Chemical Science

ROYAL SOCIETY OF CHEMISTRY

EDGE ARTICLE

View Article Online
View Journal | View Issue

Check for updates

Cite this: *Chem. Sci.*, 2025, **16**, 23103

All publication charges for this article have been paid for by the Royal Society of Chemistry

Received 5th September 2025
Accepted 15th October 2025

DOI: 10.1039/d5sc06852e

rsc.li/chemical-science

Self-sorting systems of photoresponsive polymer micelles: isomerization drives reversible and switchable self-assembly

Rikuto Kanno, Makoto Ouchi and Takaya Terashima *

Herein, we report self-sorting systems of photoresponsive polymer micelles obtained from amphiphilic statistical copolymers bearing hydrophilic poly(ethylene glycol) (PEG) chains and hydrophobic/photoresponsive azobenzene (Azo) groups. The PEG/Azo copolymers self-folded or intermolecularly self-assembled *via* the association of the azobenzene pendants to form photoresponsive unimer or multichain micelles in water, where the core-forming Azo groups show *cis*/*trans* isomerization in response to UV/vis irradiation. The PEG/Azo copolymer micelles not only induced self-sorting in the presence of other PEG copolymer micelles with different compositions and/or pendants but also exhibited photoresponsive and reversible self-sorting/co-self-assembly with an anionic copolymer micelle *via* the *cis*/*trans* isomerization of the Azo units. We successfully developed self-sorting and co-self-assembly systems of binary polymer mixtures that can be dually controlled by molecular design and UV/vis light without using externally added reagents.

Introduction

Light is a ubiquitous, non-destructive, and permeable energy source and thereby effective as an external trigger to modulate the structures (*e.g.*, stereoisomerism), motion, and association properties of molecules for desired functions. The importance of light is highlighted in photoresponsive self-assembly systems in nature: for instance, rhodopsin, a light-sensitive receptor protein, converts light signals into visual information through the photoisomerization of its retinal chromophore.[1] Such examples have inspired chemists to create photoresponsive amphiphilic self-assemblies[2] and photoresponsive supramolecular polymers,[3,4] among others.[5,6]

An even more attractive possibility is to use light for controlling self-sorting phenomena, in which molecules in complex media containing multiple components selectively recognize and organize themselves through dynamic interactions among each other.[7–9] Analogous to precision self-assembly of proteins and DNA *in vivo*,[10–12] self-sorting systems based on supramolecular compounds[13–22] and synthetic polymers[23–30] have been created. For instance, low-molecular-weight supramolecular compounds can recognize themselves from non-selves based on structural factors including size,[13,14] shape,[15–17] and chirality[18] through noncovalent interaction such as hydrogen bonding. Self-sorting on macromolecules can also be realized by tuning primary structures: molecular weight,[23,30] tacticity,[24,25] monomer unit structures,[26] and composition.[27–29] Introducing stimuli-responsive properties to such self-sorting systems would allow reversible switching of the association modes of macromolecules in response to external stimuli including light, whereas such switchable self-sorting systems are rare among previous achievements.[22]

Our group has developed self-assembly and self-sorting systems of amphiphilic random copolymer micelles in water.[27–32] Random copolymers bearing hydrophilic poly(ethylene glycol) (PEG) and hydrophobic alkyl groups as side chains induce chain-folding *via* the association of the hydrophobic segments, like proteins, in water to form small micelles. The size of the micelles is predominantly determined by the hydrophilic/hydrophobic balance, *i.e.*, composition or side chain structures. Thus, binary PEG random copolymers with different compositions and/or alkyl groups self-sort to simultaneously form discrete micelles.[27–30] In contrast, such a PEG random copolymer co-self-assembles with an ionic random copolymer into a PEG/ion-fused micelle in pure water, and the fused micelle is separated into discrete PEG or ionic micelles in water containing a salt.[31,32] These results imply that folding polymer micelles containing light-sensitive units open a new possibility to create self-sorting systems controlled by not only molecular structures (*e.g.*, molecular weight, composition, and side chain functional groups) as encoded information but also light as an external trigger.

Herein, we report self-sorting systems of photoresponsive polymer micelles in water (Fig. 1a). For this, we designed photoresponsive amphiphilic statistical copolymers bearing hydrophilic PEG and hydrophobic azobenzene (Azo) units as side chains (Fig. 1a), focusing on the fact that Azo units are

---

Department of Polymer Chemistry, Graduate School of Engineering, Kyoto University, Katsura, Nishikyo-ku, Kyoto 615-8510, Japan. E-mail: terashima.takaya.2e@kyoto-u.ac.jp

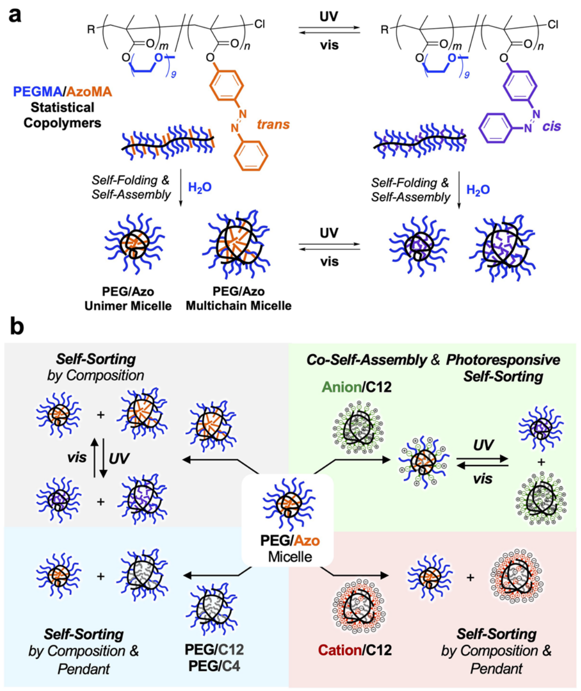

Fig. 1 (a) Design and self-assembly of amphiphilic/photoresponsive statistical copolymers bearing hydrophilic poly(ethylene glycol) (PEG) and hydrophobic azobenzene pendants into unimer or multichain micelles. (b) Self-sorting systems of the binary mixtures of photoresponsive PEG/Azo copolymer micelles and PEG or ionic random copolymer micelles in water. PEG/Azo copolymer micelles not only induce self-sorting with PEG/Azo or alkyl copolymer micelles and a cationic micelle but also afford co-self-assembly and photoresponsive self-sorting with an anionic micelle in water.

