{O}_2$ quantum yield (Φ) for each catalyst, as higher $^1\text{O}_2$ quantum yields lead to shorter oxygen-induced inhibition periods (Table 3). Therefore, we can conclude that PCs with higher Φ present better oxygen tolerance in PET-RAFT polymerization. Among the four dyes studied, RB is the best candidate for oxygen tolerance in PET-RAFT, followed by EB, PB, and EY.

Structure–Property Relationship: Effect of Halogen Substitution on Photophysical Properties.

Well established in photoredox catalysis, and recently readdressed in OATRP by Miyake and co-workers^{34–36} and also in organic photoredox catalysis by Nicewicz et al.,^{31,42} photophysical and electrochemical properties of PCs can be tuned by varying functional substituents with electron-donating/withdrawing properties.^{27,85–87} Similarly, the photophysical and electrochemical properties of organic PCs can be tuned by the introduction/modification of substituents on the aryl chromophore.^{31,34,36,52,88} Correspondingly, changes to the halogen atoms on the xanthene aryl group lead to large differences in the photophysical and electrochemical properties of the PCs, i.e., Φ_{T} and $E^0(\text{PC}^{*+}/^3\text{PC}^*)$ (Table 2). Despite these differences, the spectral profiles of these halogenated xanthene dyes are similar as shown by UV–vis spectroscopy of the PETRAFT polymerization mixtures (Figure 1C), while ϵ of the dyes at their λ_{max} varies in the range 87000–98000 $\text{M}^{-1} \text{cm}^{-1}$ (Table 1). Because halogen substitution is the only difference of EY, EB, PB, and RB, they are excellent candidates for studying the effect of halogen substitution on their properties related to PET-RAFT catalytic activity.

Interestingly, heavier atom substitution appears to increase ϵ and cause a red shift in the absorption bands (λ_{max}).⁸⁹ Some recent literature on iridium complexes has attributed the spectral red shift caused by halogen substitution to their effect in stabilizing the lowest unoccupied molecular orbital (LUMO) of the chromophore, while the highest occupied molecular orbital (HOMO) is mainly unperturbed.^{90,91} Using density functional theory (DFT) calculation, we were able to gain insights into the photoexcitation mechanism from a molecular orbital (MO) perspective.^{92,93} According to timed-dependent DFT (TDDFT) calculations, the most intense absorption peak of these dyes can be assigned to the first singlet excited state (S_1) where the π_{HOMO} to π_{LUMO} transition has over 98% contribution (denoted in Figure 4). Therefore, inspection of frontier orbitals, i.e., HOMO and LUMO, should give us insight into the halogen-controlled spectral changes. Experimentally, structural comparison between EB and EY (or between PB and RB, Figure 1A) revealed that replacing bromine (Br) substituents with iodine (I) substituents in X-positions caused an 8 nm red shift in the maximum absorption in λ_{max} , from EY to EB or from PB to RB. To interpret this change, we inspected the frontier orbitals and found a portion of HOMO located on the X-position halogens, but little LUMO composition on these halogens (Figure

4). This observation suggested that the outermost-shell n (nonbonding) electrons of X-position halogens should have an impact on the π system energy of the xanthene core⁹⁴ and thereby affect $\pi \rightarrow \pi^*$ transitions. Calculation of frontier orbitals revealed these effects. Specifically, as the n electrons of I substituents have higher energy than those of Br substituents, when compared with LUMO (which is little affected by n electrons), the HOMO energy level of X-position I-substituted EB (or RB) is moved up more than that of X-position Br-substituted EY (or PB), which results in narrower HOMO/LUMO energy gap for the Br substituted xanthenes studied here (Figure 4). A narrower HOMO/LUMO energy gap leads to lower energy S_1 excitation, which causes the 8 nm red shift in $\lambda_{\max}$ from EY to EB and from PB to RB.

