



Title	Cosolvency-Induced UCST/LCST Dual Phase Separation of Poly(2-hydroxyethyl methacrylate) in Nonaqueous Organic Solvent Mixtures
Author(s)	Takasu, Koki; Inaba, Natsuki; Takeuchi, Shu et al.
Citation	Macromolecules, 58(17), 9055-9063 https://doi.org/10.1021/acs.macromol.5c00789
Issue Date	2025-09-09
Doc URL	https://hdl.handle.net/2115/98088
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Type	journal article
File Information	Revised_MS_Macromolecules_Takasu2025.pdf



Co-solvency-Induced UCST/LCST Dual Phase Separation of Poly(2-hydroxyethyl methacrylate) in Non-aqueous Organic Solvent Mixtures

Koki Takasu¹, Natsuki Inaba¹, Shu Takeuchi², Keitaro Matsuoka^{1,3*}, Kazuki Sada^{1,3*}

¹ Graduate School of Chemical Sciences and Engineering, Hokkaido University, Sapporo 060-0810, Japan.

² Department of Chemistry, School of Science, Hokkaido University, Sapporo 060-0810, Japan.

³ Department of Chemistry, Faculty of Science, Hokkaido University, Sapporo 060-0810, Japan.

*Corresponding author, E-mail: sadatcm@sci.hokudai.ac.jp, ma2oka@sci.hokudai.ac.jp

Abstract

Mixed solvents as media are a widely used strategy for achieving UCST/LCST dual phase separation. However, due to the difficulty in controlling the solvation/desolvation of polymer chains, this phenomenon has only been realized in water and water-miscible organic solvents. Herein, we demonstrate UCST/LCST dual phase separation in non-aqueous mixed organic solvents. The ternary polymer solution consists of poly(2-hydroxyethyl methacrylate), aliphatic alcohols, and aprotic less-polar poor solvents. Systematic variation of the mixing ratio realized that UCST-type phase separation occurs in alcohol-rich mixed solvents, while LCST-type phase separation emerges in poor solvent-rich mixed solvents. This behavior was consistently observed across 15 different mixed solvents. The phase diagrams indicate that the emergence of a completely miscible region due to the co-solvency effect is crucial for achieving UCST/LCST dual phase separation, in agreement with trends observed in water/organic solvent systems. This study expands the diversity of media available for designing UCST/LCST dual phase separation.

Introduction

Thermo-responsive polymers undergo reversible coil–globule transitions with slight temperature changes, leading to drastic shifts in solubility¹⁻⁵. Their phase transition temperature is typically evaluated by cloud point (T_{cp}), determined by changes in solution turbidity/transparency during phase separations. These polymers are classified into two types; LCST (Lower Critical Solution Temperature)-type polymers, which undergo phase separation upon heating, and UCST (Upper Critical Solution Temperature)-type polymers, which undergo phase separation upon cooling. These thermal phase separations are generally understood to occur due to the imbalance between polymer-polymer interactions and polymer-solvent interactions caused by thermal stimuli, such as cooling or heating. Controlling and predicting thermo-responsiveness of a polymer in a specific media remain challenging, and exploration continues to expand the variety of thermo-responsive polymers.

For understanding the principles of thermo-responsiveness and applications for switchable smart materials, further control over thermo-responsiveness has driven interest in UCST/LCST dual phase separations⁶. They involve the coexistence of UCST-type and LCST-type phase transitions in a phase diagram along a parameter that governs the solubility of the polymer. There are generally two strategies for achieving UCST/LCST dual phase separations. One is varying the temperature ranges. Polymer solutions can exhibit both UCST-type and LCST-type phase separations within two different temperature ranges. Earlier examples include poly(ethylene glycol) in water⁷⁻⁹, exhibited LCST-type phase separation at lower temperatures and UCST-type at higher temperatures. Polystyrene in cyclohexane^{10,11} and related hydrophobic commodity polymers in non-polar or less-polar media¹² show reverse trends. Recent studies have explored various

amphiphilic thermo-responsive homopolymers¹³⁻¹⁸ and block copolymers¹⁹⁻²¹, such as schizophrenic diblock copolymers^{22,23}, in water or ionic liquid. Research effort has primarily focused on designing polymer structures optimized for their respective media.

Another important approach for achieving UCST/LCST dual thermo-responsiveness is the control of medium for the phase separations through mixing two or more components. Changes in solvent components and their mixing ratios provide continuous tuning of the physical properties of the medium. This allows for fine control of polymer-polymer interactions and polymer-solvent interactions through thermal changes in the solvation of the polymer chains via hydrogen bonding and van der Waals forces. Most recent studies have focused on the LCST-type phase separation of aqueous polymer solutions such as poly(*N*-isopropylacrylamide) (PNIPAM) and poly(ethylene oxide) (PEO). The addition of water-miscible organic solvents, such as alcohols, ethers, acetone, DMF, and DMSO, into a binary solution induces UCST-type phase separation²⁴⁻³¹. Systematic investigation of mixing ratios suggests that co-nonsolvency effect, a decrease in the solubility by mixing two solvents, and co-solvency effect, an increase in the solubility by mixing two solvents, are affected by the onset of dual phase separations³²⁻³⁴. Computational and theoretical investigations unveiled the microscopic view of hydration and solvation structures, leading to a deeper understanding of the mechanism of these UCST/LCST dual thermo-responsiveness^{35,36}. However, in non-aqueous media, UCST/LCST dual thermo-responsiveness has never been realized because of difficulty in controlling the solvation and designing LCST-type phase separation³⁷⁻⁴⁵.