reversibly switchable between a thermodynamically stable *trans*-state and a metastable *cis*-state upon visible and UV light irradiation, respectively.[33–37] The PEG/Azo statistical copolymers induce self-folding or intermolecular self-assembly *via* the association of the hydrophobic Azo pendants and form unimer or multichain micelles, depending on the content of the Azo units. The Azo units within the micelle cores allow reversible isomerization between *trans* and *cis* states in water by irradiating visible (470 nm) and UV (365 nm) light, respectively. Importantly, the PEG/Azo copolymer micelles not only induced self-sorting, depending on the difference of the composition and pendant structures, but also afforded photoresponsive self-sorting/co-self-assembly with an anionic copolymer micelle *via* the reversible isomerization of the Azo units (Fig. 1b). To the best of our knowledge, this is the first example of self-sorting/co-self-assembly systems of polymers reversibly controlled by light in complex aqueous media.

Results and discussion

Design and synthesis of PEG/Azo copolymers

The PEG/Azo statistical copolymers with different compositions (Azo = 20, 35, 55 mol%) were synthesized by ruthenium-catalyzed living radical copolymerization of PEG methyl ether methacrylate (PEGMA, M_n = 500 g mol^{-1}, average oxyethylene units = 9) and (*E*)-4-(phenyldiazenyl)phenyl methacrylate (AzoMA)[37] with ethyl 2-chloro-2-phenylacetate (ECPA) as a chloride initiator (Scheme S1). According to the AzoMA content, the PEG/Azo copolymers were named **P-Azo20**, **P-Azo35**, and **P-Azo55.** The feed ratio of PEGMA and AzoMA in the copolymerization was set to 85/15, 70/30, 55/45 to modulate the copolymer composition.

In all the cases, the two monomers were smoothly and simultaneously consumed to give PEGMA/AzoMA statistical copolymers with a controlled molecular weight and narrow molecular weight distribution (M_n = 19 200–27 200 g mol^{-1}, M_w/M_n < 1.3, by size-exclusion chromatography (SEC) in *N*,*N*-dimethylformamide (DMF) with poly(methyl methacrylate) standard calibration, Fig. S1). Although AzoMA was consumed faster than PEGMA, the averaged AzoMA content estimated from the conversion in the copolymerization was almost constant along a polymer chain without biassed sequence distribution such as gradient copolymers. The degree of polymerization of PEGMA and AzoMA units in the copolymers (*m*/*n*) was calculated from the initial monomer feed ratio and the monomer conversion. The *m*/*n* values agreed well with the monomer unit composition estimated from the area ratio of the monomer units in ^{1}H nuclear magnetic resonance (NMR) spectroscopy (Fig. S2): *m*/*n* = 49/13 (**P-Azo20**), 43/24 (**P-Azo35**), 25/30 (**P-Azo55**) (Fig. 2 and Table 1).

Besides, other amphiphilic random copolymers carrying different side chains were prepared (Table S1 and Fig. 2): **P-D50**

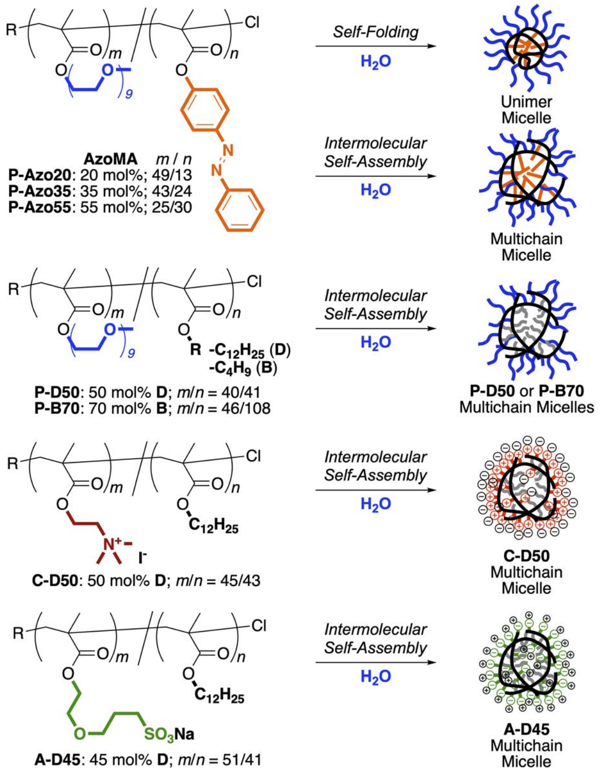

Fig. 2 Self-folding or intermolecular self-assembly of amphiphilic statistical or random copolymers into unimer or multichain micelles in water.

Table 1 Synthesis and characterization of PEG/Azo statistical copolymers

Polymer[a]	AzoMA[b] (mol%) NMR	m/n[c] calcd	M_n[d] (g mol^{-1}) SEC	M_w/M_n[d] SEC	M_n[e] (g mol^{-1}) calcd	$M_{w,DMF}$[f] (g mol^{-1}) MALLS
P-Azo20	20	49/13	27 100	1.28	24 700	35 100
P-Azo35	35	43/24	27 200	1.29	27 900	48 400
P-Azo55	55	25/30	19 200	1.29	20 600	29 000

[a] **P-Azo20**, **P-Azo35**, and **P-Azo55** were synthesized by living radical copolymerization of poly(ethylene glycol) methyl ether methacrylate (PEGMA) and (*E*)-4-(phenyldiazenyl)phenyl methacrylate (AzoMA). [b] AzoMA content (mol%) determined by ^{1}H NMR. [c] Degrees of polymerization of PEGMA (m) and AzoMA (n) were calculated from the initial monomer feed ratio and the final conversion of each monomer species. The calculated composition agreed well with the values (mol%, NMR) estimated from the area ratio of their pendant units in the ^{1}H NMR spectra of the purified polymers. [d] Number-average molecular weight (M_n) and molecular weight distribution (M_w/M_n) of **P-Azo20**, **P-Azo35** and **P-Azo55** determined by SEC in DMF containing 10 mM LiBr with PMMA standard calibration. [e] M_n of the copolymers calculated from the initial monomer feed ratio, the final conversion of each monomer species, and the molecular weight of the monomers. [f] Absolute weight-average molecular weight of the polymers (M_w) determined by SEC-MALLS in DMF (10 mM LiBr).