In contrast to the X-position halogens that are attached to the xanthene chromophore and directly involved in HOMO $\rightarrow$ LUMO transitions, the Y-position substitution is on the phenyl group, which can be regarded as an electron-withdrawing group as a whole. Given that $\chi_{\text{Cl}} > \chi_{\text{H}}$ (Figure 1B), the strong inductive effect of chlorine (Cl) makes Cl-substituted phenyl groups much more electron-withdrawing than H-substituted phenyl groups and hence more pronouncedly decreases both HOMO and LUMO energies for PB (or RB) compared with EY (or EB) (Figure 4). While the enhanced electron-withdrawing effect of the Cl-substituted phenyl group decreases both HOMO and LUMO, it decreases HOMO to a lesser extent, which leads to the 15 nm red shift in $\lambda_{\max}$ from EY (or EB) to PB (or RB).

Overall, the heavier halogen substitution at the X-positions on the xanthene core (I substitution instead of Br on Xpositions), in conjunction with the highly electron-withdrawing Cl-substituted phenyl group (Cl substitution instead of H on Y-positions), $\lambda_{\max}$ of RB is 23 nm red-shifted relative to EY, endowing it with the longest wavelength absorption among these halogenated xanthene dyes (Figure 1C). Theoretically, longer wavelength absorption can be obtained by heavier halogenation on the chromophore and the introduction of more electron-withdrawing groups.

It must be noted that the double-anion structure of the investigated dyes was chosen for DFT calculations, as the disodium salt form of these dyes was used in the polymerization system. For qualitative analysis, this approximation should yield a good comparative basis for revealing the general trends in the evolution of frontier orbitals with the change of halogen substitution. Indeed, this approximation has been shown to be accurate for calculating $E^0(\text{PC}^{•+}/^3\text{PC}^*)$, which resulted in good agreement with reported values (Table 2). However, with respect to spectral properties, where other influencing factors are more complex and thus much harder to predict by DFT calculations, possible assembly of a dye molecule with sodium cations, solvent molecules, and/or RAFT agents should all lead to significant changes in the absorption/fluorescence spectra. Indeed, in this study, we experimentally observed up to 15 nm red shift for the investigated halogenated xanthene dyes upon addition of RAFT agents (Figure S11) and observed up to 15 nm difference of the visible-range absorption/fluorescence peaks in different solvents (Table S1). Hence, it should be noted that the exact values for the frontier energy levels in Figure 4 are only valid on a comparative basis among different dyes and do not reflect the exact experimental spectral properties. However, as we aim to qualitatively reveal the general trends for structure–property–performance relationships, and the aforementioned factors generally exert equivalent

influence for the structurally analogous halogenated xanthene PCs in this study, the validity of the comparisons is sufficient for us to comment on the relationships between substitution of the chromophore and the resulting changes in spectral properties of these dyes.

As stated above, high Φ_T of a PC is one of the key requirements for efficient PET catalysis, which indicates efficient generation of T_1 states that can be accessed by the RAFT agent. However, because the intersystem crossing (ISC) from S_1 to T_1 is spin-forbidden and requires spin-orbit perturbation,⁹⁵ with the competition between slow ISC rates and fast fluorescence postulated to be a primary cause for the low Φ_T of most organic PCs.³⁶ In addition to introducing donor-acceptor charge transfer,³⁶ or core-twisted aromatics,⁹⁶ which quench unfavorable fluorescence and allows time for ISC, ISC can be accelerated by enhancing spin-orbit perturbation from the interaction between the electron-spin magnetic moment and the nucleus magnetic field from its apparent motion.⁹⁷ By increasing the atomic number, the nuclear charge and the nuclear magnetic field will increase, boosting spin-orbit perturbation and accelerating ISC.^{75,98} This phenomenon is known as the heavy atom effect,⁹⁸ where higher atomic number substituents would contribute to higher Φ_T . Therefore, in halogenated xanthene dyes, substitution at the X-position with heavier species is expected to increase Φ_T . Indeed, because of atomic numbers in the order $I > Br > Cl > H$ (Figure 1B), the heaviest atom substituted RB (I on X-positions and Cl on Y-positions) exhibits highest Φ_T among the four dyes, while EY has the lightest atoms (Br on X-positions and H on Y-positions) and the lowest Φ_T (Figure 1B).

On the other hand, Φ of the PCs, which relates to oxygen tolerance in PET-RAFT, is a consequence of TTA process (where 1O_2 is generated from 3O_2 by quenching a triplet excited PC, Scheme 1A).⁹⁹ Therefore, Φ should positively correlate to Φ_T (validated by Table 3) and hence should also be governed by the heavy atom effect (Figure 1B).