Herein, we report on the design of UCST/LCST dual phase separations of polymer solutions in mixed organic solvents by varying solvent components and mixing ratios (Figure 1). The molecular design of polymer solutions is composed of PHEMA, a

commercially available functional polymer with a hydroxy group, common aliphatic alcohols as hydrogen-bonding good solvents, and aprotic less-polar poor solvents. We previously reported that PHEMA and related poly(hydroxyalkyl (meth)acrylate)s exhibited UCST-type phase separations in pure 1-alcohols⁴⁶⁻⁴⁸ and LCST-type phase separations in the mixture of some 1-alcohols and 1,2-dichloroethane (DCE) in an appropriate mixing ratio⁴⁸. Systematic investigation of variations in polymer side chains, differing by one carbon at a time, revealed that difference in solvation state via hydrogen-bonds between the hydroxy group in polymer chains and 1-alcohols might be involved in these phase separations. However, the influence of solvent structure, solvent combination, and mixing ratio remains unclear. In this study, following the water/organic solvent mixture system, a systematic investigation of solvent components and mixing ratios revealed UCST/LCST dual phase separations of various ternary polymer solutions. Notably, this behavior was also observed when using solvent components that individually acted as poor solvents. The phase diagram of cloud points and solvent mixing ratio clearly showed that co-solvency effect⁴⁹⁻⁵⁷ was affected in the expression of UCST/LCST dual phase separations. Theoretical interpretation using ternary Flory-Huggins theory also supported these phase separations. This behavior is essentially a similar trend in the water/organic solvent mixture system. This study not only offers new macromolecular design of UCST/LCST dual thermo-responsive polymers but also expands the medium for them.

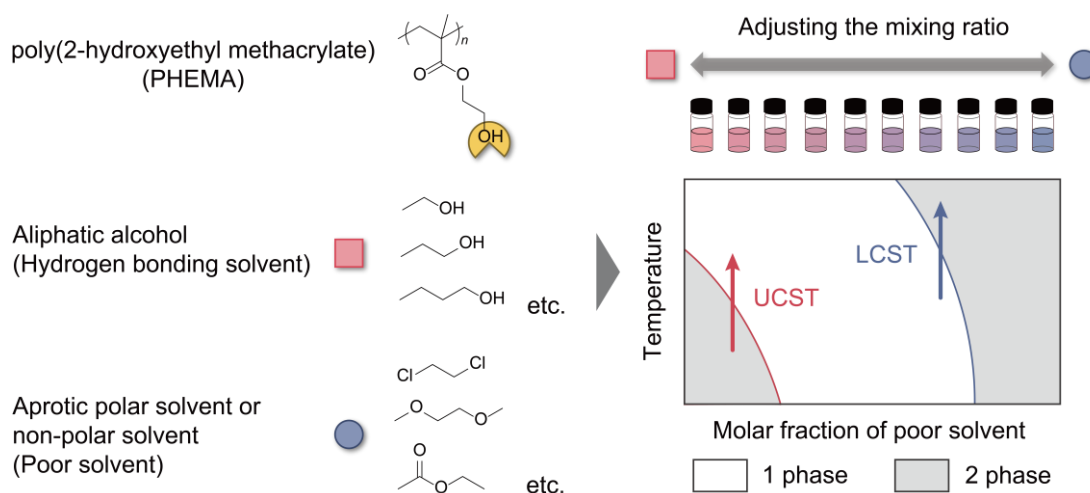


Figure 1. Molecular design of UCST/LCST dual phase separation of PHEMA solutions; Co-solvency induced UCST-type and LCST-type phase separation in organic solvent mixture of aliphatic alcohols as hydrogen-bonding good solvents and aprotic less-polar or non-polar poor solvents with different solvent mixing molar ratios.

Experimental section

Materials and Methods

Poly(2-hydroxyethyl methacrylate) (PHEMA) was purchased from Sigma-Aldrich ($M_v = 20,000$). All commercially available organic solvents were purchased from Wako Ltd. or TCI Co., Ltd. and used as received unless otherwise noted. The polymer solution was prepared by adding appropriate mixed solvents to a vial containing weighed PHEMA (25 mg/mL) and storing it at room temperature for 1 day. Solvent mixing molar fraction were set between 0 and 1 in approximately 0.02 increments. The solubility of polymer solutions was investigated at -75 to 100 °C. The cloud point for UCST-type and LCST-type phase separations were determined as the temperature at which the change in turbidity of the polymer solution, one phase or two phase, was visually observed during the cooling process and the heating process, respectively. In the low-temperature region (-75 to 25 °C), the cooling process was measured using an EYELA low-temperature constant

temperature bath PSL-1800 at a cooling rate of 1-2 °C/min, and the heating process was measured naturally at a rate of ~0.5°C/min without any special heating operation. In the high-temperature region (25 to 100 °C), the heating process was carried out using an oil bath at a heating rate of 1.5-2 °C/min, and the cooling process was carried out naturally at a rate of ~1.5 °C/min without any special cooling operation.

