Heterogenous Catalysis for Oxygen Tolerant Photoredox Atom Transfer Radical Polymerization and Small-Molecule Dehalogenation

Kriti Kapil,[a] Mingkang Sun[a], Ting-Chih Lin,[a] Hironobu Murata,[a] Grzegorz Szczepaniak,[b] Khidong Kim,[a] Stephen DiLuzio,[a] Jaepil Jeong,[a] Mitchell Baumer,[a] Stefan Bernhard,[a] Tomasz Kowalewski,[a] Krzysztof Matyjaszewski[a*]

[a] Department of Chemistry, Carnegie Mellon University, 4400 Fifth Avenue, Pittsburgh, PA 15213, United States.

[b]Faculty of Chemistry, University of Warsaw, Pasteura 1, 02-093 Warsaw, Poland.

Materials

All chemicals were purchased from commercial sources and used as received unless otherwise noted. 4-(4-Hydroxymethyl-3-methoxyphenoxy)butyric acid, polymer-bound to ChemMatrix® resin (0.40 -0.65 mmol hydroxyl/g, CM-HMPB), Aminomethyl-ChemMatrix® resin (0.5 – 0.7 mmol amine/g, CM-AM), triphenylphosphine (PPh_3), iodine (I_2), imidazole, tetrabutylammonium bromide, sodium azide, $CuSO_4$, (+)-sodium L-ascorbate, Eosin Y (EHY_2), copper (II) bromide ($CuBr_2$), 2-hydroxyethyl 2-bromoisobutyrate (HO-BiB), 1,4-bis(3-isocyanopropyl) piperazine (QA), *N*-(3-dimethylaminopropyl)-*N'*-ethylcarbodiimide hydrochloride (EDC·HCl), *N,N'*-diisopropylcarbodiimide (DIC), 4-(dimethylamino)pyridine (DMAP), trifluoroacetic acid (TFA), Tween 20, and *tert*-butanol (*t*-BuOH, anhydrous) were purchased from *Sigma-Aldrich*. Tris(2-pyridylmethyl) amine (TPMA, 99%), tris[2-(dimethylamino) ethyl] amine (Me_6TREN, 99%) ware purchased from *AmBeed*. 10X PBS were

purchased from *Thermo Fisher Scientific*. Oligo (ethylene glycol) methyl ether methacrylate (average M_n = 500, $OEOMA_{500}$) and oligo (ethylene glycol) methyl ether acrylate (average M_n = 480, $OEOA_{480}$), methyl acrylate (MA), ethyl acrylate (EA) were purchased from *Sigma-Aldrich* and passed through a column of basic alumina to remove inhibitor before use. Water (HPLC grade), *N,N*-dimethylformamide (DMF), dimethyl sulfoxide (DMSO) dichloromethane (DCM), methanol (MeOH), acetonitrile (ACN), and chloroform were purchased from *Fisher Scientific* and used as received. 3-[2-(Methacryloyloxy)ethyl]dimethylammonio]propionate (CBMA) and 2-ethynylpyridine were purchased from *TCI America*. 2-(methylsulfinyl)ethyl methacrylate (MSEMA) was synthesized according to a previously reported procedure.[1] Deionized water (DI water) was obtained from a Millipore-Sigma Milli-Q water purification system. 2-(4-(trifluoromethyl)phenyl)benzo[d]thiazole (pbtz) was synthesized *via* previously reported methods.[2, 3] The functionalization of CM was performed using an Extract-Clean SPE 8 mL reservoir.

Photoreactor

Polymerizations were carried out in the EvoluChem PhotoRedOx Box™ device purchased from HepatoChem equipped with green LEDs (λ = 520 nm, Kessil).

Instrumentation

Nuclear Magnetic Resonance (NMR)

^{1}H NMR spectra were recorded on *Bruker* Avance III 500 MHz spectrometers with D_2O or DMSO-d_6 used as the solvent.

Size Exclusion Chromatography (RI Detectors- DMF eluent)

SEC measurements of polymers were performed using PSS columns (Styrogel 10^5, 10^3, 10^2 Å) with DMF as an eluent at 50 °C and the flow rate of 1 mL/min. Linear poly(methyl methacrylate) standards were used for calibration.

Size Exclusion Chromatography with Multi-Angle Light Scattering (SEC-MALS- 1X DPBS eluent)

SEC-MALS measurements of zwitterionic poly(acrylate) and bioconjugates were performed using the Agilent SEC system (*Agilent*, 1260 Infinity II with UV detector) coupled with MALS, DLS, UV, Viscometer, and RI detectors (*Wyatt Technology*, USA). Measurements were performed using *Waters* Ultra hydrogel Linear column with 1X DPBS as an eluent at rt and the flow rate of 0.5 mL/min.

Attenuated Total Reflectance-Fourier-Transform Infrared Spectroscopy (ATR-FTIR)

FTIR was measured using a Perkin Elmer Frontier IR instrument with a germanium crystal for 16 scans from 700-4000 cm^{-1}.

Thermogravimetric Analysis (TGA)

TGA was performed on a TA Instrument TGA 550 in air, and the data was processed with TA Universal Analysis software.

Photophysical characterization

For the UV-vis absorption and photoluminescence (PL) measurement, 2.4 mg CM-HMPB or Ir-functionalized CM was dispersed in 400 μL of DI water, and PL was measured using a Tecan Infinite M1000 96-well plate reader. For the emission spectra with λ_{ext} = 365 nm, bandwidths were

set to 10 nm (emission), and 10 nm (excitation). For the emission spectra with λ_{ext} = 444 nm and λ_{ext} = 380 nm, bandwidths were set to 5 nm (emission), and 5 nm (excitation). PL lifetime was measured using a custom-made device containing an LED light source (λ_{ext} = 365 nm) powered by a 40 ns square pulse from a Siglent SDG1052 function generator. Emission was detected with a Hamamatsu H7732-11 photomultiplier tube connected to a Tektronix TDS3032B digital oscilloscope interfaced to a Raspberry Pi 3 Model B+ computer.

Density Functional Theory (DFT)

DFT calculations were performed with a Gaussian 09 package Rev A02. Structure optimization was performed at the b3lyp/GEN level.[4, 5]

Procedures

Synthesis of CM-AM-EY (Scheme 1 A)

To a solution of CM-AM (500 mg, 0.3 mmol amine/500 mg CM-AM) in acetonitrile (5 ml) in a solid phase peptide synthesis vessel having a porosity fritted glass resin support (25 mL), a mixture of Eosin Y(530 mg, 0.82 mmol), DIC (390 μL, 2.5 mmol), and DMAP (30 mg, 0.25 mmol) in acetonitrile (5 mL) was slowly added and then shaken using tube rotator at room temperature overnight. The resin was washed with deionized water (20 mL × 3) and acetonitrile (20 mL × 3). Acetic anhydride (240 μL, 2.5 mmol) and triethylamine (420 μL, 3.0 mmol) were added to the resin solution in acetonitrile (20 mL), and then the mixture was shaken using a tube rotator at room temperature overnight. The resin was washed with acetonitrile (20 mL × 5) and dried under a vacuum. The resin was stored in the refrigerator at 4ºC.