Structure-Property Relationship: Effect of Halogen Substitution on Electrochemical Properties.

As elucidated in the property-performance relationship, a more negative $E^0(PC^{•+}/^3PC^*)$ value is an indicator of how strongly reducing a $^3PC^*$ is; briefly, $E^0(PC^{•+}/^3PC^*)$ is the potential change from the T_1 state of the PC to the cation radical form of the PC. Alternatively, it can be expressed by $E^0(PC^{•+}/^3PC^*) = E^0(PC^{•+}/PC) - E_T$, where $E^0(PC^{•+}/PC)$ is ground state ionization potential and E_T is the triplet state energy. Hence, $E^0(PC^{•+}/^3PC^*)$ describes the first ionization potential of $^3PC^*$, i.e., the ability of $^3PC^*$ to donate an electron to the substrate. Inspection of the upper singly occupied molecular orbitals (upper SOMOs) of the triplet state revealed that the electron density is almost exclusively distributed on the xanthene core for all four dyes (Figure 5), which indicates that the electron participating in PET from the excited state PC should originate from the xanthene core. Therefore, the ligand substitution of the xanthene core should directly affect the electron-donating ability of the T_1 state of the PC. Indeed, the PC installed with the most electron-withdrawing atoms, i.e., PB with four Cl on the Y-positions ($\chi_{Cl} > \chi_H$, Figure 1B) and four Br on the X-positions ($\chi_{Br} > \chi_I$, Figure 1B) has the least negative $E^0(PC^{•+}/^3PC^*)$ of -0.91 V vs SCE. In contrast, EB with the least electron-withdrawing atoms yields the most negative $E^0(PC^{•+}/^3PC^*)$ of -1.34 V vs SCE. Generally, $E^0(PC^{•+}/^3PC^*)$ is only tuned

by the overall electron affinity of substituents on the chromophore, where less electron-withdrawing (or more electron-donating) substituents would yield more negative $E^0(\text{PC}^{*\cdot+}/^3\text{PC}^*)$ for the chromophore.

Employing the Structure–Property–Performance Relationship for On-Demand Design of PC in PETRAFT.

As oxygen tolerance in PET-RAFT polymerization relies on the Φ_T of the PC, oxygen-tolerant PET-RAFT is currently limited to high Φ_T PC-based systems, such as ZnTPP ($\Phi_T = 0.88$).¹⁴ Indeed, ZnTPP has been employed as the PC in nondegassed PET-RAFT-based photoflow,^{62,100} photopolymerization-induced-self-assembly,^{101,102} and photo-high-throughput polymerizations.^{103,104} Therefore, we decided to employ the structure–property–performance relationship established in this study to design a new organic PC with high Φ_T equivalent to ZnTPP and a desirable PET efficiency.

To this end, we set RB as the basis which possesses the highest Φ_T (0.76–0.86) among the xanthene derivatives and synthesized a new PC, Henry 1 (H1, Figure 6A and Figures S12–S13), that replaces Cl on Y-positions of RB with Br (Figure 6A, H1). As expected, H1 exhibited very similar spectral properties to RB (Figure 6B) due to similar electronegativity of the Y-position Br and Cl which leads to similar electron-withdrawing effects of the Y-position-substituted phenyl groups and similar excited state nature (Figure 6G,H). This similarity also leads to its comparable $E^0(\text{PC}^{*\cdot+}/^3\text{PC}^*)$ with RB. DFT calculations revealed an $E^0(\text{PC}^{*\cdot+}/^3\text{PC}^*)$ of H1 to be -1.02 V (vs SCE)—slightly more negative than that of RB due to slightly lower electronegativity of Br than Cl (Figure 1B).

