Preparation of a chiral hyperbranched polymer based on cinchona alkaloids and investigation of its catalytic activity in asymmetric reactions

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Abstract: Cinchona alkaloids-derived sulfonamides and ester dimers containing chiral hyperbranched polymers (HBPs) have been successfully synthesized and applied as catalyst to asymmetric reactions. Several hyperbranched polymers derived from cinchona alkaloids, incorporating sulfonamides and esters, have been synthesized through

Mizoroki-Heck coupling polymerization. These polymers were subsequently applied in enantioselective Michael addition reactions. As these prepared polymers are not soluble in a frequently used organic solvent, the polymers act as an efficient catalyst to the enantioselective reaction of β-ketoesters to nitroolefins to give up to 99% enantioselectivity with good yields. The insoluble property gives them extra space to satisfy 'Green chemistry' requirement and is used up to several times without losing the enantioselectivity.

Key words: Hyperbranched polymers (HBPs); sulfonamide; polymeric chiral organocatalyst; Michael addition reaction.

1. Introduction

Cinchona alkaloid is a member of the Rubiaceae family and is derived from the bark of various species of cinchona trees [1]. Cinchona alkaloids are the chemical substances with the most vivid past. There are many instances of cinchona alkaloids being used as chiral resolving agents today [2 - 5]. The key use of cinchona alkaloids in chemistry is to expedite numerous enantioselective transformations in both homogeneous and heterogeneous catalytic systems. Bredig and Fiske documented the first asymmetric reaction utilizing a cinchona basis as early as 1912 [6,7]. The use of cinchona derivatives in asymmetric catalysis has grown dramatically since the publication of many ground-breaking studies. Now, it is understood that cinchona alkaloids and derivatives of them are one of the most blatant organic chirality inducers, working to activate practically all chemical processes in a highly stereoselective manner. The chiral induction and discrimination mechanisms were explained by structural analysis of cinchona alkaloids utilizing spectroscopic and computational techniques [8,9]. The main reason for the widespread use of cinchona alkaloids by numerous researchers [10,11] in various

reactions, including hetero-[2 + 2] cycloadditions [12 - 14], phase transfer catalyzed epoxidation [15 - 18], alkylation [19], conjugate additions [20,21], and phosphonylation reactions of aldehydes [22,23], was the use of these compounds as chiral catalysts in between the 1970s and 1980s. Cinchona alkaloids have a variety of functions that are essential for producing chirality in asymmetric products, either on their own or in chemically altered forms [24], because they contain both acidic and basic sites and these behave as dual-functional chiral organocatalysts. A nucleophile and an electrophile can both be activated and oriented by the hydroxyl moiety and tertiary amine, respectively [25]. Cinchona alkaloids and their analogues are able to serve as catalysts that are chiral in four distinct type of transformations, including the formation of carbon-carbon bonds, carbon-oxygen bonds, carbon-hydrogen heteroatom bonds and also additional processes including desymmetrization and hydrogenation. Bifunctional chiral catalysts, which can concurrently interact with and activate both the reacting sites, are a reliable, efficient technique to the stereoselective production of significant asymmetric molecules. Sulfonamides, which can be produced from cinchona alkaloids, are among the most significant and essential catalysts. In contrast to tertiary nitrogen of quinuclidine, which in cinchona alkaloids may function as both a base and a hydrogen-bond acceptor, the acidic NH part of sulfonamide is capable of functioning as a hydrogen-bond donor. Since, the cinchona alkaloid-derived sulfonamides have both acidic and basic sites, they have the unusual ability to keep a substrate in a certain orientation, creating a chiral environment [26]. Additionally, C9 ester derivatives of cinchona alkaloids with free OH [27], quinuclidine nitrogen [28 - 30], and a methoxy group adjacent to the C6' position of the quinoline molecule extensively studied and used effectively in numerous asymmetric processes [31 - 33]. The natural cinchona alkaloids in addition to alternate varieties like

bifunctional cinchona alkaloid derivatives are commonly utilized as a flexible source for organocatalysts in the field of catalytic enantioselective chemical synthesis [34,35]. Along with cinchona alkaloids with the 6'-OH group [36], cinchona alkaloids with thiourea moiety [37], and cinchona alkaloids along with 9-squaramide [38], dual-functional cinchona alkaloid catalysts have also been found. Sulfonamide catalysts based on cinchona alkaloids have been used to carry out asymmetric Michael-type reactions successfully. For instance, According to Luo et al., the asymmetric Michael reaction of 1,3-dicarbonyl compounds with nitrostyrene demonstrated good catalytic activity for the quinidine-derived sulfonamide. According to research by Itsuno et al., the Michael addition reaction between ketoester and nitrostyrene exhibited greater stereoselectivity when cinchonidine sulfonamides that served as bifunctional chiral organocatalysts [39].

Polymeric chiral organocatalysts are now used to great effect in the production of diverse chiral building blocks. A chiral organocatalyst (such as cinchona squaramides, sulfonamides, quaternary ammonium salt, cinchona ester, etc.) can be incorporated to produce a polymer that can be used as a chiral polymeric organocatalyst in many asymmetric reactions. Chiral polymers that include helical polymers, side-chain chiral polymers, main-chain chiral polymers, chiral ligands with dendritic molecules, and polymers with hyperbranched chirality. Polymeric chiral organocatalysts have drawn a lot of interest in chemical synthesis of molecules that are optically active due to their ease of removal from the reaction mixture and their capacity for multiple re-use. The design of chiral polymeric catalysts for hyperbranched chiral polymer organocatalysts is the primary focus of this work. Chiral catalysts were made by copolymerizing a variety of chiral catalytic monomers with achiral monomers. A chiral catalyst is added to the main structure of the polymer during polymer immobilization. In recent years, significant

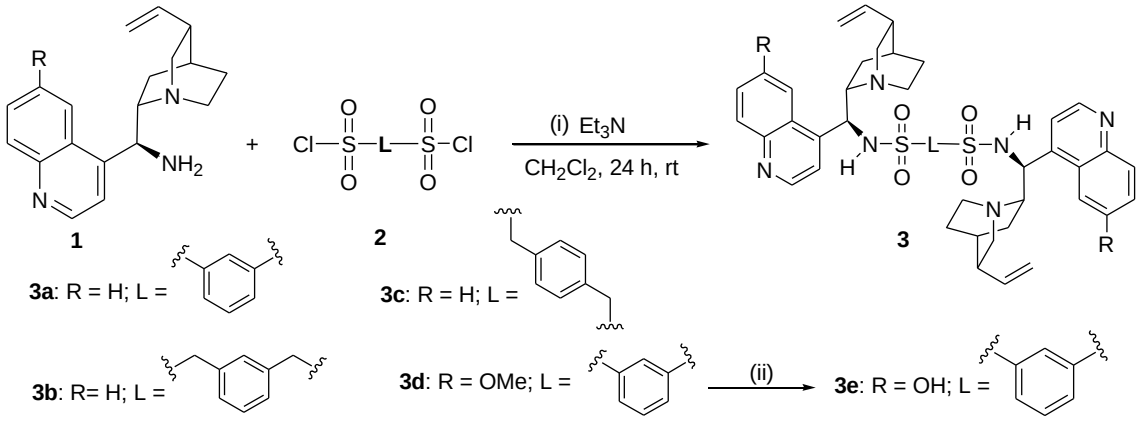
advancements have been done in the chiral main-chain polymeric catalyst synthesis process. In addition, several instances of polymer-immobilized catalysts have greater enantioselectivities compare to the corresponding catalysts that has the low-molecular-weight [40]. Different kinds of synthetic polymers, both organic and inorganic, have been employed as supports for chiral catalysts, and it has been documented which polymer network is best for each reaction [27]. As a substrate for the chiral catalyst, there are various polymers such as cross-linked, branching, dendritic as well as linear shaped have been used. A functional polymer with a chiral ligand can be polymerized to create a polymer-support chiral organocatalyst, and different monomers can be utilized depending on the kind of polymerization. Extremely branched three-dimensional (3D) macromolecules are known as hyperbranched polymers (HBPs) [41]. Due to their advantageous physical characteristics above those of their linear analogs, such as lower inherent viscosity, a lower glass transition temperature, and a higher number of terminal groups, hyperbranched polymers (HBPs) have garnered significant attention [41 - 46]. HBPs are therefore appropriate for a variety of uses, such as lubricants, coatings, medication delivery systems, and also catalysts [47 - 51]. While HBPs are relatively simple to manufacture in a single-step polymerization using the single-monomer methodology (SMM) and double-monomer methodology (DMM) [52]. As our research team has already established that the Mizoroki-Heck coupling process is trustworthy for forming C-C bonds to produce chiral polymers from cinchona alkaloid derivatives, we are concentrating on this coupling reaction in this article to synthesize HBPs [31, 53, 54]. The olefinic double bond of the sulfonamide dimer generated from cinchona alkaloid, the cinchona ester dimer, and the halide of trifunctionalized aromatic iodide were combined in the Mizoroki-Heck process to create chiral HBPs. In the asymmetric Michael Addition