or **B70** bearing PEG and alkyl groups (**P-D50**; 50 mol% dodecyl units, or **P-B70**; 70 mol% butyl units),[29,32] **A-D45** bearing a sulfonate anion and a dodecyl group (45 mol%),[32] and **C-D50** bearing a quaternary ammonium cation and a dodecyl group (50 mol%).[31]

Self-assembly of PEG/Azo copolymers into micelles in water

Micellization of PEG/Azo statistical copolymers in water was evaluated using SEC equipped with a multi-angle laser light scattering detector (SEC-MALLS) (Fig. 3a–c and Table 2). The bulk polymers were dissolved in water containing 100 mM NaCl. The aqueous solution was sonicated for 10 minutes at 25 °C and kept for 1 h at 25 °C. After filtering with a membrane filter (pore size = 0.45 μm), the aqueous solutions of the polymer micelles were injected into SEC-MALLS in water containing 100 mM NaCl as an eluent to determine the absolute weight-average molecular weight (M_{w,H_2O}) and aggregation number (N_{agg}) (for details of the sample preparation see the SI). Note that all the injected samples were prepared in water containing 100 mM salts whose concentration and species were identical to those included in eluents for the aqueous SEC.

P-Azo20, **P-Azo35**, and **P-Azo55** self-assembled into uniform micelles in water, whereas the M_{w,H_2O}, hydrodynamic radius (R_h), and N_{agg} depended on the composition. M_{w,H_2O} of their micelles increased from 45 500 to 333 000 on increasing the Azo content from 20 to 55 mol%. **P-Azo20** and **P-Azo35** mostly formed unimer micelles ($N_{agg} \sim 1$), while a more hydrophobic **P-Azo55** formed a multichain micelle ($N_{agg} \sim 11$). As analyzed by dynamic light scattering (DLS), R_h for the **P-Azo55** micelle (6.6 nm) was larger than that for the **P-Azo35** micelle (4.4 nm) (Fig. S3).

PEG/Azo copolymer micelles further showed lower critical solution temperature (LCST)-type thermoresponsive solubility in water (Fig. 3d). The cloud point temperatures (C_p) of the polymer micelles decreased with increasing Azo units (Fig. 3e and S4). The size (M_{w,H_2O}, R_h) of the PEG/Azo statistical copolymer micelles was close to that of corresponding PEG/dodecyl random copolymer micelles (Fig. 3e).[40] In contrast, C_p for PEG/Azo copolymer micelles was lower than that for PEG/dodecyl counterparts. This implies that the Azo units promote intermolecular aggregation of their micelles upon heating. Critical micellization concentration (CMC) of the copolymers was determined to be approximately 0.005–0.01 mg mL^{-1} by using the Nile Red chromophore (Fig. S5).

Photoresponsive isomerization of PEG/Azo copolymers

Photoresponsive isomerization of the PEG/Azo copolymers was evaluated by UV/vis spectroscopy. An as-prepared aqueous solution of a **P-Azo20** micelle showed a UV-vis spectrum with a strong band around 320 nm and a weak one around 430 nm, which correspond to the arrowed π–π* transition and the

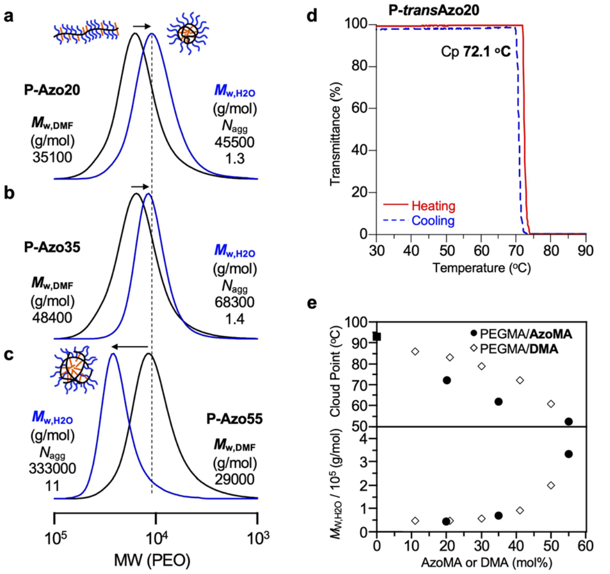

Fig. 3 Self-assembly of PEG/azo statistical copolymers in water. (a–c) SEC curves of (a) **P-Azo20**, (b) **P-Azo35**, and (c) **P-Azo55** in DMF (black lines) and their micelles in H_2O containing 100 mM NaCl (blue lines): [polymer] = 10 mg mL^{-1} in DMF or 1 mg mL^{-1} in H_2O with 100 mM NaCl. (d) Thermoresponsive solubility of **P-transAzo20** micelles in water. Transmittance of the aqueous solutions of the polymer micelles was monitored at 670 nm upon heating at 1 °C min^{-1} from 30 to 90 °C (red lines) and subsequent cooling at −1 °C min^{-1} from 90 to 30 °C (blue dashed lines): [polymer] = 4.0 mg mL^{-1}. (e) M_{w,H_2O} and cloud point (C_p) temperature of PEGMA/AzoMA statistical copolymer micelles and PEGMA/DMA (dodecyl methacrylate) random copolymers/micelles in water. M_{w,H_2O} and C_p were determined by SEC-MALLS and transmittance measurements upon heating. M_{w,H_2O} and C_p values of the PEGMA/DMA copolymers in water are cited from ref. 40.