Results and Discussion

As previously reported, PHEMA exhibits UCST-type phase separation in 1,4-dioxane and alcohols such as 1-propanol, 1-butanol, 2-methyl-1-propanol, 2-propanol, and 2-butanol, but the investigation was done to the limited temperature range⁴⁶⁻⁴⁸. To clarify the solvation/desolvation processes in various solvents, the solubility and thermal phase separations of PHEMA were investigated in a pure solvent between $-75\text{ }^{\circ}\text{C}$ to $100\text{ }^{\circ}\text{C}$ at the concentration of 25 mg/mL . UCST-type phase separation was observed in the various solvents (Table S1 in Supporting Information). At lower temperature, UCST-type phase separations were observed in methanol ($T_{\text{cp}} = -70\text{ }^{\circ}\text{C}$) and ethanol ($T_{\text{cp}} = -6\text{ }^{\circ}\text{C}$). Secondary alcohols, such as 2-propanol, 2-butanol, and 2-pentanol, showed lower cloud points than the corresponding primary alcohols. Tertiary alcohols, such as *tert*-butyl alcohol and *tert*-amyl alcohol, did not exhibit UCST-type behavior, because their cloud points are expected to be lower than their melting points. In other common organic solvents, PHEMA did not have any thermal phase separations above their melting points, whether soluble or insoluble, within the temperature range at this concentration.

Based on UCST-type phase separations of PHEMA in pure solvents, we engineered UCST/LCST dual phase separations by varying the mixing ratios in the solvent mixtures. As previously reported, PHEMA exhibits LCST-type behavior in a mixture of 1-propanol and DCE at $X_{\text{DCE}} = 0.7$ (X_{DCE} : molar fraction of DCE)⁴⁸. In this system, the influence of molecular weight for LCST-type phase separation was minimal. Therefore, we commenced the investigation of the phase diagram of PHEMA in a 1-propanol/DCE mixed solvent (25 mg/mL) over a temperature range from $-60\text{ }^{\circ}\text{C}$ to $100\text{ }^{\circ}\text{C}$, keeping molecular weight ($M_v=20,000$) constant. In this experiment, we evaluated the phase separation of polymer solutions by visually observing turbidity

changes, whether one phase or two phase, in a thermostatic bath (Figure 2a,b). This approach allowed us to assess a wide range of samples with different molar fractions effectively. The absolute values of the cloud point were not discussed; only relative comparisons were made. The addition of DCE to a 1-propanol solution of PHEMA lowered the UCST-type T_{cp} , reaching $-58\text{ }^{\circ}\text{C}$ at $X_{DCE} = 0.17$. At $X_{DCE} \geq 0.18$, phase separation was no longer observed, and completely miscible region was observed, indicating a co-solvency effect. The decrease of the solubility parameter of the solvent mixtures supported the increased miscibility as overall interaction between PHEMA and the medium. Solvation via the hydrogen bond formation between the polymer chain and 1-propanol should be promoted due to the decreased polarity by the increased content of DCE. Above $X_{DCE} = 0.64$, conversely PHEMA shifted to LCST-type phase separation at high temperature ($T_{cp} = 88\text{ }^{\circ}\text{C}$). The preferential desorption of 1-propanol should contribute to LCST-type phase separation. A further increase in DCE reduced the LCST-type T_{cp} due to hydrogen bond cleavage between PHEMA and 1-propanol, facilitating desolvation. At $X_{DCE} \geq 0.78$, the low 1-propanol content led to complete polymer insolubility. The observed LCST-type behavior was consistent with previous study using transmittance measurements with UV-vis spectrophotometer. DLS measurements at 20 to 40 $^{\circ}\text{C}$ confirmed UCST-type behavior at $X_{DCE} = 0$ and LCST-type behavior at $X_{DCE} = 0.75$, with increasing particle size upon cooling for UCST-type phase separation and increasing size upon heating for LCST-type separation (Figure 2c,d). All solutions with different polymer concentrations (2.0, 5.0, 10, 25, 50 mg/mL) showed similar phase diagrams exhibiting UCST/LCST dual phase separation, indicating that the dependence on polymer concentration would be modest (Figure S5 in the Supporting Information). Thus, PHEMA exhibited UCST-type phase separation in 1-PrOH-rich mixed solvents and LCST-type in

DCE-rich mixed solvents, with the mixing ratio determining the phase separation type. This phase diagram essentially aligns with previously reported UCST/LCST dual phase separations in water-organic solvent systems^{28,29,31}.