reaction, we employed these hyperbranched polymers as chiral polymeric organocatalysts.

2. Result and discussion:

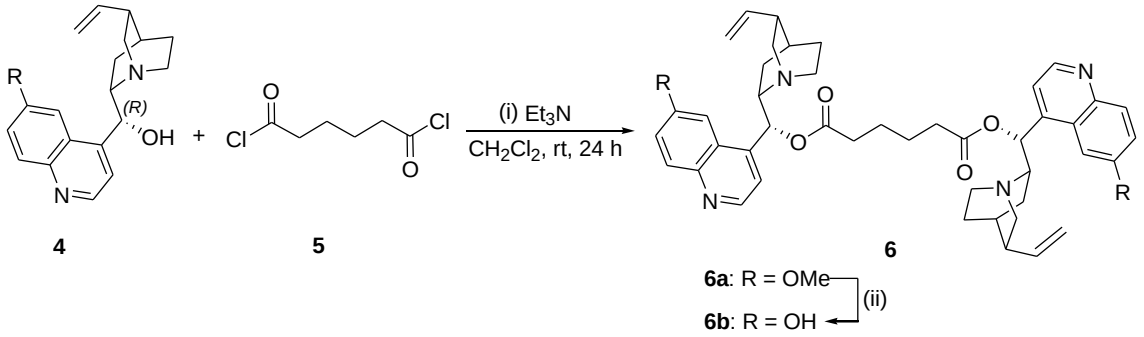
2.1 Synthesis of cinchona-derived sulfonamide and ester dimers and their corresponding chiral hyperbranched polymers

In this paper, we were mainly focusing to design HBPs based on cinchona sulfonamide and cinchona ester dimers. These HBPs contain rigid catalytic centers that are substantially more numerous, which may create a favorable microenvironment at the catalytic sites and enable systematic manipulation of their catalytic characteristics. We have synthesized various polymers of chiral organocatalyst by ion exchange polymerization, etherification polymerization, neutralization polymerization and quarternization polymerization. Sulfonyl chloride is very reactive towards amine, even in mild reaction condition to give sulfonamide derivatives. So, sulfonamide dimers **3** except **3e**, were designed and synthesized by the combination of C-9 aminated cinchona alkaloids **1** [3(*R*),4(*S*),8(*S*),9(*S*)] and disulfonyl chloride **2** (Scheme **1**) at rt. Only for 24 h reaction tine with the excess amount of **1** (~ double amount of **2)**, resulted pleasant yield. C-9 aminated cinchona alkaloids **1** was synthesized from cinchona alkaloid **4** [3(*R*),4(*S*),8(*S*),9(*R*)] having C-9 hydroxyl group by using the reported procedure [55,56].



Scheme 1**:** i) Synthesis of cinchona based sulfonamide dimers. ii) Demethylation of **3d** dimer by 1M BBr_3, dry CH_2Cl_2, Ar gas, -78°C to rt, 48h

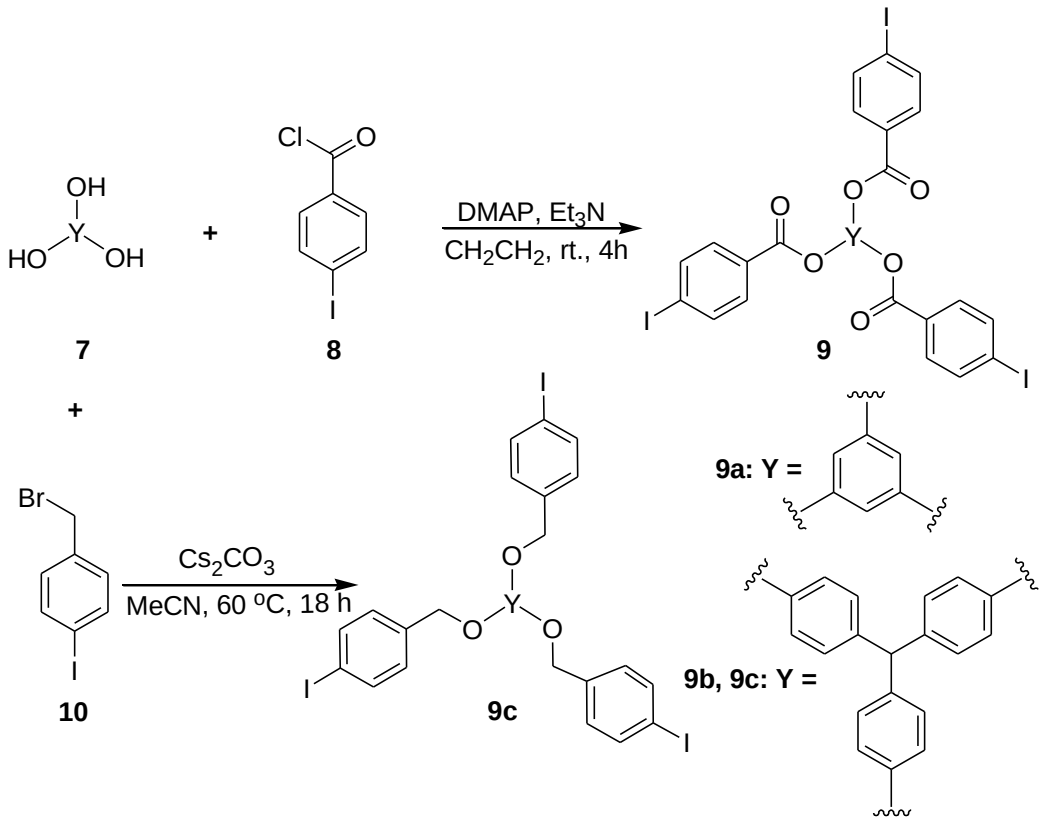
where C-6' OH carrying dimer **3e** was procured by demethylation of **3d** by using BBr_3 (scheme **1**) at -78 ºC for 2 days. On the other hand, dimeric ester **6a** were resulted from C-9 hydroxyl cinchona alkaloids **4** and hexa acid chloride **5**. Cinchona ester dimer **6b** obtained from **6a** as **3e** prepared by demethylation (Scheme **2**).