Table 2 Characterization of PEG/Azo statistical copolymer micelles in water

	R_h[a] (nm)		M_{w,H_2O}[b] (g mol^{-1})		N_{agg}[c]		C_p[d] (°C)		
Polymer[a]	*trans*	*cis*	*trans*	*cis*	*trans*	*cis*	*trans*	*cis*	CMC[e] (mg mL^{-1})
P-Azo20	5.0	5.5	45 500	46 000	1.3	1.3	72	72	0.010
P-Azo35	4.4	4.9	68 300	64 700	1.4	1.3	62	62	0.005
P-Azo55	6.6	6.7	333 000	297 000	11	10	52	51	0.005

[a] Hydrodynamic radius (R_h) of the polymer micelles was determined by DLS in H_2O containing 100 mM NaCl at 25 °C: [polymer] = 1.0 mg mL^{-1}. [b] Absolute weight-average molecular weight of the polymer micelles (M_{w,H_2O}) was determined by SEC-MALLS in H_2O containing 100 mM NaCl as an eluent. [c] Aggregation number (N_{agg}) of the polymer micelles was estimated as follows: $N_{agg} = M_{w,H_2O}$ (MALLS)/$M_{w,DMF}$ (MALLS). [d] Cloud point temperature (C_p) was determined by monitoring the transmittance of the aqueous solutions of their polymer micelles ([polymer] = 4.0 mg mL^{-1}) at 670 nm upon heating from 25 °C to 90 °C. C_p was defined as the temperature at which the transmittance became 90%. [e] Critical micellization concentration (CMC) of the copolymers in water was determined by using Nile Red.

forbidden n–π* transition, respectively, characteristic of *trans*-azobenzene (Fig. 4a, black line). After UV ($\lambda = 365$ nm) irradiation for 600 seconds, the π–π* transition band decreased and the n–π* transition band in turn slightly increased, indicative of the isomerization of the *trans*-Azo units into the *cis*-state within the micelle core (Fig. 4a). The irradiation time was then varied from 5 seconds to 600 seconds to evaluate the isomerization behavior of the Azo units. The isomerization quickly proceeded to be saturated just after 60 seconds of irradiation to reach the photostationary state (Fig. 4f and S6). By irradiating visible light

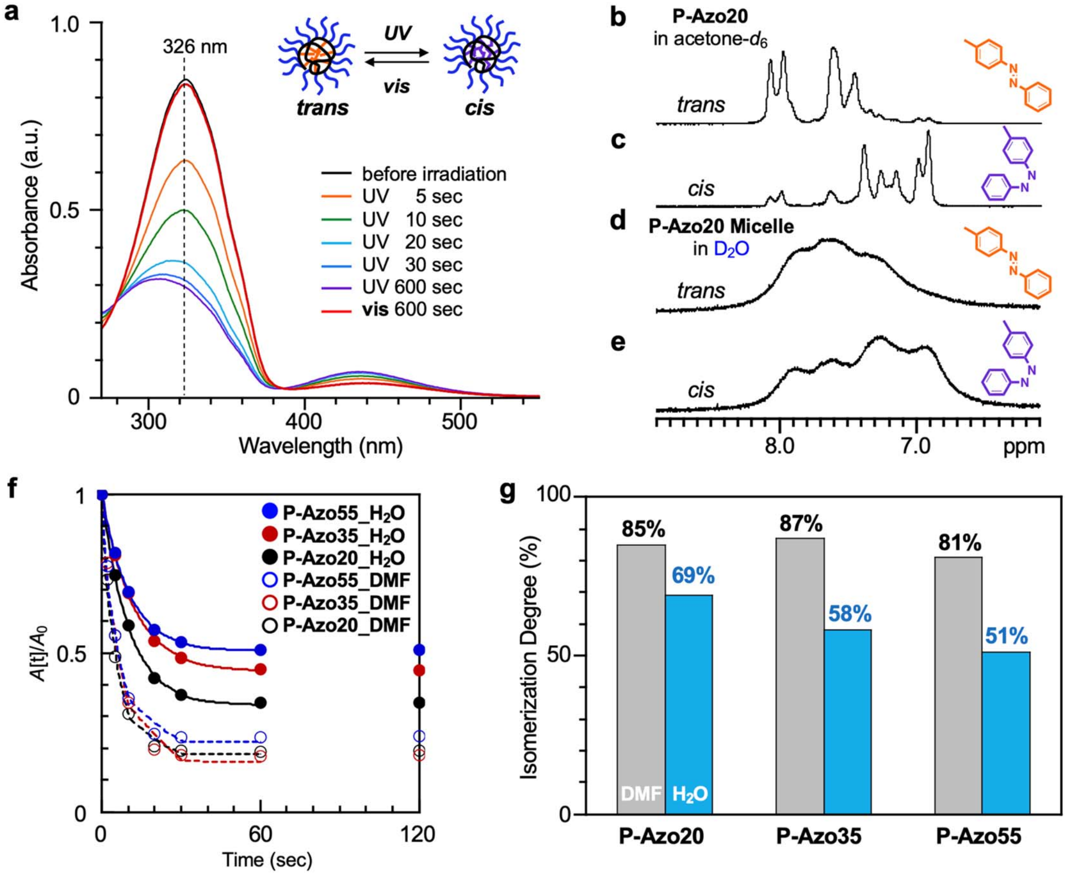

Fig. 4 Photo-induced isomerization of PEG/azo statistical copolymers in water. (a) UV-vis spectra of the **P-Azo20** micelle in water before (black line) and after being irradiated with UV light ($\lambda = 365$ nm) for 5, 10, 20, 30, and 600 seconds, and then visible light ($\lambda = 470$ nm) for 600 seconds: [polymer] = 0.1 mg mL. (b–e) ^{1}H NMR spectra of **P-Azo20** in acetone-d_6 and **P-Azo20** micelles in D_2O before (*trans*) and after (*cis*) being irradiated with UV light ($\lambda = 365$ nm) for 600 seconds. (f) Plots of $A(t)/A_0$ of the aqueous solutions of **P-Azo20** (black circle), **P-Azo35** (red circle), and **P-Azo55** (blue circle) micelles, and the DMF solutions of **P-Azo20** (black hollow circle), **P-Azo35** (red hollow circle), and **P-Azo55** (blue hollow circle) before and after UV irradiation ($\lambda = 365$ nm). The plots were obtained from the spectra in Fig. 4a, S6, and S7, and fitted using eqn (S1): [**P-Azo20**] = 0.10 mg mL^{-1}, [**P-Azo35**] = 0.050 mg mL^{-1}, [**P-Azo55**] = 0.025 mg mL^{-1}. (g) The isomerization degree of **P-Azo20**, **P-Azo35**, and **P-Azo55** in DMF and their micelles in H_2O after being irradiated with UV light for 600 seconds.

($\lambda = 470$ nm), the PEG/*cis*-Azo micelle was again transformed to its initial *trans*-state (Fig. 4a, red line).