Quantitative analysis of EY immobilized on CM-AM-EY

CM-AM-EY resin (2.5 - 10 μL) in 100mM sodium phosphate buffer (pH 8) containing 0.05 v/v% Tween 20 (total volume 200 μL) was placed in the well of 96 well plates. Fluorescence intensities of the suspension solution were measured at an excitation of 525 nm and an emission of 555 nm with 10 nm bandwidths by a Synergy H1 reader (Biotek). The amount of EY on the CM resin was calculated from standard curves prepared from EY in 100mM sodium phosphate buffer (pH 8) containing 0.05 v/v% Tween 20.

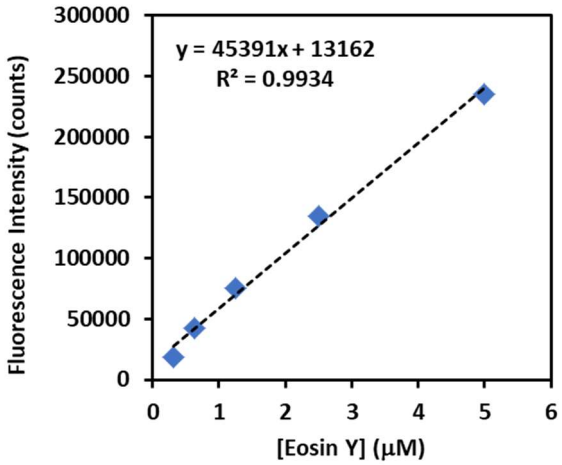


Figure S1. Calibration curve of free Eosin Y in the 100 mM sodium phosphate (pH 8.0) containing 0.05 v% of Tween 20.

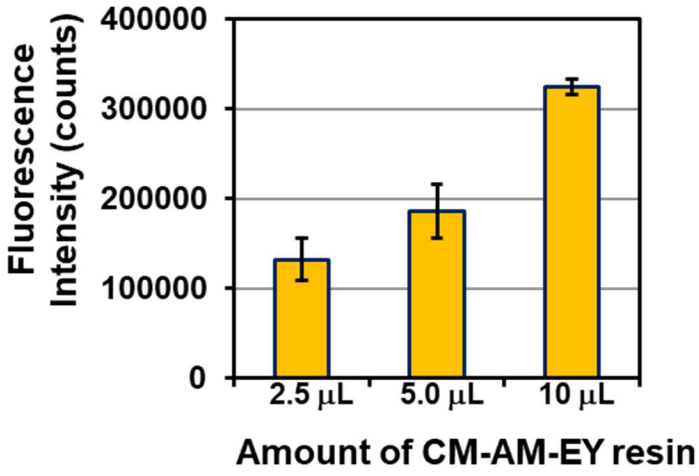


Figure S2. Relationship between fluorescence intensity and the different amounts of CM-AM-EY in the 100 mM sodium phosphate (pH 8.0) containing 0.05v% of Tween 20.

Synthesis of CM-HMPB-EY (Scheme 1 B)

To a solution of CM-HMPB (1 g, 0.41 mmol hydroxyl/g CM-HMPB) in DMF (5 ml) in a solid phase peptide synthesis vessel having a porosity fritted glass resin support (25 mL), a mixture of

Eosin Y(530 mg, 0.82 mmol), EDC·HCl (470 mg, 2.5 mmol), and DMAP (30 mg, 0.25 mmol) in DMF (5 mL) was slowly added and then shaken using tube rotator at room temperature overnight. The resin was washed with DMF (20 mL × 5). The resin was stored in the refrigerator at 4ºC.

Quantitative analysis of EY immobilized on CM-HMPB-EY

CM-HMPB-EY (2.5 - 10 μL) in 100 mM sodium phosphate buffer (pH 8) containing 0.05 v/v% Tween 20 (total volume 200 μL) were placed in the well of 96 well plate. Fluorescence intensities of the suspension solution were measured at an excitation of 525 nm and an emission of 555 nm with 10 nm bandwidths by a Synergy H1 reader (Biotek). The amount of EY on the CM resin was calculated from standard curves prepared from EY in 100mM sodium phosphate buffer (pH 8) containing 0.05 v/v% Tween 20.

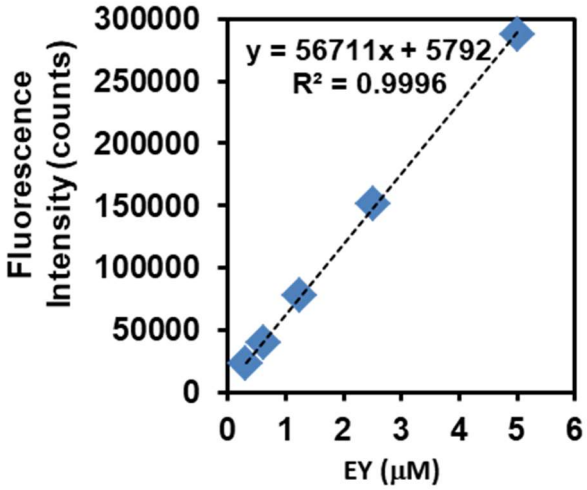


Figure S3. Calibration curve of free Eosin Y in the 100 mM sodium phosphate (pH 8.0) containing 0.05 v% of Tween 20.

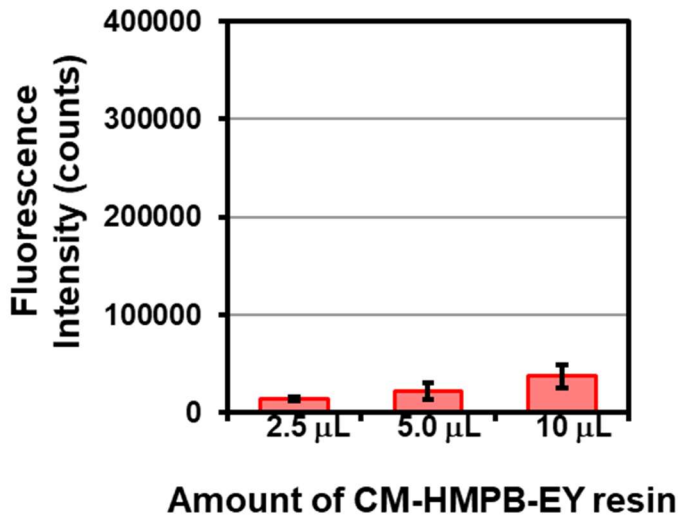
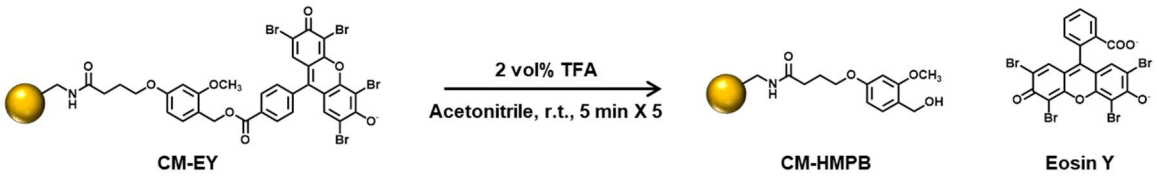


Figure S4. Relationship between fluorescence intensity and the different amounts of CM-HMPB-EY in the 100 mM sodium phosphate (pH 8.0) containing 0.05 v% of Tween 20.