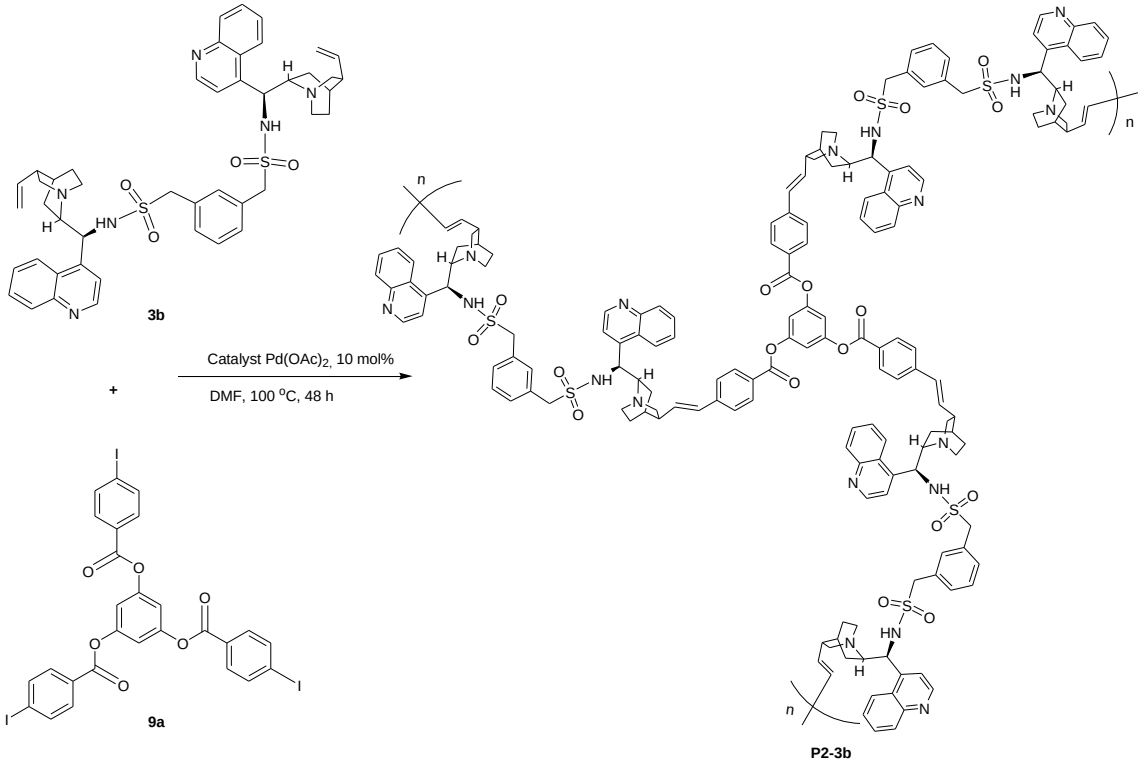
Scheme 2: i) Synthesis of ester dimers of cinchona. ii) Demethylation of **6a** dimer by 1M BBr_3, dry CH_2Cl_2, Ar gas, -78 °C to rt, 48h.

Novel chiral hyperbranched polymers holding cinchona based sulfonamide and ester dimers were designed by accumulating of bifunctional dimers and trifunctional aromatic halides, **9**. The two C3-vinyl groups in the structure of cinchona dimers make it possible to carry out the polymerization process with aromatic iodides using a two-component type approach the Mizoroki-Heck coupling reaction is the most effective reaction among the numerous reactions that can proceed a C-C bond with a vinylic double bond [53, 54]. In order to produce polymers, we therefore used the Mızorokı-Heck reaction between aromatic triiodides and divinylic compounds. These trifunctional aromatic iodide compound **9a** and **9b** were prepared from trihydroxybenzene and tris phenol with iodobenzoylchloride **8** respectively at room temperature (Scheme **3**) [57, 58]. Tris phenol and iodobenzylbromide **10** were used to make another class of trifunctional compounds **9c** which has three iodophenyl groups. (Scheme **3**) [57]. Repeated MH reactions take

place in the presence of a catalyst, $Pd(OAc)_2$ when these triiodo aromatic compounds **9** are combined with cinchona dimers **3** or **6**, and the resulting chiral hyperbranched polymers (Scheme **4**) are produced with a high yield (up to 93%, entry 6). One reaction route has been shown in (Scheme **4**).



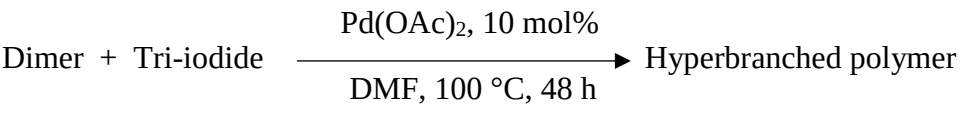
Scheme 3: Different synthetic route of trifunctional aromatic iodides.



Scheme 4: Synthesis of chiral HBP **P2-3b**.

The reaction mixture became precipitated in ether after polymerization, and then washed with ether and water to yield the polymer powder. The desired polymers of entry **1-5** were prepared by the Mızorokı-Heck polymerization using cinchona alkaloids based sulfonamide dimers **3** and the entry **8-9** resulting from cinchona ester dimers **6** with tri-iodide **9a**, where entry **6-7** are procured from different type of trifunctional aromatic iodide **9b** and **9c** with sulfonamide dimers **3b**. The HBPs that we obtained were soluble in DMF and DMSO, except **P6-3b** and **P7-3b** those were dissolved minimally. But all polymers were slightly dissolved in other prevalently used organic solvents, for instance, dichloromethane, methanol, diethyl ether, ethyl acetate, THF, hexane as well as acetone. The outcomes of the MH polymerization of aromatic triiodides and cinchona dimers are shown in Table **1**. In every cases, chiral HBPs gives higher molecular weight of around over 10,000 was found. But we couldn't take molecular weight for polymer **P6-3b** and **P7-3b** due to poor solubility in DMF.

Table 1: Synthesis of chiral hyperbranched polymers of different cinchona dimers and trifunctional aromatic iodides by applying Mizoroki-Heck polymerization.



Entry	Dimer	Iodides	Chiral HBP	Yield [%]	M_n [a]	M_w [a]	M_w/M_n [a]
1	**3a**	**9a**	**P1-3a**	79	8000	13000	1.65
2	**3b**	**9a**	**P2-3b**	81	10000	19000	1.97
3	**3c**	**9a**	**P3-3c**	70	24000	63000	2.63
4	**3d**	**9a**	**P4-3d**	86	23000	61000	2.72
5	**3e**	**9a**	**P5-3e**	55	16000	23000	1.43
6[b]	**3b**	**9b**	**P6-3b**	93	-	-	-
7[b]	**3b**	**9c**	**P7-3b**	88	-	-	-
8	**6a**	**9a**	**P8-6a**	73	15000	25000	1.67
9	**6b**	**9a**	**P9-6b**	77	18000	27000	1.52

[a]Determined by GPC with a flow rate of 1.0 mL per minute at 40 °C and DMF as the solvent (polystyrene standard). [b]Not soluble in DMF.