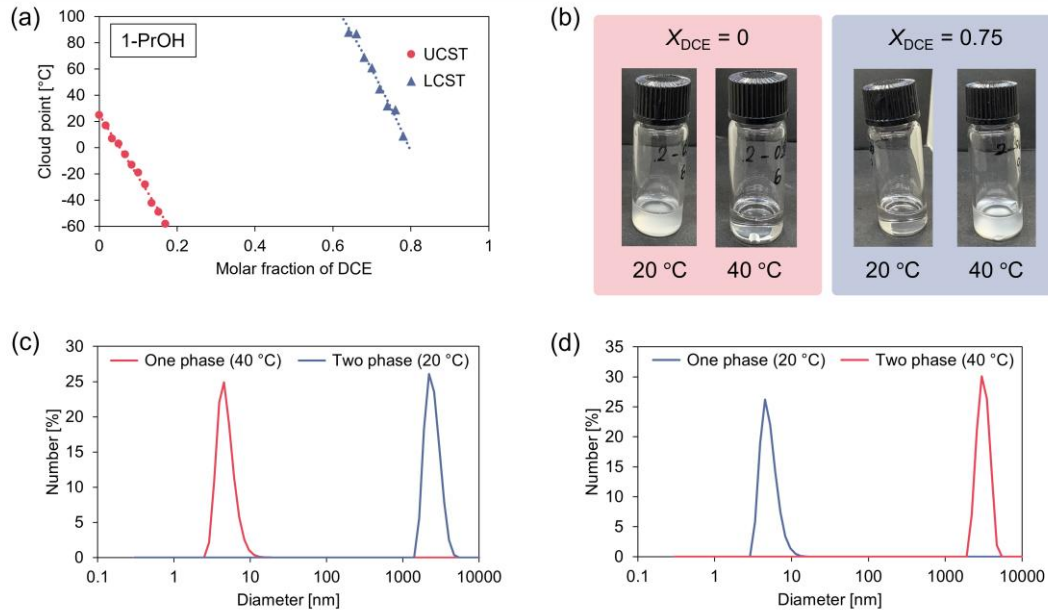


Figure 2. (a) Phase diagrams of PHEMA in the solvent mixtures of 1-propanol and DCE; The red circle and the blue triangle represent the cloud points of UCST-type and LCST-type phase separations, respectively. (b) Photos for UCST-type phase separations on $X_{DCE} = 0$ at 20 °C (2 phases) and 40 °C (1 phase) and for LCST-type phase separations on $X_{DCE} = 0.75$ at 20 °C (1 phase) and 40 °C (2 phases). Dynamic light scattering measurement of PHEMA (c) in 1-propanol ($X_{DCE} = 0$) and (d) in 1-propanol : DCE = 2.5 : 7.5 ($X_{DCE} = 0.75$).

We further examined the phase diagram of PHEMA in mixtures of DCE and various alcohols to investigate the effects of hydrogen-bonding good solvents for UCST/LCST dual phase separations (Figure 3). Because of low UCST-type T_{cp} in pure

methanol ($-70\text{ }^{\circ}\text{C}$), PHEMA exhibited only LCST-type phase separation in methanol/DCE (Figure 3a). Ethanol, 1-butanol, 2-methyl-1-propanol, and 1-pentanol provided similar phase behavior, with UCST/LCST dual phase separations dependent on DCE mole fraction (Figure 3b,d,e,g). Notably, while PHEMA was insoluble in pure 1-hexanol, both UCST- and LCST-type phase separations emerged as X_{DCE} increased, with an overlapping coexistence region at $X_{\text{DCE}} \approx 0.40\text{--}0.42$ (Figure 3i). These results indicate that the co-solvency effect generated both UCST-type and LCST-type phase separations by varying the mixing ratios. As shown in Figure 3j, for UCST-type phase separations, increasing the 1-alcohol's carbon number raised the cloud point observed at $X_{\text{DCE}} = 0$ and shifted the maximum X_{DCE} to higher values. This trend reflects the decreased solubility of PHEMA with longer-chain alcohols, requiring higher DCE content for miscibility. For LCST-type phase separations, the minimum X_{DCE} gradually shifted to higher values as the carbon number increased up to 1-butanol, then shifted to lower values beyond 1-pentanol. As reported previously⁴⁸, this is attributed to van der Waals forces along with hydrogen bonding between the polymer and the 1-alcohols, which enhance solubility up to 1-butanol. As the carbon number further increases, the hydrophobic alkyl group has a greater impact on solvation, reducing the solubility of PHEMA. Additionally, compared to primary alcohols, secondary alcohols weakened hydrogen bonding due to steric bulk, reducing UCST-type region while expanding the LCST-type region (Figure c,f,h).