According to the relationships, compared to RB, the only significant impact of the Y-position Br of H1 is from the heavy atom effect, which leads to higher Φ_T and thus provides better oxygen tolerance and higher k_p^{app} in H1-catalyzed PET-RAFT polymerization. An oxygen inhibition period of 14 min and a $k_p^{\text{app}} = 0.012 \text{ min}^{-1}$ measured from the model PET-RAFT system aligned with our expectation (Figure 6B). Kinetic studies in PET-RAFT polymerization were performed with H1 (Figure 6C–F), using identical experimental conditions of previous dyes. Moreover, after fitting the Φ_T and Φ for the four commercial dyes with a first-order approximation approach (Figure S14), we were able to estimate the Φ_T of H1 to be ranging between 0.82 and 0.90, equivalent to that of ZnTPP. Considering that the k_p^{app} for PET-RAFT with H1 (0.012 min^{-1}) is similar to EY (0.014 min^{-1}), the design of H1 through consideration of the structure–property–performance relationships is considered successful.

An Extension of the Structure–Property–Performance Relationship.

To provide further examination and extension to the postulated relationships developed here, we tested one additional xanthene dye, eosin B (EOB). This molecule is interesting due to its substitution by highly electron-withdrawing nitro groups ($-\text{NO}_2$) on two of the X-positions (Figure 7A). Because of the reduced number of Br atoms on the xanthene core, ϵ_{max} of EOB is only around a third of the value for EY. Additionally, because of the stronger electron-withdrawing $-\text{NO}_2$ groups, λ_{max} of EOB is slightly red-shifted compared to EY (Figure 7B). Experimentally, performing PET-RAFT polymerization with EOB as catalyst yielded

$k_p^{\text{app}} = 0.003 \text{ min}^{-1}$ (Figure 7C) and an oxygen inhibition period of 35 min from the oxygen tolerance study (Figure S15A). On the basis of the reduced oxygen inhibition period for EOB compared to EY, EOB should exhibit a higher Φ_T compared to EY; however, the xanthene core of EOB is only disubstituted with Br, and the heavy atom effect is not as significant for EB compared to EY. Interestingly, from the ground state frontier orbitals (Figure 7E), we observed distinct intermolecular charge shift character upon excitation, evidenced by accumulation of electron density on the $-\text{NO}_2$ side of LUMO, which was also reported as charge transfer (CT) for EOB¹⁰⁵ (as it is not a typical donor–acceptor CT,³⁴ we prefer the term charge shift, which is used herein). This character is in principle due to the strongly electron-withdrawing $-\text{NO}_2$ groups distributed on a single side of the xanthene core, which results in a charge shift from Br to $-\text{NO}_2$ upon excitation (Figure 7E). This charge shift effect would reduce fluorescence and boost Φ_T by retarding the back-transition of S_1 to the ground state. In line with this recognition, incorporating intermolecular charge shift or more commonly donor–acceptor CT is widely known as another way to enhance Φ_T ^{35,106,107} in addition to heavy atom effects. Indeed, the reported lower Φ_F below 0.1¹⁰⁵ and a higher $\Phi_T = 0.37$ ¹⁰⁸ for EOB, compared to the four-Br-substituted EY (despite EOB being only disubstituted with Br), supported our assumption. As a result of the higher Φ_T , higher $\Phi = 0.52$ was also reported,¹⁰⁸ in line with the oxygen tolerance experiment where an oxygen inhibition period of 35 min was determined for EOB-catalyzed PET-RAFT (Figure S15A).

Meanwhile, because of the presence of highly electron-withdrawing $-\text{NO}_2$, a computed $E^0(\text{PC}^{*+}/^3\text{PC}^*)$ as low as -0.72 V for EOB was revealed, which explained the lower k_p^{app} of EOB-catalyzed PET-RAFT (in spite of the higher Φ_T of EOB) and further strengthened the structure–property–performance relationship theories.

CONCLUSIONS

In this study, we demonstrate the compatibility of halogenated xanthene dyes with PET-RAFT polymerization systems in the presence or absence of oxygen. By the aid of DFT calculations, detailed comparison of the dyes correlated their structures with their ability to mediate PET-RAFT polymerization. A red shift of λ_{max} was achieved by the combined introduction of heavy halogens and electron-withdrawing substituents in the xanthene structure, whereas higher k_p^{app} were obtained by the introduction of heavy atoms (or CT character, to enhance Φ_T) and less electron-withdrawing/more electron-donating substituents (yielding more negative $E^0(\text{PC}^{*+}/^3\text{PC}^*)$). Through heavy atom substitution or incorporation of photoinduced intermolecular CT, better oxygen tolerance was achieved by increased Φ . Following the relationships, a new halogenated xanthene H1 was designed and synthesized allowing a more efficient oxygen-tolerant PET-RAFT system. To confirm our correlations, an additional xanthene dye, EOB with charge-shift characters, was investigated. By considering these structurally similar xanthene PCs, this work presents a fundamental understanding of the relationships of PC structures with their performances in PET-RAFT polymerization as well as their ability to confer oxygen tolerance in these polymerization systems.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