2.2 Catalytic activity of cinchona alkaloid derived dimers and Hyperbranched polymers (HBPs):

We have selected the asymmetric Michael addition of methyl 2-oxocyclopentanecarboxylate **11** to *trans*- β-nitrostyrene **12** as the model reaction (Scheme **5**) to examine the catalyst's function of the cinchona based chiral Hyperbranched polymers. Initially, we took a look for dimeric low-molecular-weight catalysts in the enantioselective Michael addition reaction in CH_2Cl_2 at room temperature, reaction proceeded smoothly and got excellent enantioselectivites up to 99% with preferable yield

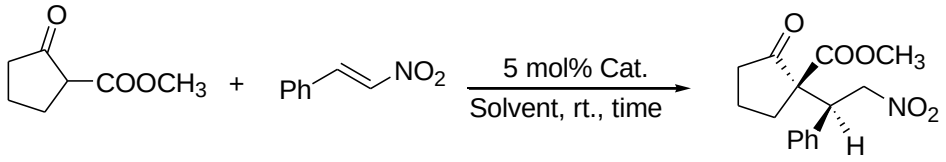
(up to 96%) except **6a** which gave only 44% ee (Table 2 entry 6). Table **2** provides a summary of the results of the asymmetric Michael reaction of **11** and **12** using low-molecular dimeric catalysts. We are encouraged by these results to use the corresponding sulfonamide polymers as a catalyst by applying the same procedure. Then, HBPs of the respective dimers have been synthesized as polymeric organocatalysts and employed for the same reaction. In the first instance, we trialled hyperbranched polymeric catalyst **P1-3a**.

Table 2: Asymmetric Michael addition[a] of β-ketoesters (**11)** with *trans*-β-nitrostyrene (**12)** using various dimers.

Entry	Catalysts	Reaction time [h]	Yield[b] [%]	*dr*[c] [%]	*ee*[c] [%]
1	**3a**	24	93	7.6:1	99
2	**3b**	24	96	15:1	99
3	**3c**	28	79	7.9:1	98
4	**3d**	42	62	4.7:1	99
5	**3e**	3	92	10:1	97
6	**6a**	32	72	0.6:1	44
7	**6b**	20	94	5.3:1	99

[a]At room temperature, asymmetric reactions involving **11** (0.50 mmol), **12** (0.55 mmol), and the dimeric catalyst (5 mol%) were conducted in 2.5 mL of CH_2Cl_2. [b]Isolated yield after purification by the column chromatography [c]Enantioselectivity (ee), as assessed by HPLC (flow rate: 1.0 mL/min on chiral cel OD-H).

Although it was insoluble in CH_2Cl_2 gives heterogeneous mixture, the asymmetric Michael addition of *trans*-nitrostyrene **12** and methyl 2-oxocyclopentanecarboxylate **11** progressed without any cumbersome



11 **12** **13**

Scheme **5**: Asymmetric Michael addition[a] of β-ketoesters (**11**) with *trans*-β-nitrostyrene (**12**).

at the room temperature to provide corresponding asymmetric product up to 99% ee with 96% yield. However, a higher reaction time was demanded owing to heterogeneous system for polymeric catalysts. It was almost similar result compared with previously reported cinchona based sulfonamide main chain type linear polymer [58]. In this case, half (5 mol %) catalyst loading was required compared to linear polymers.

Table 3: Asymmetric Michael addition[a] of β-ketoesters (**11**) with *trans*-β-nitrostyrene (**12**) using different HBPs.

1.	**Entry**	Catalysts	Reaction time [h]	Yield[b] [%]	*dr*[c] [%]	*ee*[c] [%]
	1	**P1-3a**	36	96	4.5:1	99
	2	**P2-3b**	24	84	8:1	>99
	3	**P3-3c**	30	86	6.4:1	98
	4	**P4-3d**	36	81	6.4:1	98
	5	**P5-3e**	24	75	5.5:1	99
	6	**P6-3b**	36	63	10.5:1	94
	7	**P7-3b**	36	67	11.3:1	96
	8	**P8-6a**	24	59	1.1:1	64
	9	**P9-6b**	24	73	5.9:1	>99

[a]At room temperature, asymmetric reactions involving **11** (0.50 mmol), **12** (0.55 mmol), and the polymeric catalyst (5 mol%) were conducted in 2.5 mL of CH_2Cl_2. [b]Isolated yield after purification by the column chromatography [c]Enantioselectivity (ee), as assessed by HPLC (flow rate: 1.0 mL/min on chiral cel OD-H).

Shorter reaction time needed when **P2-3b** more flexible structure than **P1-3a** was used as catalyst, the chiral product **13** obtained with nearly perfect enantioselectivity of the major

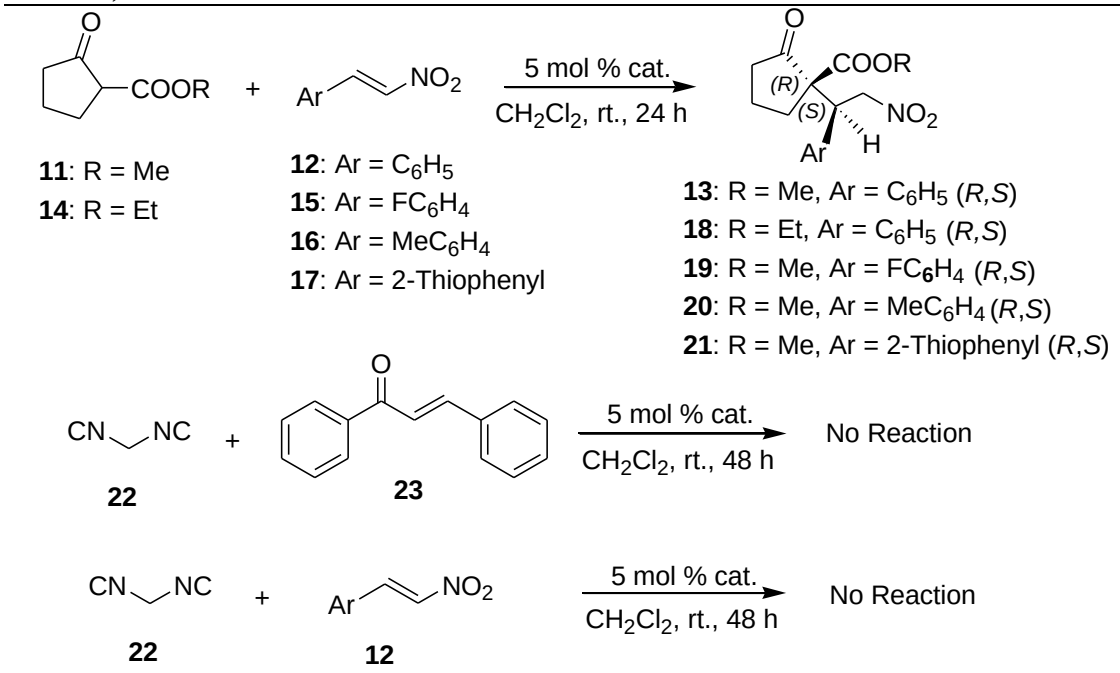
diastereomer (over 99%) within 24 hours (Table **3** entry 2). Though it gave better enantioselectivity comparing with corresponding dimer, but diastereoselectivity somewhat diminished. A competent performance was executed by chiral HBPs in particular asymmetric reaction might be because of creating microenvironment in chiral polymer network. Other polymers also demonstrated splendid enantioselectivity (94 to 99%) except for the result obtained by using **P8-6a** (Table 3 entry 8). It was derived from quinine ester dimer **6a** having C6′ methoxyl group which gave lower enantioselectivity for the selected model Michael reaction due to lack of acidic proton. Poor enantioselectivity also displayed by dimeric catalyst **6a** dimer. The enantioselective Michael addition reaction proceeded under the same conditions when the chiral hyperbranched polyester **P9-6b** with C6'-OH was used as a catalyst, yielding **13** with significantly better enantioselectivity (99% ee, Table 3 entry 9). Compared with the result obtained by using corresponding dimer catalyst **6b**, **P9-6b** catalyst took somewhat longer time because of heterogeneous condition. Changing trifunctional aromatic compound **9b** and **9c** instead of **9a**, lower enantioselectivity and yield obtained with longer reaction time for HBPs **P6-3b** and **P7-3b** (Table **3** entry 6 & 7) compared with **P2-3b** (Table 3 entry 2). Then we screened the influence of solvents on the catalytic activity by using HBP **P2-3b**. The results of the Michael addition reaction for **P2-3b** catalyst have been recapitulated in Table **4** with the diversity of solvents. The reactions were highly enantioselective above 95% ee for all the selected solvents with good yields. But in case of ethyl acetate only 27% yield obtained with 97% *ee* (entry 4, table 4). Though acetonitrile, THF, acetone gave somewhat lower yield (entry 2, 6, 7 table **4**) compared with dichloromethane, but still maintaining pleasant enantioselectivity. The most effective solvent for this model