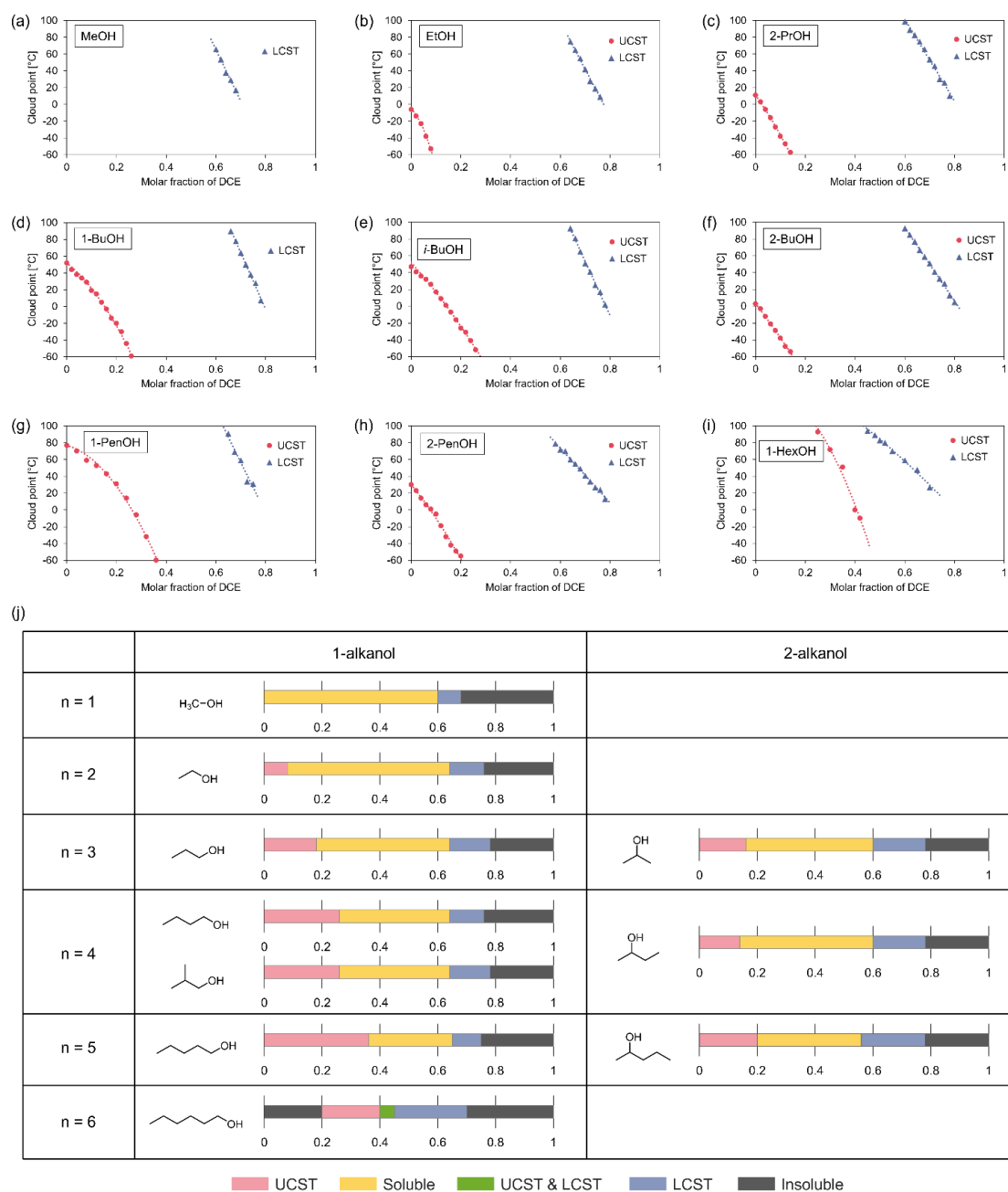


Figure 3. The effects of hydrogen-bonding good solvents for phase diagrams of PHEMA in the binary organic solvents. (a) methanol/DCE, (b) ethanol/DCE, (c) 2-propanol/DCE, (d) 1-butanol/DCE, (e) 2-methyl-1-propanol, (f) 2-butanol/DCE, (g) 1-pentanol/DCE, (h) 2-pentanol/DCE, (i) 1-hexanol/DCE; The red circle and the blue triangle represent the cloud points of UCST-type and LCST-type phase separations, respectively. (j) Indicators of the phase behavior against the molar fraction of DCE.

To elucidate the UCST/LCST dual phase separations, we investigated the effects of poor solvents using 1-propanol as a good solvent that induces UCST-type phase separation (Figure 4). In mixtures with poor solvents possessing hydrogen bond acceptors (e.g., acetone, THF, 1,2-dimethoxyethane DME, ethyl acetate, etc.), similar UCST/LCST dual phase separations were observed, with appearing the completely miscible region at intermediate compositions due to co-solvency effects (Figure 4a-d). For UCST-type phase separation, both the cloud point and the mole fraction of poor solvent (X_{poor}) were comparable across these solvents. However, for LCST-type separation, X_{poor} varied: acetone and THF induced LCST-type phase separation at $X_{\text{poor}} \approx 0.88$, while DME and ethyl acetate triggered it at lower fractions ($X_{\text{poor}} = 0.6$ and 0.46 , respectively). When halogenated hydrocarbons were used as poor solvents, 1,4-dichlorobutane (1,4-DCB) and 1,6-dichlorohexane (1,6-DCH) also led to UCST/LCST dual phase separations (Figure 4e,f). For 1,4-DCB, the maximum X_{poor} for UCST-type separation was similar to DCE, but LCST-type separation emerged at a lower X_{poor} (≈ 0.46). With 1,6-DCH, UCST-type separation first appeared, followed by simultaneous UCST/LCST separations within $X_{\text{poor}} = 0.26\sim 0.34$, and PHEMA eventually became insoluble at higher X_{poor} . This resulted in a V-shaped phase boundary for UCST-type separation, and in this crossover region of the phase separations, UCST/LCST dual phase separations were also observed by the change of the temperature ranges with decreasing the miscibility gap between them. These results demonstrate that the general shape of the phase diagram is consistent across different poor solvents when UCST/LCST dual phase separations occur. Adding aprotic less-polar poor solvents to 1-propanol solutions causes a co-solvency effect, lowering the UCST-type cloud point and inducing complete miscibility around $X_{\text{poor}} \approx 0.2$. The onset of LCST-type separation, however, depended strongly on the specific poor solvent. As the poor solvent's

dielectric constant and Hansen solubility parameter, especially the hydrogen bonding term (δ_H) (Table S28 in Supporting Information), decreased, the required X_{poor} for LCST-type separation shifted to lower values, likely due to the increasing immiscibility imposed by the poor solvent.