Quantitative analysis of EY immobilized on CM-HMPB-EY by cleavage method.

CM-HMPB-EY (20 μL) and 2 vol% TFA in acetonitrile (200 μL) was placed in the centrifugal filter (Ultrafree^{TM}-MC centrifugal filter, MilliporeSigma), and the mixture was shaken by tube rotator at room temperature for 5 min. The supernatant was collected by centrifugal filtration. This procedure was repeated 5 times in total (1 mL). The aliquot (10 μL) of the EY solution was added to the 100 mM sodium phosphate (990 μL, pH 8), and then the absorption of the solution at 517 nm was measured by UV/Vis spectrometer (Lambda 45, Perkin Elmer). The concentration of EY was calculated from standard curves prepared from EY in 100 mM sodium phosphate buffer (pH 8).



Scheme S1. Cleavage of EY from CM-HMPB-EY resin.

Distance between Eosin Y molecules in the CM resin.

Case of CM-AM-EY resin.

The distance between the EY molecules immobilized on the AM-CM was estimated to be 15.3 nm, by calculating the amount of EY and the swelling volume of the resin as shown below.

$$\text{CM-AM-EY (4.6 µmol EY/g CM)} \xrightarrow{\text{Avogadro's number } (6.02 \times 10^{23}\ \text{mol}^{-1})} 2.77 \times 10^{18}\ \text{EY / g}$$

$$1\ \text{g CM} = 10\ \text{mL} = 10 \times 10^{-6}\ \text{m}^3$$

$$\text{Volume occupied by EY molecule} = \frac{10 \times 10^{-6}\ \text{m}^3}{2.77 \times 10^{18}\ \text{EY}} = 3.61 \times 10^{-24}\ \text{m}^3 \xrightarrow{\text{cube root}} = 1.53 \times 10^{-8}\ \text{m} = 15.3\ \text{nm}$$

Case of CM-HMPB-EY resin.

The distance between EYs on HMPB-CM was estimated to be 4.8 nm as shown below.

$$\text{CM-HMPB-EY (150 µmol EY/g CM)} \xrightarrow{\text{Avogadro's number } (6.02 \times 10^{23}\ \text{mol}^{-1})} 9.03 \times 10^{19}\ \text{EY / g}$$

$$\text{Volume occupied by EY molecule} = \frac{10 \times 10^{-6}\ \text{m}^3}{9.03 \times 10^{19}\ \text{EY}} = 1.11 \times 10^{-25}\ \text{m}^3 \xrightarrow{\text{cube root}} = 4.81 \times 10^{-9}\ \text{m} = 4.8\ \text{nm}$$

Procedure for heterogenous CM-EY catalyzed photo-ATRP

Prior to polymerizations, stock solutions of alkyl halide initiator, 2-hydroxyethyl 2-bromoisobutyrate, HO-BiB (15.8 mg in 1.0 mL DMSO), $CuBr_2$ (33.5 mg in 20.0 mL DMSO), Tris[2-(dimethylamino) ethyl] amine, TPMA (13.1 mg in 1.0 mL DMSO) TEOA (6.71 mg in 1.0 mL H_2O) were prepared.

In a 5 mL volumetric flask, 750 mg of $OEOMA_{500}$ was weighed. $CuBr_2$ stock (200 µL), TPMA stock (100 µL), HO-BiB stock (100 µL), TEOA stock (100 µL), DMF (50 µL), DMSO (50 µL) and 10X PBS solution (500 µL) were then added and the remaining volume was made up by HPLC grade water. The final concentrations were $OEOMA_{500}$ (300 mM), HO-BiB (1.5 mM), $CuBr_2$ (0.3

mM), TPMA (0.9 mM), TEOA (0.9 mM), DMSO (10% v/v). Then 8 mg of CM-AM-EY was transferred to an 8 mL fritted syringe reservoir (purchased from UCT 0.2-micron filter) equipped with a magnetic stirrer with a cap covering the tip of the syringe. 5.0 mL of the ATRP cocktail was added to it. The polymerization mixture was stirred at 500 rpm for 30 mins under ambient light to enable swelling of CM-AM-EY beads and proper homogenization. Finally, the reservoir was irradiated under green LEDs (520 nm, 25.0 mW/cm^2) to start polymerization. Samples were taken and analyzed by 1H NMR and SEC techniques.

The polymerizations were also conducted using CM-HMPB-EY (2 mg/5 mL) under the same concentrations of other ATRP components as described above.

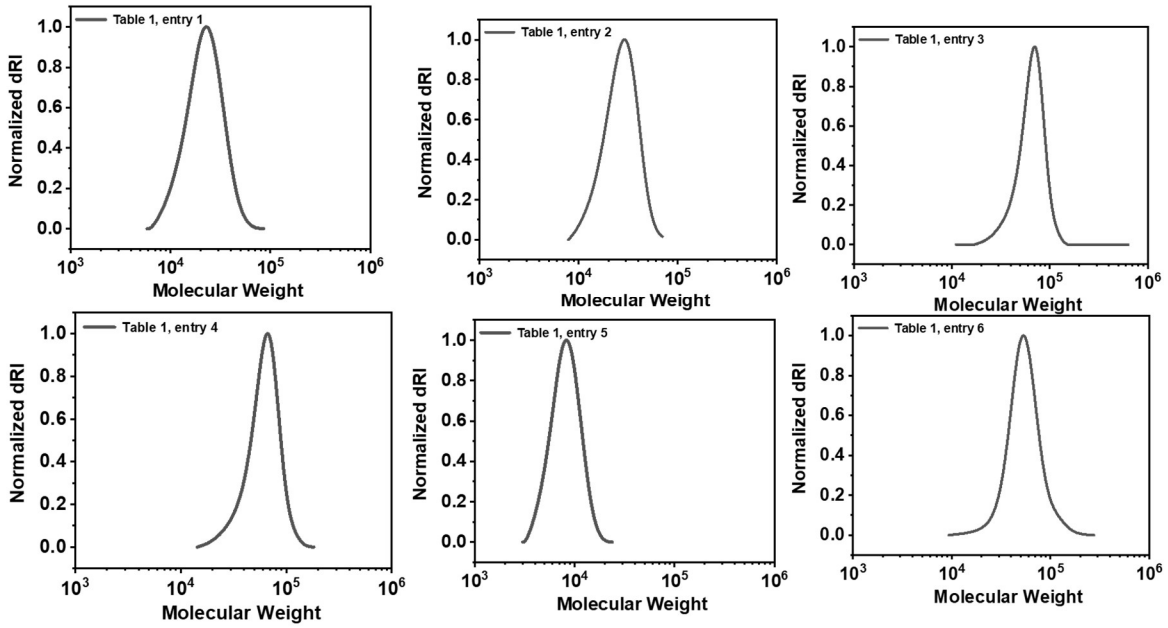


Figure S5. SEC traces of polymers reported in Table 1.