The effects of composition and solvents (water or DMF) on the photoisomerization of **P-Azo20**, **P-Azo35**, and **P-Azo55** were examined. The isomerization degree of the Azo units at the photostationary state was calculated from eqn (1):[38,39]

$$\text{Isomerization degree (\%)} = 100 \times 1.055 \times (1 - A_{\text{after}}/A_0) \quad (1)$$

where A_0 is the absorbance at $\lambda_{\max}$ before the light irradiation and A_{after} is the absorbance at the same wavelength after 600 seconds of UV (365 nm) irradiation.

In all the copolymers, the isomerization degree of the Azo pendants in DMF (~85%) was higher than that in water. The isomerization degree in water decreased from 69% to 51% on increasing the Azo content from 20 to 55 mol%, though the isomerization degree in DMF was independent of the composition (Fig. 4g). This is probably because, in water, multiple Azo pendants are accumulated within a hydrophobic core to sterically hinder the *trans*-Azo groups from transforming into the *cis*-state.[39] The isomerization rate was hardly affected by either Azo content (hydrophobicity) of the copolymers or solvents (Fig. 4f, S6, S7, and Table S2).

The in-core *cis*-Azo groups showed gradual relaxation into *trans*-Azo ones in water at 30 °C even under dark conditions (*e.g.*, **P-Azo20**: from *cis* 68% to 44% in 24 h). However, the process was much slower than that by irradiating visible light (Fig. S8); the *cis*-Azo state is virtually kept at 30 °C at least for 1 h. The isomerization degree from the *trans* to *cis*-state for **P-Azo20** in acetone-d_6 was estimated to be 81% from ^{1}H NMR (Fig. 4b–e). This was close to that (82%) determined by UV-vis spectroscopy in DMF. The Azo units within the micelle cores in D_2O showed peaks broader than those in acetone-d_6 (Fig. 4d and e), indicative of the reduced mobility.

The size ($M_{\text{w,H}_2\text{O}}$, R_h), C_p values, and N_{agg} of PEG/*cis*-Azo micelles were further examined after UV irradiation (Fig. S3, S4, S9, and Table 2), and the values were almost identical to those for PEG/*trans*-Azo micelles. These results indicate that the isomerization of the in-core Azo units hardly affects the associated structures of the micelles.

Self-sorting or co-self-assembly in binary mixtures of copolymer micelles

We then investigated self-sorting and co-self-assembly of PEG/Azo statistical copolymers in the presence of other amphiphilic copolymers with different compositions and/or side chains. The aqueous solution of a **P-Azo20** micelle was mixed with the aqueous solutions of **P-Azo55**, **P-D50**, **P-B70**, **C-D50**, and **A-D45** micelles. The aqueous micelle solutions were prepared with 100 mM NaCl (PEG and/or anion micelle mixtures) or $NaNO_3$ (PEG/cation micelle mixtures). The micelle mixtures were then heated at 50 °C for 24 hours. After cooling to 25 °C, the mixtures were injected into SEC in water containing 100 mM NaCl or $NaNO_3$ as an eluent; the SEC system was equipped with a refractive index (RI) detector and a UV-vis detector whose absorbance was set at 320 nm for the selective detection of the Azo unit.

The binary mixtures consisting of a **P-Azo20** micelle and **P-Azo55**, **P-D50**, **P-B70**, or **C-D50** micelles (1/1 wt ratio) showed bimodal SEC curves on the RI detector, whose peak tops were at the same retention time as their corresponding micelles before mixing (Fig. 5a–f and S10a, b). The UV-vis SEC curves originating from **P-Azo20** were intact before and after mixing. These results indicate that a **P-Azo20** unimer micelle ($N_{\text{agg}} = 1.3$) induced self-sorting in the presence of a **P-Azo55** multichain micelle ($N_{\text{agg}} = 11$, Table 2) or other PEG or cation/alkyl random copolymer multichain micelles ($N_{\text{agg}} > 5$, Table S1) in water. Such a self-sorting was achieved not only in the binary mixture of **P-*cis*Azo20** micelles and **P-*cis*Azo55** micelles but also by the direct dissolution of a bulk blend of **P-Azo20** and **P-Azo55** in water (Fig. S10c–h). It should be noted that, in the direct dissolution method, their discrete micelles are gradually formed *via* dynamic chain exchange during the solubilization process of the polymers. It means that the self-sorting is the thermodynamically stable state independent of the isomerization or the mixing procedures. Self-sorting against the **C-D50** micelle was also realized with the **P-Azo35** micelle and **P-Azo55** micelles (Fig. S11). This is in clear contrast to our previous

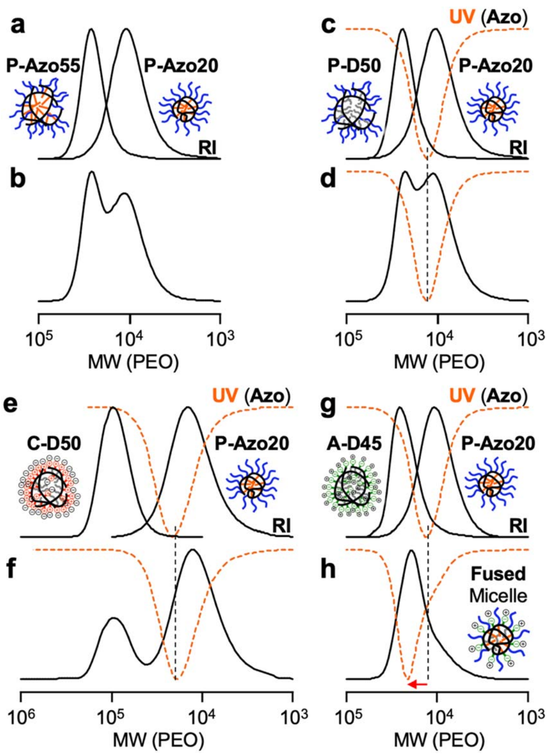

Fig. 5 Self-sorting and co-self-assembly of a **P-Azo20** micelle with other copolymer micelles in water. (a–h) SEC curves of (a) **P-Azo55** or **P-Azo20** micelles, (b) the binary mixture of **P-Azo55** and **P-Azo20** micelles, (c) PEG/dodecyl random copolymer (**P-D50**) or **P-Azo20** micelles, (d) the mixture of **P-D50** and **P-Azo20** micelles, (e) cation/dodecyl random copolymer (**C-D50**) or **P-Azo20** micelles, (f) the mixture of **C-D50** and **P-Azo20** micelles, (g) anion/dodecyl random copolymer (**A-D45**) or **P-Azo20** micelles, and (h) the mixture of **A-D45** and **P-Azo20** micelles in water using refractive index (black solid lines) and UV-vis (for Azo: absorbance = 320 nm, orange dashed lines) detectors: $[\text{polymer}]_{\text{total}} = 1$ mg mL^{-1} in H_2O with (a–d, g and h) 100 mM NaCl or (e and f) 100 mM $NaNO_3$.