Finally, we examined hydrocarbons as poor solvents. Adding hexane or dodecane to 1-propanol solutions of PHEMA led to a monotonic increase in the UCST-type T_{cp} , indicating reduced polymer solubility—typical behavior in poor solvents (Figure 4g,h). With toluene, a slight initial decrease in UCST-type T_{cp} was observed around $X_{\text{poor}} \approx 0.2$ due to weak co-solvency, followed by an increase as X_{poor} increased, eventually leading to polymer insolubility (Figure 4i). This phase diagram in 1-propanol/toluene is quite similar to that of PNIPAM in the aqueous mixtures with methanol, 1,4-dioxane, and THF although the phase changes are reversed^{32,33}. Notably, none of these hydrocarbons induced LCST-type phase separation, likely because they lack hydrogen bond acceptors and have extremely low solubility parameters (Table S28 in Supporting Information). These results indicate that the presence of a completely miscible region, induced by co-solvency, plays a crucial role in enabling UCST/LCST dual phase separations in mixed organic solvents (Figure 4j). This induces lowering the cloud point of LCST-type T_{cp} in a high X_{poor} region to express LCST-type phase separation at ambient temperature.

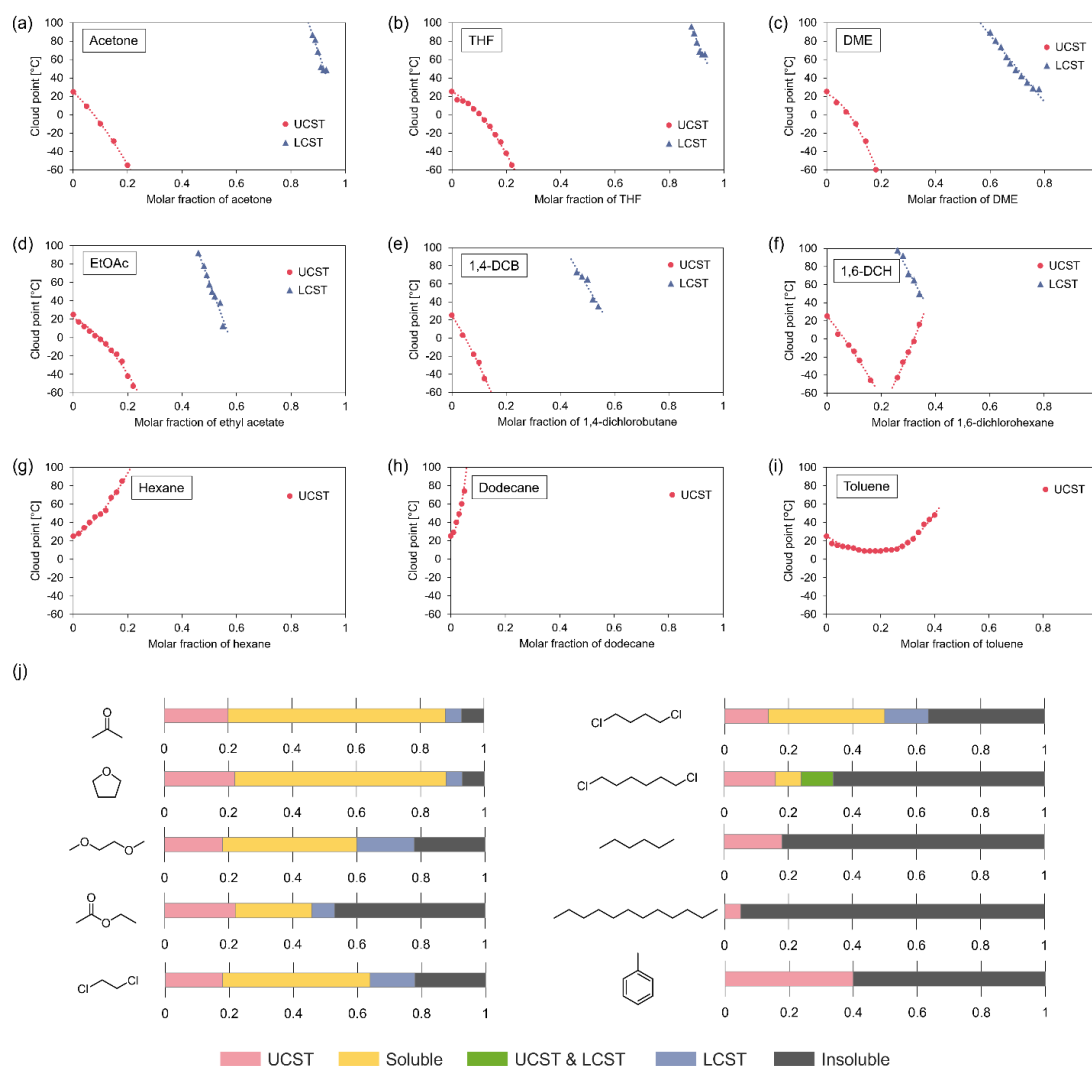


Figure 4. The effects of poor solvents for phase diagrams of PHEMA in the binary organic solvents. (a) 1-propanol/acetone, (b) 1-propanol/THF. (c) 1-propanol/DME, (d) 1-propanol/ethyl acetate, (e) 1-propanol/1,4-dichlorobutane (1,4-DCB), (f) 1-propanol/1,6-dichlorohexane (1,6-DCH), (g) 1-propanol/hexane, and (h) 1-propanol/dodecane, (i) 1-propanol/toluene; The red circle and the blue triangle represent the cloud points of UCST-type and LCST-type phase separations, respectively. (j) Indicators of the phase behavior against the molar fraction of poor solvents.