Kinetics of heterogeneous CM-AM-EY catalyzed photo-ATRP

The ATRP cocktail (5 mL) was prepared according to the general procedure described above. The final concentrations were $OEOMA_{500}$ (300 mM), HO-BiB (1.5 mM), $CuBr_2$ (0.3 mM), TPMA (0.9

mM), TEOA (0.9 mM), DMSO (10% v/v). 50 µL of DMF was used as an internal standard. Then 5.0 mL of the ATRP cocktail was transferred to an 8 mL fritted syringe reservoir equipped with a magnetic stir bar and 8 mg of CM-AM-EY resulting in the following molar ratio ([$OEOMA_{500}$]/[HOBiB]/[CM-AM-EY]/[CuBr2]/[TPMA]/[TEOA]) = 200/1/0.005/0.2/0.6/0.6. The polymerization mixture was stirred at 500 rpm for 20 mins under ambient light and then an additional 40 min under green LEDs (520 nm, 25.0 mW/cm^2) in open air conditions. Samples were drawn at regular intervals and monitored by ^{1}H NMR in D_2O and by SEC-MALS using 1X PBS as an eluent. (Figure 1 A-C)

Varying targeted degrees of polymerization

The target degrees of polymerization (DP) were varied across a broad range (DP 50-1000). The concentration of the OH-BiB initiator was varied (6 mM- 0.30 mM), while keeping the other polymerization components [$OEOMA_{500}$]= 300 mM, [CM-AM-EY] = 7.5 µM, [CuBr2] = 0.3 mM, [TPMA] = 0.9 mM, [TEOA] = 0.9 mM) identical.

Then 5.0 mL of the ATRP cocktail with desired targeted DP was added to an 8 mL fritted syringe reservoir equipped with a magnetic stir bar and 8 mg of CM-AM-EY. The polymerization mixture in an uncapped syringe was stirred at 500 rpm for 20 mins under ambient light, followed by irradiation for 30 mins under green LEDs (525 nm, 25.0 mW/cm^2). Samples were taken and analyzed by ^{1}H NMR and SEC techniques (Figure 2 D).

In-situ chain extension

The ATRP polymerization mixture (5 mL) with a target DP_T = 50 was prepared according to the general procedure described above. The final concentrations were: [$OEOMA_{500}$]= 300 mM, [OH-BiB] = 6.0 mM, [CM-AM-EY] = 7.5 µM, [CuBr2] = 0.3 mM, [TPMA] = 0.9 mM, [TEOA] = 0.9

mM) Then 5.0 mL of the ATRP cocktail was transferred to an 8 mL fritted syringe reservoir equipped with a magnetic stir bar and 8 mg of CM-AM-EY. The polymerization mixture in an uncapped vial was stirred at 500 rpm for 20 mins under ambient light followed by 25 min under green LEDs (525 nm, 25.0 mW/cm^2). The macroinitiator POEOMA$_{500}$ was synthesized with 64% monomer conversion ($M_{n,\,abs}$ = 15 500, $Đ$ = 1.26).

Post-polymerization, the macroinitiator POEOMA$_{500}$ was collected by removing the cap from the tip of a syringe by simple filtration. Without further purification, this macroinitiator was used to chain extend with a second block of the same monomer OEOMA$_{500}$. Using 1 mL of the first block as macroinitiator (1.2 mM) a new polymerization mixture was prepared in a 5 mL volumetric flask containing 750 mg of OEOMA$_{500}$, $CuBr_2$ stock (200 µL), TPMA stock (100 µL), TEOA stock (100 µL), DMF (50 µL), DMSO (50 µL) and 10X PBS solution (500 µL) and the remaining volume was made up by HPLC grade water. CM-AM-EY from the previous polymerization was thoroughly washed and reused from the chain-extension experiment. The polymerization mixture with target DP = 250 was mixed with recycled CM-AM-EY in the syringe. The polymerization was stirred in an open syringe at 500 rpm for 20 mins under ambient light and then 30 mins under green light LEDs (525 nm, 25.0 mW/cm^2) to start polymerization. The monomer reached 74% conversion resulting in chain-extended POEOMA$_{500}$ ($M_{n,\,abs}$ = 115 400, $Đ$ = 1.10) with excellent control over molecular weight and dispersity.

Temporal Control

The photo-ATRP was set up in the same way as described in the procedure above. The molar concentrations used were [OEOMA$_{500}$]= 300 mM, [OH-BiB] = 1.5 mM, [CM-AM-EY] = 7.5 µM, [$CuBr_2$] = 0.3 mM, [TPMA] = 0.9 mM, [TEOA] = 0.9 mM in 1X PBS buffer and DMSO (10% v/v) including DMF (50 µL) as internal standard. Then 5.0 mL of polymerization was transferred

to an 8 mL fritted syringe reservoir equipped with a magnetic stir bar and 8 mg of CM-AM-EY. The polymerization mixture in an uncapped vial was stirred at 500 rpm for 20 mins under ambient light followed by 30 min under green LEDs (525 nm, 25.0 mW/cm^2) with the light being turned on/off at 10 min intervals. Samples (50 µL) were drawn out and quenched with 20 µL of 1,4-bis(3isocyanopropyl)piperazine (10 mg/mL in D_2O) and then analyzed by ^{1}H NMR.

The final polymer sample after 70 minutes was collected by filtration from the heterogenous CM-AM-EY and then analyzed by SEC-MALS using 1X PBS as the eluent (Figure S6).

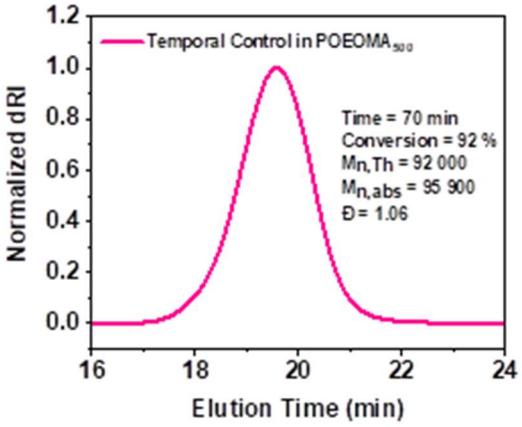


Figure S6. SEC trace of a final polymer sample from temporal control experiment showing high-retention of chain end functionality.

Recycling of CM-AM-EY over multiple cycles

In a 25 mL volumetric flask, 7.5 g of $OEOMA_{500}$, $CuBr_2$ stock (1.0 mL), TPMA stock (500 µL), TEOA stock (500 µL), OH-BiB (500 µL) DMF (250 µL), DMSO (250 µL) and 10X PBS solution (2.5 mL) was added and the remaining volume was made up by HPLC grade water. Separately, in an 8 mL fritted syringe reservoir equipped with a magnetic stir bar, 8 mg of CM-AM-EY was weighed. To this syringe reservoir 5 mL of polymerization mixture was transferred resulting in

molar concentration as follows: [$OEOMA_{500}$]= 300 mM, [OH-BiB] = 1.5 mM, [CM-AM-EY] = 7.5 μM, [$CuBr_2$] = 0.3 mM, [TPMA] = 0.9 mM, [TEOA] = 0.9 mM in 1X PBS buffer and DMSO/DMF (10% v/v).

The polymerization mixture was stirred in the syringe reservoir at 500 rpm for 20 mins under ambient light followed by 30 min under green LEDs (525 nm, 25.0 mW/cm^2). The final polymer sample was collected after 30 min by simple filtration from the heterogenous CM-AM-EY and was analyzed by ^1H NMR and SEC-MALS using 1X PBS as the eluent.