report: the mixture of a PEG/alkyl copolymer and a cation/alkyl copolymer induced co-self-assembly to yield a PEG/cation fused micelle.[31] This importantly indicates that the structural difference between dodecyl groups of **C-D50** and azobenzene pendants of PEG/Azo copolymers is a driving force for the self-sorting (immiscible) behavior, similar to the self-sorting of PEG/dodecyl micelles and PEG/butyl ones.[29]

In contrast, the mixture of **P-*trans*Azo20** and **A-D45** showed a unimodal RI SEC curve, whose peak top was at the middle between single micelles of the two copolymers (Fig. 5g and h). The UV-vis curve of the mixture was shifted to a higher molecular weight region compared to that of an original **P-*trans*Azo20** unimer micelle. This indicates that **P-*trans*Azo20** co-self-assembled with **A-D45** to form an **A-D45/P-*trans*Azo20**-fused micelle in water.

We evaluated effects of the mixing molar ratio of an **A-D45** micelle and a **P-Azo20** micelle (1/0.2 to 1/2) on their co-self-assembly behavior in water. In both SEC curves using RI and UV-vis detectors, the shoulder peak originating from a **P-Azo20** micelle turned smaller as the molar ratio of **P-Azo20** decreased, and the SEC curve became almost unimodal at the mixing ratio of 1/0.5 (Fig. 6a and b). Importantly, the UV-vis SEC curves for 1/0.5 and 1/0.2 mixtures were almost identical. This supports the observation that the yield of the **A-D45/P-Azo20**-fused micelle is the highest at the 1/0.5 ratio while there are excess **A-D45** micelles in addition to the fused micelles at the 1/0.2 ratio. We thus concluded that the 1/0.5 mixing ratio almost quantitatively yielded the **A-D45/P-Azo20**-fused micelle. $M_{\mathrm{w,H_2O}}$ and N_{agg} of the fused micelle was determined to be 125 000 g mol^{-1} and 4.0 (**A-D45/P-Azo20** = 2.7/1.3) by SEC-MALLS (Fig. 6c), and R_{h} of the fused micelle by DLS was 5.6 nm (Fig. S12). The zeta potential of the fused micelle in water was −35 mV, whose value was between −11 mV (**P-Azo20** micelle) and −42 mV (**A-D45** micelle) (Fig. S13).

These results indicate the following co-self-assembly process and mechanism: by mixing a **P-Azo20** unimer micelle (N_{agg} = 1.3) and an **A-D45** multichain micelle (N_{agg} = 5.5) at 50 °C, a **P-Azo20** unimer micelle collides with the **A-D45** micelle to associate with two or three **A-D45** chains into the **A-D45/P-Azo20**-fused micelle. N_{agg} of **P-Azo20** in the fused micelle is almost the same as that of the original unimer micelle, whereas N_{agg} of **A-D45** decreased from 5.5 to 2.7. This is consistent with the fact that the zeta potential value of the fused micelle is ranged in the middle between that of the **P-Azo20** micelle and that of the **A-D45** micelle. The co-self-assembly is thus driven by the reduction of electrostatic repulsion among anionic pendants of **A-D45** *via* the co-self-assembly with a neutral **P-Azo20.** A similar trend was observed previously in the formation of the fused micelles of an anion/dodecyl random copolymer and a PEG/dodecyl counterpart.[32]

While the contrasting outcomes observed for the two systems—self-sorting of the **C-D50/P-Azo20** mixture or co-self-