In recent years, Zhang has conducted theoretical studies on ternary polymer solutions using the ternary Flory–Huggins theory, aiming to elucidate co-solvency⁵⁸ and co-nonsolvency effects⁵⁹. Motivated by these developments, we attempted a theoretical interpretation of the phase behavior induced by the co-solvency effect in our non-aqueous ternary polymer solutions. According to the previous study⁵⁸, we constructed the binodal and spinodal curves of PHEMA solution in mixture of binary solvents (detailed computational method: see Section S6). We denote the volume fractions of the polymer ϕ , solvent A ϕ_A , solvent B ϕ_B , and the volume ratio of solvent B $x_B = \phi_B/(\phi_A + \phi_B)$, as well as the Flory–Huggins interaction parameters χ_{pA} , χ_{pB} , and χ_{AB} , representing the interactions between the polymer and solvent A, the polymer and solvent B, and between solvents A and B, respectively. We first examined the co-solvency effect in the PHEMA solution of 1-hexanol (solvent A) and DCE (solvent B) because they individually served as poor solvents. To accurately reflect the experimental behavior, we imposed the condition $0.5 < \chi_{pA} < \chi_{pB}$ and performed stepwise fitting of the interaction parameters. As a result, we were able to represent the binodal curve, spinodal curve, and critical points in the ϕ – x_B plane at $\chi_{pA} = 0.75$, $\chi_{pB} = 0.85$, $\chi_{AB} = 1.00$, revealing a split into two distinct curves as phase boundaries (Figure 5a). Adjusting to the experimental conditions as $\phi = 0.02$ (polymer concentration: 25 mg/mL; PHEMA density: ~ 1.15) led to the emergence of a one-phase region between two-phase regions. The phase boundary in terms of x_B showed good agreement with experimental observations (Figure 5b). For other solvent combinations as well, the calculated phase boundaries were in close agreement with the experimental values (Figure S6). These results quantitatively validate the rationality and versatility of co-solvency through its connection to Flory–Huggins theory. The theoretical interpretation can predict the

composition range in which a one-phase region appears and suggests the possibility of predicting the composition ratios at which two distinct phase boundaries and dual phase separations occur. The temperature dependence of the interaction parameters was not thoroughly investigated in this study, and further research is needed for a more refined theoretical understanding of thermally induced UCST/LCST dual phase separations in mixed organic solvents.

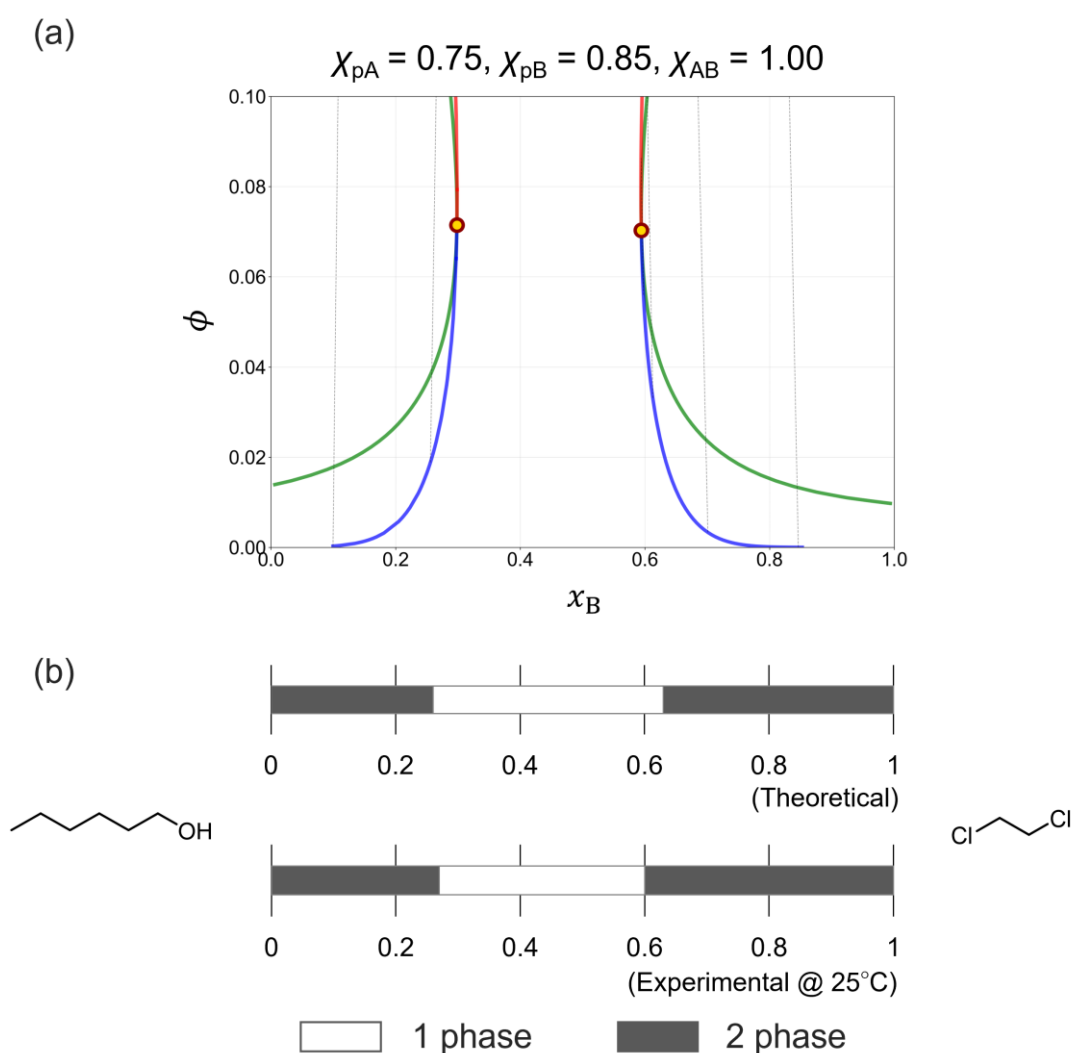


Figure エラー! 指定したスタイルは使われていません。 **5.** Comparison of theoretical and experimental phase behavior in PHEMA solution of 1-hexanol and DCE. (a) Spinodal and binodal curve at given parameters (red line: binodal curve of polymer rich phase, blue

line: binodal curve of polymer poor phase, green line: spinodal curve). (b) Miscibility region determined from binodal curve in $\phi=0.02$ (upper row) and that obtained experimentally at 25 °C (lower row).