The same syringe reservoir containing CM-AM-EY from the first cycle was washed thoroughly with deionized water (50 mL) and then, without any additional treatment, reused for the second polymerization cycle using the same polymerization cocktail stock prepared in the beginning.

After each cycle of polymerization carried out by 30 min irradiation under green LEDs (525 nm, 25.0 mW/cm^2), the polymer samples were collected by filtration and analyzed by ^1H NMR and SEC-MALS using 1X PBS as the eluent. This was repeated up to 5 times and no leaching of EY in the polymer samples was observed (Figure S7). Additionally, each polymerization cycle reached high monomer conversion and exhibited excellent control over molecular weight and molecular weight distribution of the polymer samples (Figure 2).

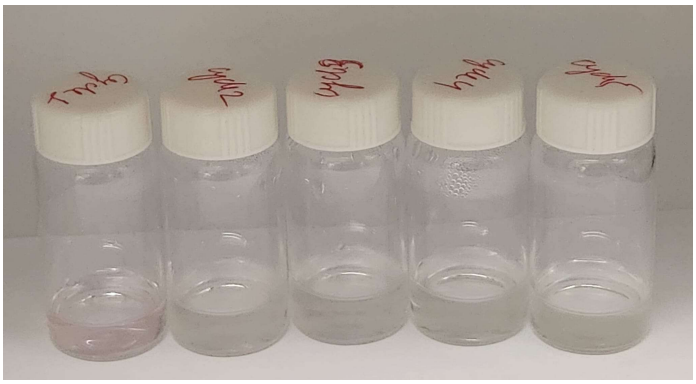


Figure S7. Photograph of polymerization reactions during recycling of the CM-AM-EY showing no contamination of the polymer by EY dye.

Photostability of CM-EY:

To evaluate the photostability of CM-EY in comparison to free EY, a time-dependent fluorescence intensity analysis was conducted. A 7.5 µM solution of EY in 1 mL of 1X PBS was added to two fritted 3 mL syringe reservoirs. One syringe contained free EY in a homogeneous solution, while the other contained the same concentration of EY immobilized onto CM. The heterogeneous CM-EY was stirred and allowed to swell in the dark for 15 minutes prior to taking the initial fluorescence measurement (T = 0) for both samples. Both syringes were then irradiated with green light LEDs (λmax = 520 nm, 25.0 mW cm^{-2}) at room temperature with continuous stirring at 500 rpm. Fluorescence intensity measurements were taken at T = 1 hour and T = 3 hours. The results indicated that while free EY exhibited significant photobleaching over the 3-hour period, immobilized CM-EY retained over 80% of its fluorescence under identical conditions (Figure S8 A-B), demonstrating superior photostability.

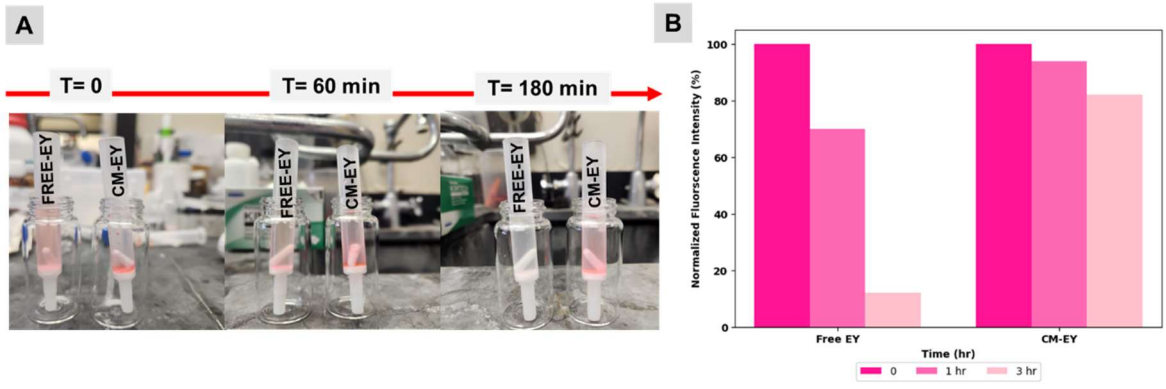


Figure S8. (A) Digital images of free and immobilized EY over the course of irradiation under green light LEDs (λmax = 520 nm, 25.0 mW cm^{-2}). (B) Normalized fluorescence intensity vs the irradiation time.

Expanding monomer scope to aqueous and organic media

Table S1. Expanding the scope of monomers for heterogenous CM-AM-EY catalyzed photo-ATRP

S.No.	[M]	[Cu]/[L]/[CM-AM-EY]/[I]	α_M(%)	$M_{n,th}$	$M_{n,app}$	$M_{n,abs}$	$Đ$
1.	$OEOMA_{300}$	0.2/0.6/0.005/1	80	48 000	35 000	40 000	1.04
2.	CBMA	0.2/0.6/0.005/1	99	47 000	-	58 000	1.23
3.	MSEMA	0.2/0.6/0.005/1	92	34 000	20 000	36 200	1.12
4.	$OEOA_{480}$	0.2/0.3/0.005/1	84	84 000	61 550	86 600	1.18
5.	MA	0.05/0.3/0.0005/1	90	15 500	15 700	15 000	1.13
6.	EA	0.05/0.3/0.0005/1	97	18 500	15 700	15 000	1.13

Reaction conditions for each entry have been outlined below.

Entry 1-3. [M]/[HOBIB]/[$CuBr_2$]/[TPMA]/[CM-AM-EY]/[TEOA]: 200/1/0.2/0.6/0.005/0.6, [M] = [$OEOMA_{300}$]/[CBMA]/[MSEMA]= 300 mM, [HOBIB] = 1.5 mM, in 1X PBS buffer and 10% DMSO, irradiated for 30 min under green light LEDs (λ_{max} = 520 nm, 25.0 mW cm^{-2}) at room temperature. [a][M] conversion was determined by using ^{1}H NMR spectroscopy. [b]Theoretical molecular weight was calculated using the equation $M_{n,th}$ =[M] * MW_M *αM +MW_I. [a]pparent molecular weight ($M_{n,app}$) was analyzed by SEC using DMF as the eluent and PMMA as calibration standards. [d]$M_{n,abs}$ analyzed using SEC-MALS run using 1X PBS as eluent.

Entry 4. [M]/[HOBIB]/[$CuBr_2$]/[Me_6Tren]/[CM-AM-EY]/[TEOA]: 200/1/0.2/0.3/0.005/0.3, [M] = [$OEOA_{480}$] = 300 mM, [HOBIB] = 1.5 mM, in 1X PBS buffer and 10% DMSO, irradiated for 30 min under green light LEDs (λ_{max} = 520 nm, 25.0 mW cm^{-2}) at room temperature. [a][M] conversion was determined by using ^{1}H NMR spectroscopy. [b]Theoretical molecular weight was calculated using the equation $M_{n,th}$ =[M] * MW_M *αM +MW_I. [a]pparent molecular weight ($M_{n,app}$) was analyzed by SEC using DMF as the eluent and PMMA as calibration standards. [d]$M_{n,abs}$ analyzed using SEC-MALS run using 1X PBS as eluent.