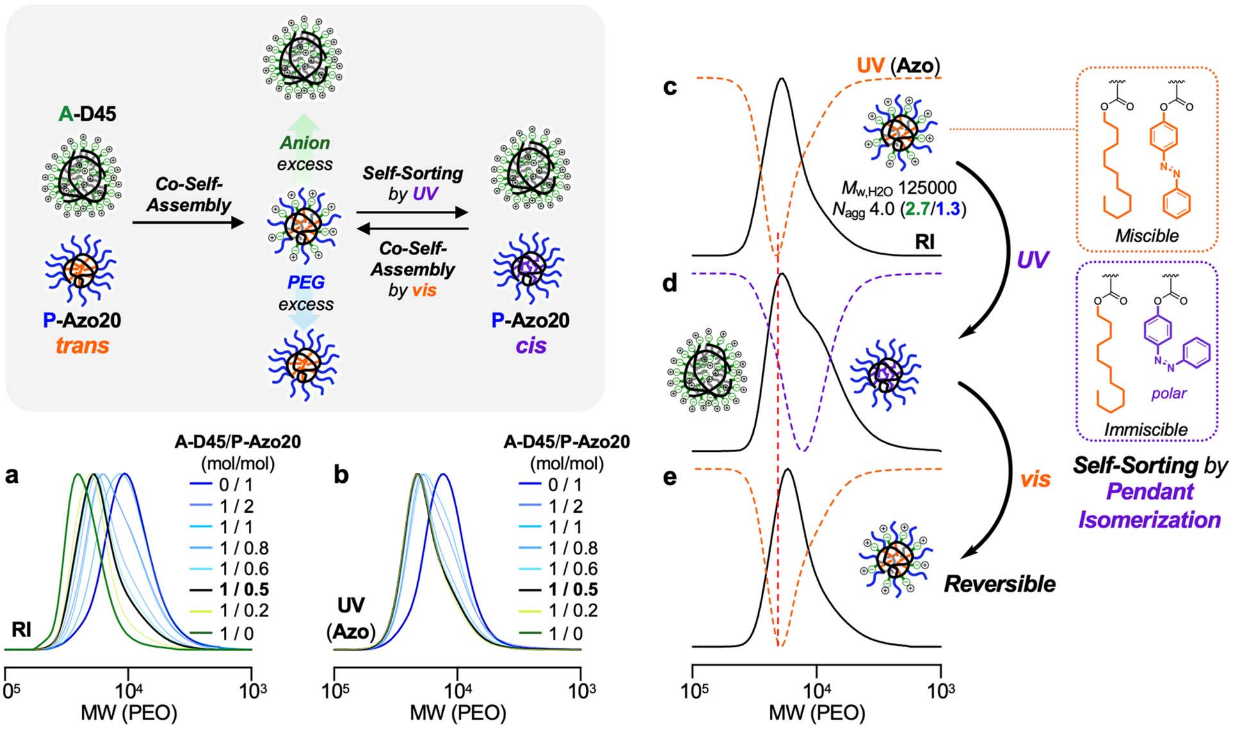

Fig. 6 Reversible co-self-assembly and self-sorting of the **A-D45** micelle and **P-Azo20** micelle in water controlled by UV/vis light irradiation. (a and b) SEC curves of the **A-D45/P-Azo20** mixture in water containing 100 mM NaCl at various mixing molar ratios (**A-D45/P-Azo20** = 0/1, 1/2, 1/1, 1/0.8, 1/0.6, 1/0.5, 1/0.2, or 1/0) using (a) refractive index and (b) UV-vis (for Azo: absorbance = 320 nm) detectors: $[\text{polymer}]_{\text{total}} = 1$ mg mL^{-1} in H_2O with 100 mM NaCl. (c–e) SEC curves of the mixture of **A-D45** and **P-Azo20** in water containing 100 mM NaCl (c) before and (d) after UV irradiation (λ = 365 nm), and (e) then after visible light irradiation (λ = 470 nm) using refractive index (black solid lines) and UV-vis (for Azo: absorbance = 320 nm, orange or purple dashed lines) detectors: $[\text{polymer}]_{\text{total}} = 1$ mg mL^{-1} in H_2O with 100 mM NaCl, **A-D45/P-Azo20** = 1/0.5.

assembly into **A-D45/P-Azo20** fused micelles—may appear contradictory, they suggest that differences in hydrophilic pendants can have a significant impact on the self-assembly of binary mixtures of random copolymer micelles. In fact, the absolute value of zeta potential of the **A-D45** micelle (−42 mV) was larger than that of the **C-D50** micelle (23 mV). This means that the former **A-D45** micelle has larger electrostatic repulsion in water and thus co-self-assembles with **P-Azo20** to minimize the repulsion even though the core-forming hydrophobic groups are different. Namely, the strength of electrostatic repulsion among ionic pendants may play an important role in determining whether co-self-assembly or self-sorting occurs.

Reversible co-self-assembly and self-sorting *via* isomerization

The aqueous solution of the **A-D45/P-Azo20**-fused micelle was irradiated with UV light (365 nm) at 50 °C for 24 hours to induce isomerization of the *trans*-Azo units into the *cis*-state (Fig. 6c, d, and S14). Interestingly, the irradiated sample showed a shoulder peak at a lower molecular weight region in the RI SEC curve. Moreover, the UV-vis SEC curve turned to be almost identical to that of an original **P-Azo20** micelle. This means that a **P-Azo20** unimer micelle carrying *cis*-Azo groups was released from the fused micelle *via* self-sorting in water. Such self-sorting was also confirmed by mixing an **A-D45** micelle and a **P-Azo20** micelle containing *cis*-Azo groups (irradiated with UV) in water (Fig. S15). By irradiating visible light, the discrete **A-D45** or **P-Azo20** micelles were once again co-self-assembled into an **A-D45/P-Azo20**-fused micelle (Fig. 6e). Self-sorting is probably due to the change of polarity: *cis*-Azo units are more polar than *trans*-ones. This results in less miscibility of the *cis*-Azo units against apolar dodecyl groups within the micelle core, leading to the separation of the *cis*-state **P-Azo20** from **A-D45**. To wrap up these results, co-self-assembly/self-sorting can reversibly be switched by UV/vis light irradiation without using externally added reagents.[32]

Conclusions

In conclusion, we developed self-sorting systems of photo-responsive polymer micelles formed by the self-assembly of amphiphilic statistical copolymers bearing PEG and Azo pendants in water. The PEG/Azo statistical copolymer micelles induced not only self-sorting in the presence of other PEG micelles with different compositions or alkyl groups but also reversible co-self-assembly and self-sorting with an anionic random copolymer micelle *via* photoresponsive *trans*–*cis* isomerization of the Azo units. The reversible self-sorting system can be controlled by photo-irradiation without any chemical additives, in sharp contrast to previous counterparts driven by the external addition of a salt. This study offers a new strategy to create self-assembled and self-sorting polymer materials with not only photoresponsive properties and functions but also association properties dynamically controlled by light as desired in complex aqueous media.

Author contributions

Takaya Terashima and Rikuto Kanno suggested the project and conceptualized the research. Rikuto Kanno conducted all experimental studies under the supervision of Takaya Terashima and Makoto Ouchi. All authors contributed to the writing and editing of the manuscript and agreed on the final version.

Conflicts of interest

There are no conflicts to declare.

Data availability

The data supporting this study have been included as part of the supplementary information (SI). Supplementary information: experimental details of the synthesis and characterization of polymers and SEC, NMR, DLS, thermoresponsive solubility, and UV-vis spectroscopy. See DOI: https://doi.org/10.1039/d5sc06852e.

Acknowledgements

This work was supported by Japan Society for the Promotion of Science KAKENHI Grants (JP19K22218, JP20H02787, JP20H05219, JP22H04539, JP23H02008, JP23K26701, JP23KJ135, and JP25H00425), JST PRESTO Grant Number JPMJPR24M6, the Ogasawara Foundation for the Promotion of Science and Engineering, the Noguchi Institute, the Iketani Science and Technology Foundation, and the Kurita Water and Environment Foundation.