As noted by Hore, Hammouda, Cheng, and coworker, co-solvency or co-nonsolvency plays a crucial role in inducing UCST/LCST dual phase separation³⁴. However, previous studies have been so far only demonstrated in the water/organic solvent mixture system using nonionic amphiphilic polymers, with most cases attributed to co-nonsolvency effects. For example, in the well-known PNIPAM–water/ethanol system, adding ethanol to an aqueous PNIPAM solution initially lowers the cloud point of LCST-type phase separation, leading to a completely immiscible region^{24,25,27}. Further ethanol addition then induces UCST-type phase separation. Although less common, co-solvency-induced UCST/LCST dual phase separations were also reported^{28,29,31}. In such cases, adding an organic solvent to a polymer solution exhibiting LCST-type phase separation in water increases LCST-type cloud points, creating a completely miscible region before UCST-type phase separation observes. Thus, completely miscible or immiscible regions, induced by co-solvency or co-nonsolvency effects, respectively, divide UCST-type and LCST-type regions in the phase diagrams. This behavior aligns perfectly with the phase behavior observed in mixed organic solvents, indicating that our study extends the understanding of co-solvency and co-nonsolvency effects beyond aqueous systems. To the best of our knowledge, we demonstrate for the first time that these mechanisms universally govern UCST/LCST dual phase separation in non-aqueous systems as well. By using aliphatic alcohols as a solvent instead of water, compatibility with various organic solvents was improved, allowing for a more flexible choice of cosolvents. Furthermore, it was demonstrated that hydrogen-bond-based interaction

control enables quantitative tuning of moderate repulsion between polymer–solvent and solvent–solvent pairs. These results not only significantly expand the choice of media as the molecular design for UCST/LCST dual phase separation but also provide deeper insights into the interaction between polymer chains and solvent molecules toward solvation/desolvation on the phase transition process.

Conclusion

In this study, we demonstrated UCST/LCST dual phase separation of PHEMA in mixtures of common aliphatic alcohols and aprotic less-polar or non-polar solvents. By selecting rational solvent combinations, we achieved UCST/LCST dual phase separation in 15 different mixed organic solvent systems. Notably, this included the solvent mixture of 1-hexanol and DCE, where PHEMA is insoluble in both pure solvents. The phase diagrams revealed that in alcohol-rich regions, UCST-type cloud points decreased with increasing amounts of poor solvents. Conversely, in poor-solvent-rich regions, LCST-type phase separation occurred due to the dissociation of solvated alcohols from the polymer chain upon heating. Between these two regions, a completely miscible phase emerges, characterized by very low UCST-type cloud points and very high LCST-type cloud points, enabling UCST/LCST dual thermo-responsiveness. The phase diagrams further indicate that co-solvency of PHEMA in these organic solvent mixtures underlies the observed UCST/LCST dual phase separation. By applying the ternary Flory–Huggins theory, we were able to theoretically interpret the phase separation behavior and cosolvency observed in mixed PHEMA solutions. Incorporating the temperature dependence of interaction parameters would enable deeper theoretical understanding and more accurate

prediction of phase behavior—an important direction for future research in polymer science.

While previous studies have primarily focused on amphiphilic polymers in mixtures of water and water-miscible organic solvents, also highlighting the role of co-solvency and co-nonsolvency, our study extends this concept to entirely organic solvent systems. This broader perspective enhances the understanding of UCST/LCST dual phase separation mechanisms and provides new opportunities for designing polymer solutions with tunable phase behavior. Expanding the molecular design of UCST/LCST dual phase separation in organic solvents may pave the way for advanced applications, including polymer micelles and nanoparticles, in non-aqueous environments.

AUTHOR INFORMATION

Corresponding Author

Kazuki Sada – Department of Chemistry, Faculty of Science, Hokkaido University, Kita 10, Nishi 8, Sapporo, 060-0810, Japan; orcid:0000-0001-7348-0533

Keitaro Matsuoka – Department of Chemistry, Faculty of Science, Hokkaido University, Kita 10, Nishi 8, Sapporo, 060-0810, Japan; orcid: 0000-0002-6213-1220

Author

Koki Takasu, Natsuki Inaba –Graduate School of Chemical Sciences and Engineering, Hokkaido University Kita 10, Nishi 8, Sapporo, 060-0810, Japan

Shu Takeuchi – Department of Chemistry, Faculty of Science, Hokkaido University Kita 10, Nishi 8, Sapporo, 060-0810, Japan

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website.

Detailed experimental and theoretical conditions and other supporting data (PDF)

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

We acknowledge Prof. K. Konishi in HU for DLS measurements. This work was supported in part by JSPS KAKENHI Grant Number JP21H01980 for K.S.

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