Entry 5-6. [M]/[EBiB]/[$CuBr_2$]/[Me_6Tren]/[CM-AM-EY]/[TEA]: 200/1/0.05/0.3/0.0005/0.3, [M] = [MA]/[EA] = 5.5 M, [EBIB] = 27.5 mM, in DMSO, irradiated for **120 min** under green light LEDs (λ_{max} = 525 nm, 25.0 mW cm^{-2}), in an ambient atmosphere. Reaction volume 5.0 mL. [a]MA conversion was determined by using ^{1}H NMR spectroscopy. [a][M] conversion was determined by using ^{1}H NMR spectroscopy. [b]Theoretical molecular weight was calculated using the equation $M_{n,th}$ =[M] * MW_M *αM +MW_I. [a]pparent molecular weight ($M_{n,app}$) was analyzed by SEC using THF as the eluent and PMMA as calibration standards. [d]$M_{n,abs}$ analyzed using SEC-MALS using THF as the eluent.

Synthesis of Protein-Polymer Hybrids (PPH)

The synthesis of BSA and CT macroinitiator was achieved by reaction of NHS-functionalized ATRP initiator (NHS-Br) with purified BSA and CT according to the previously reported procedure.[6] The number of functionalized sites on BSA and CT was determined by fluorescamine assay as reported in our previous publication.[7] The estimated molecular weight of BSA-$ibbr_{22}$ was 71.4 kDa and CT-$ibbr_{12}$ was 27.2 kDa.

The polymerization reaction mixture was prepared in a 5 mL volumetric flask according to the general procedure described above. The molar concentrations used were [CBMA]= 300 mM, [$CuBr_2$] = 0.3 mM, [TPMA] = 0.9 mM, [TEOA] = 0.9 mM in 1X PBS buffer and DMSO (10% v/v) including DMF (50 µL) as internal standard. The mixture was vortexed and transferred to a 20 mL vial containing protein-macroinitiator (BSA-$ibbr_{22}$ (24.0 mg) or CT-$ibbr_{12}$ (17 mg). The ATRP initiator concentration was 1.5 mM. The protein macroinitiator was dissolved and the reaction mixture was pipetted to an 8 mL fritted syringe reservoir equipped with a magnetic stir bar and 8 mg of CM-AM-EY as heterogeneous PC. The mixture was stirred at 500 rpm for 20 minutes under ambient light and then under green light (λ_{max} = 525 nm, 25.0 mW cm^{-2}) for 20 minutes. The reaction was kept at ambient temperature throughout the polymerization using the built-in fan for cooling. Pots-polymerization the synthesized PPH was separated from the CM-AM-EY by filtration. The monomer conversion was analyzed by ^1H NMR in D_2O. The PPH was further purified by dialysis for 48 hours at 4ºC using a 10 kDa membrane. The purified PPHs were analyzed by SEC-MALS running on 1X PBS buffer.

Solid-phase synthesis of polymers

Synthesis of CM resin functionalized with ATRP initiators (CM-BiB)

CM-HMPB (1 g, 0.40-0.65 mmol -OH/g CM-HMPB) was transferred to a 100 mL round bottom flask with a magnetic stirrer. DCM (50 mL) and triethyl amine (0.8 mmol, 112 µL) were added to the flask and placed in an ice bath. Next, α-bromoisobutyryl bromide (BIB-Br, 0.8 mmol, 100 µL) in DCM (10 mL) was slowly added. The reaction mixture was kept stirring overnight at room temperature and filtered off. The filtered functionalized CM resin was washed with water and methanol and dried under vacuum to give pure CM-BiB.

Procedure for solid-phase polymerization

In a 5 mL volumetric flask the polymerization reaction mixture in DMSO was prepared with molar ratios of reagents as follows: [M]/[EBiB]/[$CuBr_2$]/[Me_6Tren]/[CM-AM-EY]/[TEA]: 200/1/0.05/0.3/0.0005/0.3, where [M] = [MA]= 5.5 M, [EBiB] = 27.5 mM. EBiB was used as the homogenous sacrificial initiator to target the desired degree of polymerization. The polymerization mixture was vortexed and transferred to an 8 mL fritted syringe reservoir equipped with a magnetic stir bar and pre-weighed 16 mg of CM-AM-EY as heterogeneous PC and 20 mg of CM-BiB as the solid support for grafting polymers. The polymerization was stirred at 750 rpm for 20 minutes under ambient light, followed by irradiation under green light LEDs (520 nm, 25.0 mW/cm^2) for 120 minutes at ambient temperature. The syringe was capped during polymerization to prevent the loss of volatile monomers. However, no degassing was necessary.

Post-polymerization, the solid supports which are CM-PMA, and CM-AM-EY were separated from the solution phase by filtration and then thoroughly washed with DMSO (25 mL). The solid support mixture was further treated in two different ways. One for either chain extension with a second block of polymer onto the solid support. Second, for cleavage of PMA from the CM support and then its functionalization with BiB to regenerate CM-BiB.

Chain extension on solid support.

The CM-PMA and CM-AM-EY mixture from the previous step was used directly for chain extension in the next step. A new polymerization mixture comprising EA monomer was added to it. The molar ratios of polymerization components were as follows: [M]/[EBiB]/[$CuBr_2$]/[Me_6Tren]/[CM-AM-EY]/[TEA]: 200/1/0.05/0.3/0.0005/0.3. The polymerization was stirred at 750 rpm for 20 minutes under ambient light, followed by irradiation

under green light LEDs (520 nm, 25.0 mW/cm^2) for 120 minutes at ambient temperature. The solution phase was separated from the solid phase and analyzed by ^{1}H NMR and SEC using THF as an eluent. The solid phase was subjected to 20% TFA/H_2O to hydrolyze ester linkage and release PMA-b-PEA from the solid support. The cleaved polymer sample was analyzed by THF-SEC and revealed successful synthesis of block copolymer by photo ATRP catalyzed by heterogenous CM-AM-EY (Figure 5B).

Recycling the solid-supports

The CM-PMA and CM-AM-EY can also be recycled. The mixture of solid supports was subjected to 20% TFA/H_2O to hydrolyze ester linkage and release PMA forming HMPB-CM while CM-AM-EY remained unchanged. After thoroughly washing the solid-supports post hydrolysis, they were mixed TEA (0.4 mmol, 56 μL) in DMF (50 mL) and then α-bromoisobutyryl bromide (BIB-Br, 0.4 mmol, 50 μL) was slowly added while keeping syringe in the ice bath. The reaction was allowed to stir overnight and then filtered, washed, and dried with DMF. The regenerated CM-BiB together with CM-AM-EY were then tested for solid-phase grafting of PMA. Upon analysis, we observed that successful grafting from regenerated CM-BiB was achieved under the described conditions (Figure 5 C).