Michael reaction is CH_2Cl_2, with over 99% ee and 84% yield, was determined after investigating the impact of the solvent (entry 1, table 4).

Table 4: Asymmetric Michael addition[a] of β-ketoesters **11** to *trans*- β-nitrostyrene **12** using hyperbranched polymeric catalyst **P2-3b** in different solvents.

Entry	Solvent	Yield[b] [%]	*dr*[c] [%]	*ee*[c] [%]
1	CH_2Cl_2	84	8:1	>99
2	Acetone	60	6:1	98
3	MeOH	70	3.7:1	95
4	EtOAc	27	3.4:1	97
5	Hexene	81	7.9:1	97
6	THF	52	6.6:1	96
7	CH_3CN	55	4.9:1	98

[a]At room temperature, asymmetric reactions involving **11** (0.50 mmol), **12** (0.55 mmol), and the polymeric catalyst (5 mol%) were conducted in 2.5 mL of CH_2Cl_2. [b]Isolated yield after purification by the column chromatography [c]Enantioselectivity (ee), as assessed by HPLC (flow rate:1.0 mL/min on chiral cel OD-H).



Scheme 6: Michael addition reaction of various Michael donors and acceptors by using polymer **P2-3b** as catalyst.

Afterward, we applied chiral HBP **P2-3b** to monitor asymmetric Michael addition reaction by changing the Michael acceptor substituents as well as Michael donors (Scheme **6**), and the results are summarized in Table **5**. Higher enantioselectivity was observed by using methyl 2-oxocyclopentanecarboxylate **11** and ethyl 2-oxocyclopentanecarboxylate **14** as Michael donor for all of the reactions (entries 1-4, Table **5**) except entry 2.

Table 5: Enantioselective Michael addition[a] reaction resulted from the combination of different donors and acceptors using polymeric catalyst, **P2-3b**.

Entry	Michael donor	Michael acceptor	Product	Reaction time [h]	Yield[b] [%]	dr[c] [%]	ee[c] [%]
1	**14**	**12**	**18**	42	77	14.4:1	92
2	**11**	**15**	**19**	48	87	9.3:1	73
3	**11**	**16**	**20**	46	82	1.7:1	>99
4	**11**	**17**	**21**	38	89	13:1	99

[a]At room temperature, asymmetric reactions involving **11** (0.50 mmol), **12** (0.55 mmol), and the polymeric catalyst (5 mol%) were conducted in 2.5 mL of CH_2Cl_2. [b]Isolated yield after purification by the column chromatography [c]Enantioselectivity (ee), as assessed by HPLC (flow rate: 1.0 mL/min on chiral cel OD-H).

In this instance, 4-Fluoro-*trans*-nitrostyrene **15** and methyl 2-oxocyclopentanecarboxylate **11** interacted with **P2-3b** to produce Michael adducts **19** with just 72% ee. However, chiral catalyst **P2-3b** was ineffective to catalyse the reaction between malononitrile **22** with chalcone **23** and *trans*-β-nitrostyrene **12** respectively to give chiral product at room temperature. The polymeric catalysts utilised in the asymmetric reaction were easily separated and recovered from the reaction mixture by normal filtration since chiral HBPs were insoluble in frequently used organic solvent to give suspension. The recovered HBPs were applied to the same asymmetric reaction multiple times. To confirm the authenticity chiral HBP **P2-3b** used as model catalyst in

the asymmetric reaction in dichloromethane at room temperature. This polymer was reused up to **5** cycle to check the catalytic activity. The yield in entry **3** is higher compare to entry 2 due to the increasing of reaction time 24 to 30 h. The results of the recyclability were summarized in Table **6**. Although, **P2-3b** catalyst maintaining the enantioselectivity and diastereoselectivity as fresh one, but decreased the yield in some extend.

Table 6: Enantioselective Michael addition[a] of β-ketoesters **11** with *trans*- β-nitrostyrene **12** using different HBP **P2-3a** to look on recyclability performance.

Entry	Cycle	Reaction time [h]	Yield[b] [%]	*dr*[c] [%]	*ee*[c] [%]
1	fresh	24	84	8:1	>99
2	1	24	77	9.8:1	97
3	2	30	85	9.4:1	99
4	3	30	81	7.8:1	98
5	4	36	67	8.6:1	99

[a]At room temperature, asymmetric reactions involving **11** (0.50 mmol), **12** (0.55 mmol), and the polymeric catalyst (5 mol%) were conducted in 2.5 mL of CH_2Cl_2. [b]Isolated yield after purification by the column chromatography [c]Enantioselectivity (ee), as assessed by HPLC (flow rate: 1.0 mL/min on chiral cel OD-H).

3. Experimental:

3.1 Synthesis of cinchona derived sulfonamide and ester dimers:

3.1.1 Synthesis of compound 3b

Cinchonidine amine **1** (1099.0 mg, 3.7456 mmol; 2 equiv or double amount of 2), α,α′-m-xylene sulfonyl chloride **2** (545.0 mg, 1.7977 mmol), triethyl amine (522 μL, 3.7456 mmol) and magnetic stir bar were added in a 20 mL volumetric flask. The mixture was then given 10.0 mL of dry CH_2Cl_2 and kept it at rt. while being stirred. Reaction progress was observe by TLC. The crude compound was purified using silica gel (100-200 mesh) column chromatography with a CH_2Cl_2: MeOH = 9:1 eluent after 24 hours, yielding the target component **3b** in 48% yield as a white solid, mp: 151-153 ºC. $[\alpha]_D^{26.4}$ = –7.53 (*c*

0.19 g/dL in DMF). 1HNMR (400 MHz, $CDCl_3$, 25 ºC) δ 8.95-8.92 (m, 2H), 8.23-8.28 (m, 2H), 8.10-8.12 (m, 2H), 7.68-7.45 (m, 2H), 7.50-7.63 (m, 4H), 7.32 (d, J=4.8, 1H), 7.02 (s, 1H), 6.83-6.92 (m, 2H), 6.59-6.92 (m, 2H), 6.59 (d, *J*=11.2, 1H), 5.54-5.22 (m, 2H), 4.85-4.99 (m, 4H), 4.58 (d, J=8.8, 1H), 3.58-3.77 (m, 4H), 3.14-3.24 (m, 4H), 2.86-3.02 (m, 2H), 2.68-2.77 (m, 4H), 2.28 (br, 2H), 1.57-1.69 (m, 6H), 1.25-1.31 (m, 2H), 0.74-0.92 (m, 2H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$, 25 °C) δ 150.3, 148.5, 145.9, 141.2, 132.3, 130.8, 130.4, 129.7, 128.9, 127.4, 124.9, 122.8, 120.0, 114.8, 60.7, 59.8, 55.5, 52.7, 40.4, 39.5, 27.6, 25.5 ppm. IR (KBr) *v* 3213, 2938, 2865, 1708, 1590, 1509, 1455, 1424, 1319, 1222, 1149, 1128, 988, 764 cm^{-1}. HRMS (ESI) calcd for $C_{46}H_{52}N_6O_4S_2$ $[M+Na]^+$: 817.02 found: 817.3606.