References

1 O. P. Ernst, D. T. Lodowski, M. Elstner, P. Hegemann, L. S. Brown and H. Kandori, *Chem. Rev.*, 2014, **114**, 126–163.
2 S. Chen, R. Costil, F. K.-C. Leung and B. L. Feringa, *Angew. Chem., Int. Ed.*, 2021, **60**, 11604–11627.
3 S. Yagai and A. Kitamura, *Chem. Soc. Rev.*, 2008, **37**, 1520–1529.
4 F. Xu and B. L. Feringa, *Adv. Mater.*, 2023, **35**, e2204413.
5 R. Göstl, A. Senf and S. Hecht, *Chem. Soc. Rev.*, 2014, **43**, 1982–1996.
6 E. Blasco, M. Wegener and C. Barner-Kowollik, *Adv. Mater.*, 2017, **29**, 1604005.
7 J.-M. Lehn, *Science*, 2002, **295**, 2400–2403.
8 A. Wu and L. Isaacs, *J. Am. Chem. Soc.*, 2003, **125**, 4831–4835.
9 M. M. Safont-Sempere, G. Fernández and F. Würthner, *Chem. Rev.*, 2011, **111**, 5784–5814.
10 A. C. Mendes, E. T. Baran, R. L. Reis and H. S. Azevedo, *Wiley Interdiscip. Rev.: Nanomed. Nanobiotechnol.*, 2013, **5**, 582–612.
11 B. J. G. E. Pieters, M. B. van Eldijk, R. J. M. Nolte and J. Mecinović, *Chem. Soc. Rev.*, 2016, **45**, 24–39.
12 J. D. Watson and F. H. Crick, *Nature*, 1953, **171**, 737–738.
13 A. Pal, S. Karthikeyan and R. P. Sijbesma, *J. Am. Chem. Soc.*, 2010, **132**, 7842–7843.

14 M. Obana, T. Fukino, T. Hikima and T. Aida, *J. Am. Chem. Soc.*, 2016, **138**, 9246–9250.

15 N. Tomimasu, A. Kanaya, Y. Takashima, H. Yamaguchi and A. Harada, *J. Am. Chem. Soc.*, 2009, **131**, 12339–12343.

16 S. Takahashi and S. Yagai, *J. Am. Chem. Soc.*, 2022, **144**, 13374–13383.

17 K. Matsumoto, N. Bäumer, S. Ogi and S. Yamaguchi, *Angew. Chem., Int. Ed.*, 2024, e202416361.

18 F. Helmich, M. M. J. Smulders, C. C. Lee, A. P. H. J. Schenning and E. W. Meijer, *J. Am. Chem. Soc.*, 2011, **133**, 12238–12246.

19 S. Onogi, H. Shigemitsu, T. Yoshii, T. Tanida, M. Ikeda, R. Kubota and I. Hamachi, *Nat. Chem.*, 2016, **8**, 743–752.

20 Q. Xiao, J. D. Rubien, Z. Wang, E. H. Reed, D. A. Hammer, D. Sahoo, P. A. Heiney, S. S. Yadavalli, M. Goulian, S. E. Wilner, T. Baumgart, S. A. Vinogradov, M. L. Klein and V. Percec, *J. Am. Chem. Soc.*, 2016, **138**, 12655–12663.

21 A. Sarkar, R. Sasmal, C. Empereur-Mot, D. Bochicchio, S. V. K. Kompella, K. Sharma, S. Dhiman, B. Sundaram, S. S. Agasti, G. M. Pavan and S. J. George, *J. Am. Chem. Soc.*, 2020, **142**, 7606–7617.

22 Y.-Y. Zhan, T. Kojima, K. Ishii, S. Takahashi, Y. Haketa, H. Maeda, S. Uchiyama and S. Hiraoka, *Nat. Commun.*, 2019, **10**, 1440.

23 A. Harada and K. Kataoka, *Science*, 1999, **283**, 65–67.

24 J. Kumaki, T. Kawauchi, K. Ute, T. Kitayama and E. Yashima, *J. Am. Chem. Soc.*, 2008, **130**, 6373–6380.

25 J. M. Ren, J. Lawrence, A. S. Knight, A. Abdilla, R. B. Zerdan, A. E. Levi, B. Oschmann, W. R. Gutekunst, S.-H. Lee, Y. Li, A. J. McGrath, C. M. Bates, G. G. Qiao and C. J. Hawker, *J. Am. Chem. Soc.*, 2018, **140**, 1945–1951.

26 B. Bilgiçer, X. Xing and K. Kmar, *J. Am. Chem. Soc.*, 2001, **123**, 11815–11816.

27 Y. Hirai, T. Terashima, M. Takenaka and M. Sawamoto, *Macromolecules*, 2016, **49**, 5084–5091.

28 S. Imai, Y. Hirai, C. Nagao, M. Sawamoto and T. Terashima, *Macromolecules*, 2018, **51**, 398–409.

29 S. Imai, M. Takenaka, M. Sawamoto and T. Terashima, *J. Am. Chem. Soc.*, 2019, **141**, 511–519.

30 Y. Kimura, M. Takenaka, M. Ouchi and T. Terashima, *Macromolecules*, 2020, **53**, 4942–4951.

31 R. Kanno, K. Tanaka, T. Ikami, M. Ouchi and T. Terashima, *Macromolecules*, 2022, **55**, 5213–5221.

32 R. Kanno, H. Kono, A. Ryoki, M. Ouchi and T. Terashima, *J. Am. Chem. Soc.*, 2024, **146**, 30848–39859.

33 F. D. Jochum and P. Theato, *Chem. Commun.*, 2010, **46**, 6717–6719.

34 Y. Huang, R. Dong, X. Zhu and D. Yan, *Soft Matter*, 2014, **10**, 6121–6138.

35 E. Blasco, B. V. K. J. Schmidt, C. Barner-Kowollik, M. Piñol and L. Oriol, *Macromolecules*, 2014, **47**, 3693–3700.

36 M. Younis, S. Ahmad, A. Atiq, M. Amjad Farooq, M.-H. Huang and M. Abbas, *Chem. Rec.*, 2023, **23**, e202300126.

37 M. Moniruzzaman, C. J. Sabey and G. F. Fernando, *Macromolecules*, 2004, **37**, 2572–2577.

38 J. G. Victor and J. M. Torkelson, *Macromolecules*, 1987, **20**, 2241–2250.

39 Y. Li, Y. Deng and X. Wang, *Macromolecules*, 2006, **39**, 1108–1115.

40 M. Hishida, R. Kanno and T. Terashima, *Macromolecules*, 2023, **56**, 7587–7596.