Ir (III)-Functionalized ChemMatrix (Ir@CM)

Iodination of OH-functionalized CM

A solid-phase extraction (SPE) reservoir (syringe) was used to perform the multistep functionalization of ChemMatrix. The iodization was designed based on a reported protocol.[8] Imidazole (39 mg, 12 equiv. compared to the -OH group in ChemMatrix) and triphenylphosphine (150 mg, 4.4 equiv. compared to -OH) were dissolved in 4 mL DCM, followed by the addition of

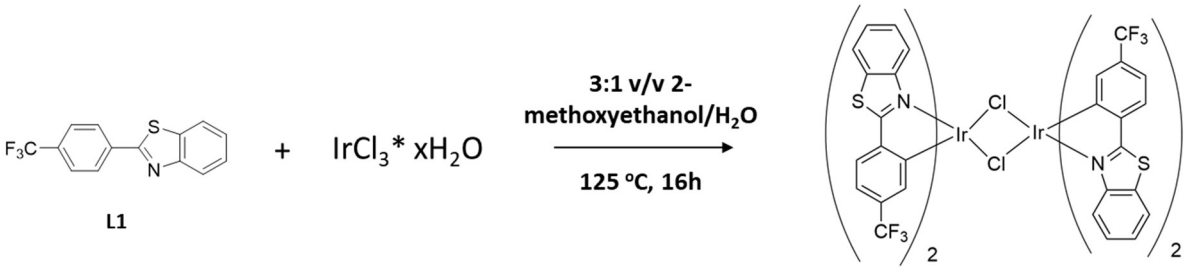
I_2 (132 mg in 2 mL DCM, 4.0 equiv. compared to -OH). The solution was stirred for 10 min and transferred to the SPE reservoir containing 200 mg ChemMatrix-HMPB (CM-HMPB, loading of -OH is 0.65 mmol/g). The reaction continued for 3 h, and the solution phase was removed by washing the reaction mixture. The product was further washed with DCM (5 mL×4 times) and acetonitrile (5 mL×2 times), and dried in air, giving iodine-functionalized CM (CM-I).

Azidation of iodine-functionalized CM

The azidation (step 2, Figure 1) was performed in the same SPE syringe. Iodine-functionalized CM (CM-I) was swollen in a 5 mL acetonitrile solution containing tetrabutylammonium bromide (369 mg, 8.8 equiv. compared to -I) and sodium azide (68 mg, 8.0 equiv.). The reaction continued at room temperature for 3 h, and the liquid phase was removed by washing the reaction mixture in the SPE reservoir. The product was washed with acetonitrile (5 mL×4 times) before being dried in the air and finally yielded azide-functionalized CM (CM-N_3).

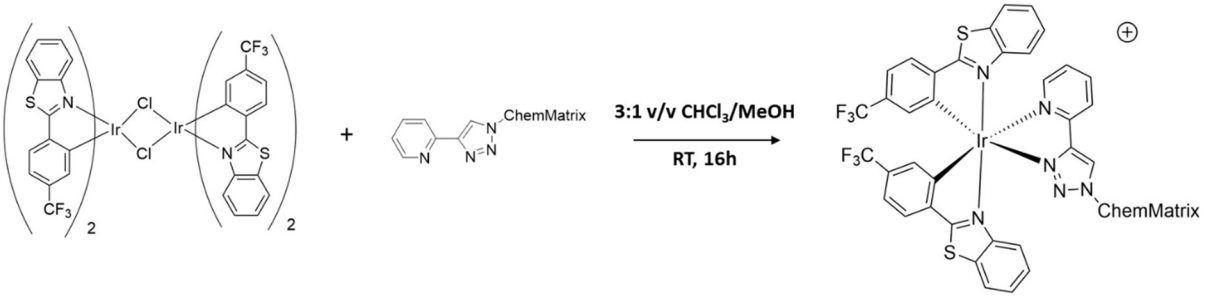
Synthesis of CM-L (L = ligand) via Cu-catalyzed azide-alkyne cycloaddition

$CuSO_4$ aqueous solution (10 mg in 1 mL H_2O) was added to the SPE syringe containing azide-functionalized CM. (+)-Sodium L-ascorbate (103 mg in 1 mL H_2O, 4 equiv.) and 2-ethynylpyridine (80 mg in 1 mL *t*-BuOH, 6 equiv.) were added to the syringe. The mixture was reacted (step 3, Figure 1) at room temperature for 24 h, followed by the removal of the liquid phase using the same method described in previous steps. The crude product was washed with the following solvents: H_2O (5 mL×4 times), acetonitrile (5 mL×4 times), NH_4OH (5 mL×4 times), H_2O (5 mL×4 times), MeOH (5 mL×4 times) and DCM (5 mL×4 times). The washed product was dried and yielded 2-triazol-pyridine functionalized CM (CM-L).



Scheme S2. Synthesis of the (pbtz)2Ir(μ-Cl)Ir(pbtz)2 complex. pbtz = 2-(4-(trifluoromethyl)phenyl)benzo[d]thiazole.

CM functionalized with the 2-triazole-pyridine ligand was reacted with different Ir dimer complexes to facilitate the incorporation of Ir species onto the CM network. The synthesis of phenyl-pyridine coordinated Ir complexes was based on previous methods.[2] Phenyl-thiazole coordinated Ir complexes were synthesized using methods described herein. First, the Ir dimer was formed using reactions shown in Scheme S1. 2-(4-(trifluoromethyl)phenyl)benzo[d]thiazole was reacted with iridium(III) chloride hydrate with a 2.1:1 molar ratio at 125 °C for 16 hours in a 3:1 vol/vol solution of 2-methoxyethanol/water. The dimeric Ir(III) product ($[IrCl(\mathbf{L1})_2]_2$) was precipitated by the addition of water after the reaction was cooled to room temperature. The dimer was isolated using vacuum filtration and washed with diethyl ether to remove excess or unreacted cyclometalated ligand (**L1**).



Scheme S3. Attachment of Ir moieties to a ligand-functionalized ChemMatrix network.

Pyridine-azide functionalized CM was reacted with the dimeric Ir(III) product ([IrCl(**L1**)$_2$]$_2$) with a 2.1:1 molar ratio at room temperature for 16 hours in a 3:1 vol/vol solution of chloroform/methanol. The colored and emissive gel was filtered and washed with methanol, leading to the desired gel product functionalized with a cationic Ir(III) complex (Scheme S2).