Other cinchona derived sulfonamide and ester dimers **3c**, **3d** & **3e** were prepared from different cinchona derivatives and sulphonyl chloride using the same process that were reported in the supporting information section.

3.1.2 Synthesis of trifunctional aromatic triiodides

Synthesis of compound 9b

50 mL of CH_2Cl_2 were used to mix 4, 4', 4''-Trihydroxyphenylmethane **7** (1.461 g, 5.0 mmol), 4-iodobenzoyl chloride **8** (4.132 g, 15.5 mmol), Et_3N (2.2 mL, 15.5 mmol), and DMAP (0.20 g). At room temperature, the resulting reaction mixture was stirred constantly for 4 hours. The layers were then separated after the addition of water. Additional CH_2Cl_2 was used to extract the aqueous phase, and the mixed organic layer was washed with brine, 10% aq. HCl solution, and 5% aq. NaOH solution before being dried over anhydrous $MgSO_4$. The crude product was obtained after filtration and solvent removal, and the chemical was then refined using silica gel column chromatography (with a Hex: EtOAc = 9:1) to produce a white solid **9b** with a 48% yield. mp: 104-107 ºC.

1HNMR ($CDCl_3$, 400 MHz, 25 °C) δ 7.86-7.91 (m, 12H), 7.15-7.21 (m, 12H), 5.63 (s, 1H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$, 25 °C) δ 164.6, 149.2, 141.0, 137.9, 131.4, 130.4, 128.9, 121.5, 101.6, 55.0 ppm.

Synthesis of compound 9c

In a 30 mL flask, 15.0 mL of CH_3CN was employed to dissolve 4,4',4"-Trihydroxyphenylmethane 7 (292.34 mg, 1.0 mmol) and 4-Iodobenzyl bromide 10 (979.5 mg, 3.3 mmol). Cesium carbonate Cs_2CO_3 (1075.2 mg, 3.3 mmol) was then added to the mixture. Under an Ar environment, the mixture was stirred at 60 °C for 18 hours. After that, 60 mL of CH_2Cl_2 was filled with the reaction mixture. Yellow solid product was formed and separated by filtering and evaporating the organic solution under reduced pressure after it had been cleaned with water (2/30) and brine (2/30). The organic solution had also been dried over anhydrous magnesium sulphate. Compound 9c was obtained with a 31% yield as a white solid after the crude product was refined using silica gel (100-200 mesh) column chromatography (using Hex: DCM = 1:1) R_f: 0.42 (DCM/Hex = 5.0/5.0). Other experimental data are found in the supporting information section.

3.2 Synthesis of HBPs by Mizoroki-Heck polymerization reaction:

Synthesis of polymer P1-3a

In a 30 mL flask, compounds **3a** (100.0 mg, 0.12674 mmol) and **9a** (104.0 mg, 0.12674 mmol) were combined with triethyl amine (double the amount, 35 µL, 0.2535 mmol). Palladium acetate (10 mol %) and DMF solvent (3 mL) were added, and the mixture was stirring at 100 ^oC for 48 hours. NMR was used to observe the course of the process of the reaction. Then the solvent was evaporated and washed with a suitable solvent, diethyl ether and finally water. The desired polymeric compounds were then dried again in a vacuum oven to produce the small compound **P1-3a** as a brown solid in 79% of the cases.

$[\alpha]_D^{24.4}$ = +39.40 (*c* 0.05 g/dL in DMF). 1HNMR (400 MHz, DMSO-d_6, 25 ºC) δ 8.68, 7.27-8.22 (aromatic H), 6.37-6.63 (vinylic H), 5.10, 0.61-2.92 (quinuclidine H) ppm. IR (KBr) *v* 3178, 3067, 2942, 2865, 1733, 1652, 1604, 1509, 1458, 1327, 1257, 1177, 1069, 1004, 758, 683 cm^{-1}. M_n (SEC) = 8.0 x 10^3, M_w/M_n = 1.65.

Using the same procedure described in the supporting information section, additional optically active hyperbranched polymers were synthesized from various sulfonamide and ester dimers derived from cinchona. Table **1** summarizes the relevant results.

3.3 General procedure for the asymmetric Michael addition reaction of β-ketoesters to nitroolefins using the chiral sulfonamide polymers:

Trans-nitrostyrene **12** (82.05 mg, 0.55 mmol) and methyl 2-oxocyclopentanecarboxylate **11** (63 L, 0.50 mmol) were taken in a reaction vessel with 2.5 mL of solvent. HBPs catalyst was then poured into the mixture (5 mol %). The reaction mixture was then stirred for a predetermined amount of time at room temperature. A rotary evaporator was used to evaporate the solvent once all **11** had been consumed (as determined by TLC). To remove the utilized polymeric catalyst from the reaction mixture, the solution containing the asymmetric compound was collected by pipette after being washed with ether. In order to obtain the name "asymmetric compound," the solution was concentrated in vacuo and the compound was purified using column chromatography on silica gel (100–200 mesh) with hexane/EtOAc = 6.0/1.0 as the eluent to afford the title asymmetric compound as a colorless oil. 1HNMR (400 MHz, 25 °C, $CDCl_3$); δ 7.29–7.23 (m, 5H), 5.14 (dd, *J* = 13.8 Hz, 3.8 Hz, 1H), 5.00 (dd, *J* = 13.8 Hz, 10.7 Hz, 1H), 4.08 (dd, *J* = 10.8 Hz, 3.8 Hz, 1H), 3.74 (s, 3H), 2.38–2.33 (m, 2H), 2.04–1.84.

The outcomes of further asymmetric Michael additions were carried out in a similar way, and they are compiled in the Tables **2**, **3**, **4**, **5**, and **6** as well as in Scheme **5**.

4. Conclusion:

In summary, we successfully developed novel chiral hyperbranched polymers (HPBs) using the Mizoroki-Heck polymerization method, and these HPBs have a primary chain repeating unit made of a sulfonamide and ester structure based on cinchona. For the chiral polymerization, two components were employed as the approach. Despite the fact that these chiral polymers are insoluble in commonly used organic solvents, they function as a superb catalyst to the asymmetric Michael addition of ketoesters to nitroolefins, resulting in up to 99% enantioselectivity and good yield. Chiral HBP **P2-3b** shows excellent level of enantioselectivity (>99% *ee*) with good yield as low molecular catalyst. The insoluble property give them extra space to satisfy 'Green chemistry' requirement and used up to several times without losing enantioselectivity. Those are the HBPs polymer based on sulfonamide and ester dimer of cinchona alkaloids, and successfully applied on enentioselective synthesis.