ACKNOWLEDGMENTS

C.B. and J.X. acknowledge the Australian Research Council (ARC) for their Future Fellowships (FT120100096 and FT160100095). G.M.M. acknowledges support by Colorado State University and the National Institute of General Medical Sciences of the National Institutes of Health under Award R35GM119702. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health. C.H.L. is grateful for an NIH F32 Postdoctoral Fellowship (F32GM122392).

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Figure 1.

(A) Structural variation of halogenated xanthene dyes investigated in this work. (B) Properties of PCs and halogen substituents. (C) UV-vis spectra of dyes determined in model DMSO solution of a typical PET-RAFT system (top) and the corresponding $\lambda_{\max}$ (bottom).

Figure 2.

Kinetics studies of degassed PET-RAFT polymerizations of DMA catalyzed by (A, E, I) EB, (B, F, J) EY, (C, G, K) RB, and (D, H, L) PB. (A–D) Plot of $\ln([M]_0/[M]_t)$ versus time to reveal k_p^{app} and temporal control. (E, F) M_n and M_w/M_n versus monomer conversion. (I–L) Molecular weight distributions of four GPC aliquots taken during polymerization, denoted as S1, S2, S3, and S4, which correspond to blue arrows in (A–D) following the time order.

Figure 3.

Oxygen tolerance studies of PET-RAFT polymerizations of DMA catalyzed by (A, E, and I) EB, (B, F, and J) EY, (C, G, and K) RB and (D, H, and L) PB. (A–D) Evolution of $\ln([M]_0/[M]_t)$ versus time. (E, F) Evolution of M_n and M_w/M_n versus monomer conversion. (I–L) Molecular weight distributions taken during polymerization, denoted as S1, S2, S3, and S4, which correspond to red arrows in (A–D) following the time order.

Figure 4.

Frontier orbitals, energy levels, their gaps and orbital composition on X-position halogens of the ground state (A) EB, (B) EY, (C) RB, and (D) PB. Top: LUMO; bottom: HOMO.

Contribution of HOMO $\rightarrow$ LUMO transitions to S_1 is denoted under the dye label. DFT calculations for frontier orbitals and TDDFT calculations for excited state contribution were employed with the B3LYP (6-31+G** basis set for C, H, O and LanL2DZ basis set for heavy atoms Cl, Br, I) level of theory and the CPCM-DMSO solvation model. Atom color: C in yellow, H in white, O in red, Cl in green, Br in blue, and I in purple. q is the portion of the corresponding molecular orbital located on the enclosed element, in percentage.

Figure 5.

Upper and lower SOMOs, their energy levels and gaps between upper SOMO and lower SOMO of the T_1 state of (A) EB, (B) EY, (C) RB, and (D) PB. Top: upper SOMO; bottom: lower SOMO. Unrestricted DFT calculations for T_1 frontier orbitals and TDDFT calculations for excited state contribution were employed with the B3LYP (6-31+G** basis set for C, H, O and LanL2DZ basis set for heavy atoms Cl, Br, I) level of theory and the CPCM-DMSO solvation model.

Figure 6.

(A) Dye structure of the synthesized dye H1 and its (B) UV-vis spectrum determined in model DMSO solution of a typical PET-RAFT system. (C) Evolution of $\ln([M]_0/[M]_t)$ versus time, (D) M_n and M_w/M_n versus monomer conversion, (E, F) molecular weight distributions taken during polymerization in the presence (E) and absence (F) of oxygen, denoted as S1, S2, S3, and S4, which correspond to blue arrows in (D) following the time order of H1-catalyzed PET-RAFT polymerization. (G) HOMO, LOMO, and their energy levels and (H) upper SOMO, lower SOMO, and their energy levels of H1. (I) Table summarizing property-performance evaluation of four commercial xanthene dyes and the synthesized H1; the quantum yield range of H1 was estimated from the first-order approximation fitting of the reported data for EY, EB, PB, and RB (Figure S14) based on the oxygen inhibition time of 14 min for H1-catalyzed PET-RAFT polymerization in the presence of oxygen.