Additional characterization data

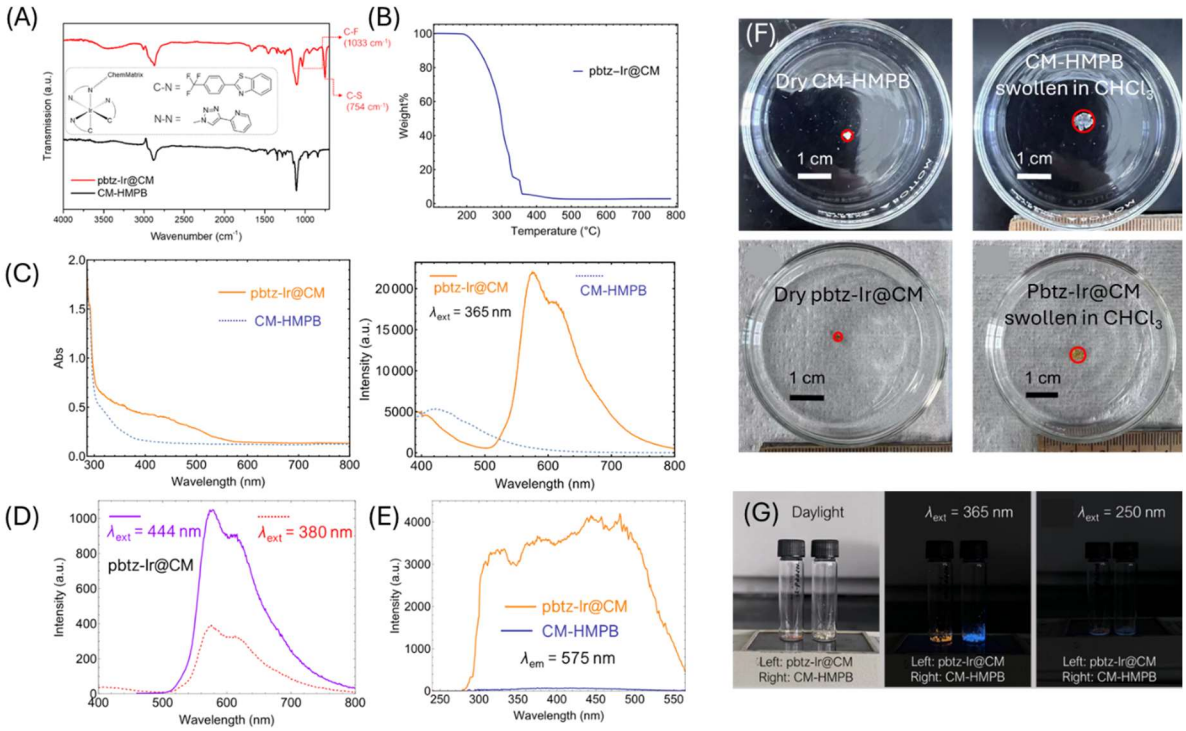


Figure S9. Characterization of Ir@CM. (A) FTIR spectra of pbtz-Ir@CM (red, top) and CM-HMPB (black, bottom). (B) Thermogravimetric analysis (TGA) results of pbtz-Ir@CM in air. (C) Photophysical properties of pbtz-Ir@CM (orange, solid) and CM-HMPB (dark blue, dashed) were measured using a 96-well plate reader. Left: UV-vis absorption spectra, right: PL emission spectra with λ_{ext} = 365 nm. (D) PL excitation spectra of pbtz-Ir@CM (orange) and CM-HMPB (dark blue) with the emission wavelength λ_{em} set to 575 nm. (E) PL emission spectra of pbtz-Ir@CM using different excitation wavelengths, λ_{ext} = 444 nm (magenta, solid) and λ_{ext} = 380 nm (red, dashed).

For (B), the emission and excitation bandwidths were both set to 5 nm for the two emission scans. (F) Pictures of CM-HMPB and pbtz-Ir@CM in Petri dishes (red circles indicate the position of the resin). (G) Pictures of pbtz-Ir@CM or CM-HMPB under different light irradiations.

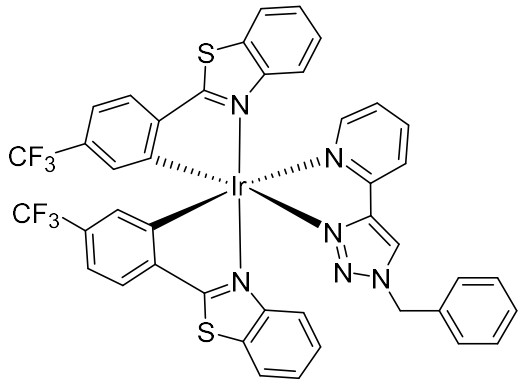


Figure S10. Structure of pbtz-Ir@CM model compound.

Table S2. Excited state lifetimes of model compound and pbtz-Ir@CM. Measurements were conducted with a pulsing 365nm LED with a photomultiplier tube detector.

Substance	**Lifetime (ns)**
Model compound	3417
Dry pbtz-Ir@CM	972
pbtz-Ir@CM swollen in H_2O	867

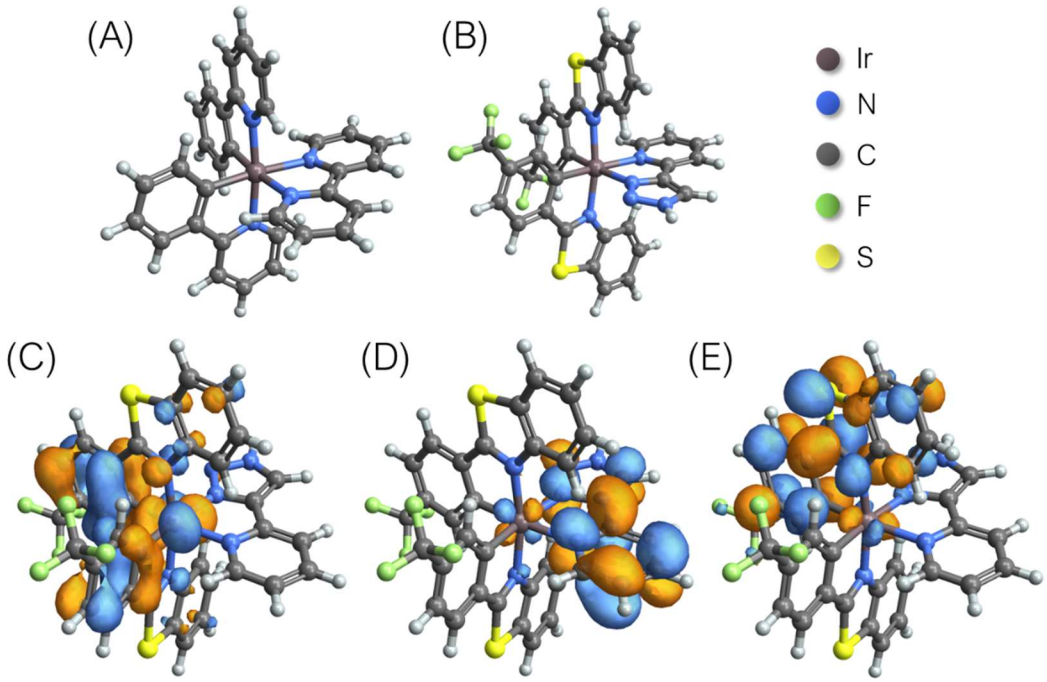


Figure S11. Geometry and molecular orbitals (MOs) obtained from density functional theory (DFT) calculations of model Ir complexes. (A) Archetypal $[Ir(C^N)_2(N^N)]^+$ complex composed of 2-phenylpyridine and 2,2-bipyridine ligands. (B) A model Ir(III) complex used in this study, $[Ir(pbtz)_2(tpy)]^+$ (tpy: 2-triazol-pyridine), pbtz: 2-(4-(trifluoromethyl)phenyl)benzo[d]thiazole). (C) HOMO (highest occupied molecular orbital) of $[Ir(pbtz)_2(tpy)]^+$. (D) LUMO (lowest unoccupied molecular orbital) of $[Ir(pbtz)_2(tpy)]^+$. (E) HSOMO (highest singly occupied molecular orbital) of triplet excited state $[Ir(pbtz)_2(tpy)]^+$. Optimizations were performed at the b3lyp/LANL2DZ[9, 10] for Ir and b3lyp/3-21g level for all other atoms.[4, 5]

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