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Conflicts of Interest: The authors declare no conflict of interest.

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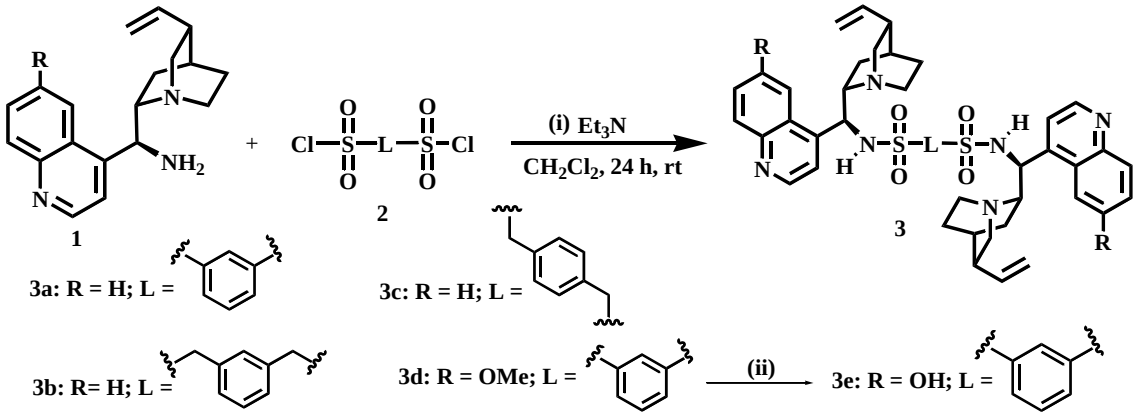
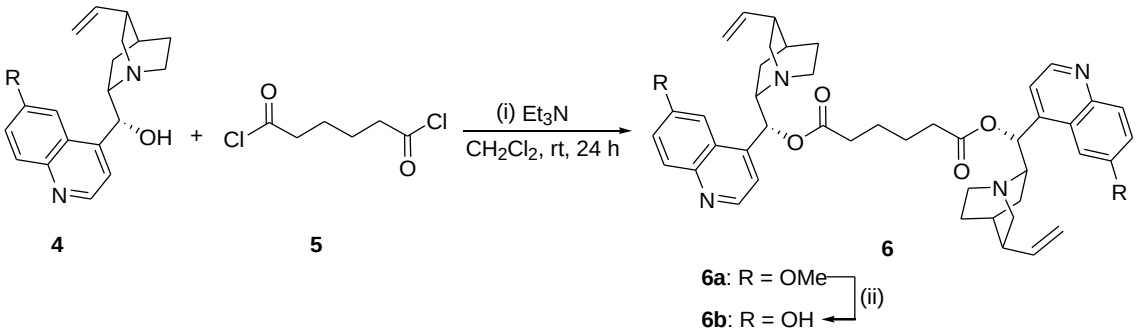
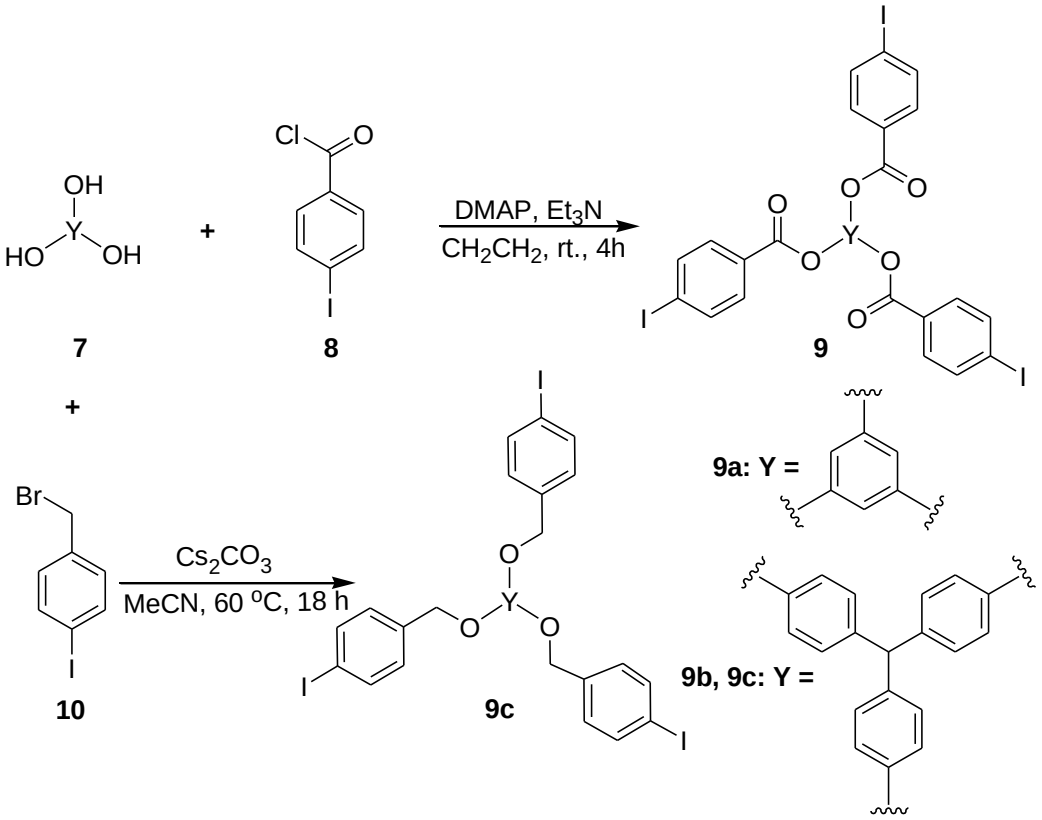


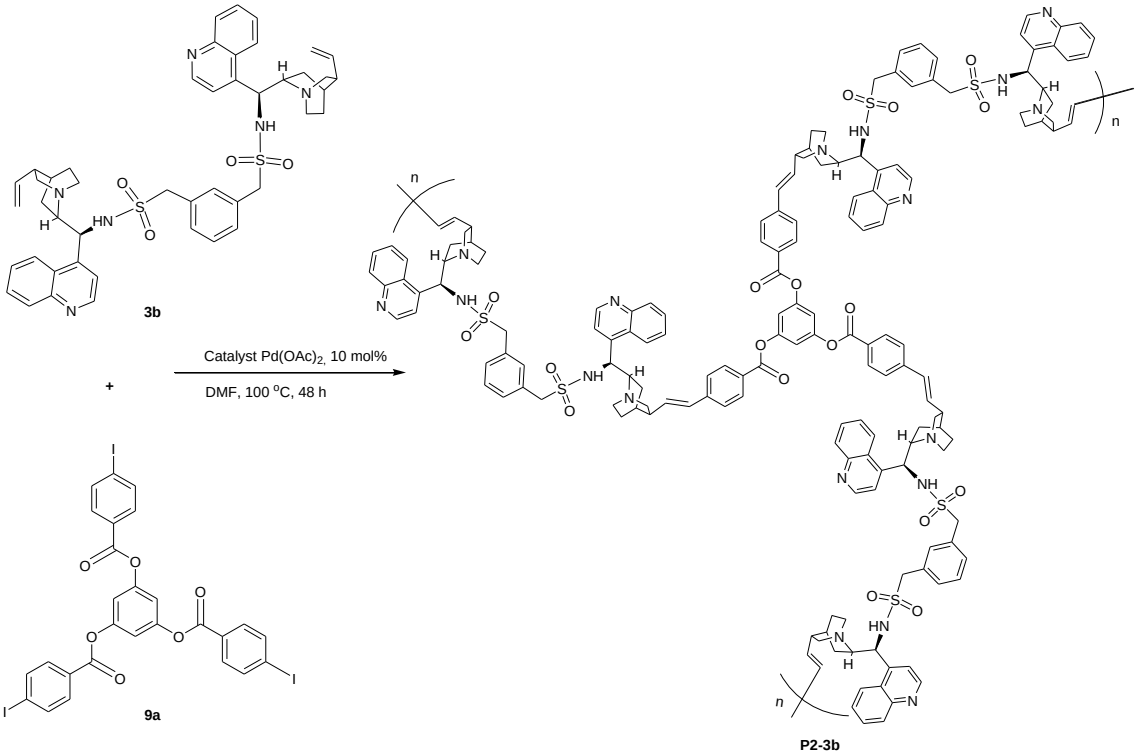
Scheme 1**:** i) Synthesis of cinchona based sulfonamide dimers. ii) Demethylation of **3d** dimer by 1M BBr_3, dry CH_2Cl_2, Ar gas, -78°C to rt, 48h