Figure 7.

(A) EOB chemical structure, (B) UV-vis spectrum determined in DMSO using a typical PET-RAFT concentration, (C) evolution of $\ln([M]_0/[M]_t)$ versus time, and (D) evolution of M_n and M_w/M_n versus monomer conversion of the EOB-catalyzed PET-RAFT polymerization. (E) EOB HOMO, LOMO, and their energy levels. (F) EOB upper SOMO, lower SOMOs, and their energy levels.

Scheme 1. (A) Proposed Mechanism of Oxygen-Tolerant PET-RAFT Polymerization;^a (B) Chemical Structures of Commercial Halogenated Xanthene Dyes; and (C) the Model RAFT Agent and Monomer for Investigation of PC Structure Property–Performance Relationships in This Work

^aTTA: triplet–triplet annihilation for oxygen elimination; $^3\Sigma$: molecular oxygen; $^1\Delta$: singlet oxygen.

Table 1.

Photophysical Properties of Halogenated Xanthene Dyes

	Φ_F	$\Phi_I^{55,64-68}$	$k_r^{69} (10^8 s^{-1})$	$k_{nr}^{69} (10^8 s^{-1})$	$\tau_I^a (ms)$	$\lambda_{max}^b (nm)$	$\epsilon_{max}^b (M^{-1} cm^{-1})$
EB	0.08 ⁶⁹	0.62–0.69	1.60	18.4	0.35–0.65 ⁷⁰	548	95000
EY	0.60 ⁶⁹	0.28–0.32	1.83	1.22	0.6–4.0 ^{70,71}	540	87800
RB	0.08 ⁶⁹	0.76–0.86	1.22	14.0	0.26–1.91 ⁷²	563	97300
PB	0.24 ⁷³	0.4	N/A ^c	N/A ^c	0.12–1.75 ⁷³	555	93800

^a τ_I usually has a wide variability depending on conditions; although their values are in the submilliseconds range, this is sufficient for PET processes to proceed.³¹

^b Determined in model DMSO solution of a typical PET-RAFT system (*vide infra*).

^c Not available. k_r : radiative decay constant; k_{nr} : nonradiative decay constant; Φ_F : fluorescence quantum yield; Φ_I : triplet quantum yield.

Table 2.

k_p^{app} of PET-RAFT Polymerization in Comparison with Photophysical and Electrochemical Properties of the Photocatalysts

entry	PC	$E^0(\text{PC}^{\bullet+}/^3\text{PC}^*)$ (V, vs SCE)		Φ_T	k_p^{app} (min^{-1})
		calculated	reported ^{82,83}	reported ^{55,64-68}	measured
1	EB	-1.34	-1.39	0.62-0.69	0.023
2	EY	-1.26	-1.35	0.28-0.32	0.014
3	RB	-1.00	-1.16	0.76-0.86	0.010
4	PB	-0.91	N/A	0.4	0.007

Table 3.Inhibition Periods of PET-RAFT in the Presence of Oxygen and Photocatalyst Properties^a

entry	PC	$\Phi_T^{55,64-68}$	$\Phi^{55,64-68}$	O_2 inhibition period (min)
		reported	reported	measured
1	RB	0.76–0.86	0.75–0.79	23
2	EB	0.62–0.69	0.62–0.63	41
3	PB	0.40	0.59–0.65	47
4	EY	0.28–0.32	0.39–0.57	90

^a Φ_T : triplet quantum yield, i.e., the quantum yield of the lowest triplet excited state of PC. Φ : singlet oxygen quantum yield. O_2 inhibition period: the length of retardation time caused by the presence of oxygen, i.e., the length of the right shift along the time axis between kinetics of the deoxygenated and nondeoxygenated sample where k_p^{app} stays constant. The O_2 inhibition periods were determined by measuring the time delay between kinetics in the absence/presence of oxygen in each dye-catalyzed PET-RAFT system (Figure 2A-D).