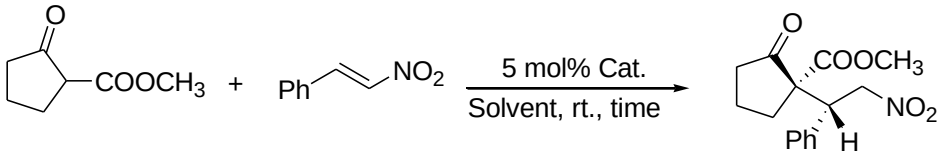
Scheme 2: i) Synthesis of ester dimers of cinchona. ii) Demethylation of **6a** dimer by 1M BBr_3, dry CH_2Cl_2, Ar gas, -78 °C to rt, 48h.



Scheme 3: Different synthetic route of trifunctional aromatic iodides.

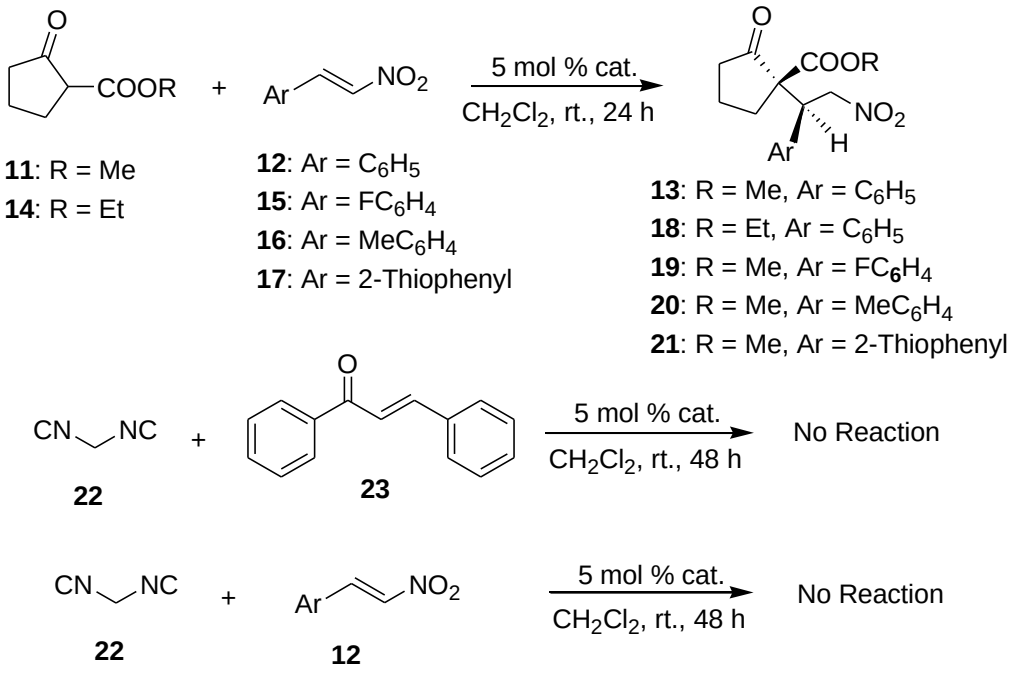


Scheme 4: Synthesis of chiral HBP **P2-3b**.



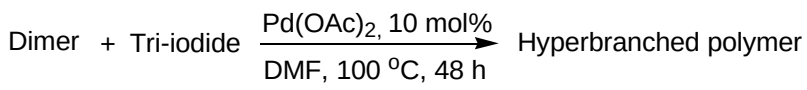
11 **12** **13**

Scheme **5**: Asymmetric Michael addition[a] of β-ketoesters (**11**) with *trans*-β-nitrostyrene (**12**).



Scheme 6: Michael addition reaction of various Michael donors and acceptors by using polymer **P2-3b** as catalyst.

Table 1: Synthesis of chiral hyperbranched polymers of different cinchona dimers and trifunctional aromatic iodides by applying Mizoroki-Heck polymerization.



Entry	Dimer	Iodides	Chiral HBP	Yield [%]	M_n [a]	M_w [a]	M_w/M_n [a]
1	**3a**	**9a**	**P1-3a**	79	8000	13000	1.65
2	**3b**	**9a**	**P2-3b**	81	10000	19000	1.97
3	**3c**	**9a**	**P3-3c**	70	24000	63000	2.63
4	**3d**	**9a**	**P4-3d**	86	23000	61000	2.72
5	**3e**	**9a**	**P5-3e**	55	16000	23000	1.43
6[b]	**3b**	**9b**	**P6-3b**	93	-	-	-
7[b]	**3b**	**9c**	**P7-3b**	88	-	-	-
8	**6a**	**9a**	**P8-6a**	73	15000	25000	1.67
9	**6b**	**9a**	**P9-6b**	77	18000	27000	1.52

[a]Determined by GPC with a flow rate of 1.0 mL per minute at 40 °C and DMF as the solvent (polystyrene standard). [b]Not soluble in DMF.

Table 2: Asymmetric Michael addition[a] of β-ketoesters (**11)** with *trans*-β-nitrostyrene (**12)** using various dimers.

Entry	Catalysts	Reaction time [h]	Yield[b] [%]	*dr*[c] [%]	*ee*[c] [%]
1	**3a**	24	93	7.6:1	99
2	**3b**	24	96	15:1	99
3	**3c**	28	79	7.9:1	98
4	**3d**	42	62	4.7:1	99
5	**3e**	3	92	10:1	97
6	**6a**	32	72	0.6:1	44
7	**6b**	20	94	5.3:1	99

[a]At room temperature, asymmetric reactions involving **11** (0.50 mmol), **12** (0.55 mmol), and the dimeric catalyst (5 mol%) were conducted in 2.5 mL of CH_2Cl_2. [b]Isolated yield after purification by the column chromatography [c]Enantioselectivity (ee), as assessed by HPLC (flow rate: 1.0 mL/min on chiral cel OD-H).

Table 3: Asymmetric Michael addition[a] of β-ketoesters (**11**) with *trans*-β-nitrostyrene (**12**) using different HBPs.

2. **Entry**	Catalysts	Reaction time [h]	Yield[b] [%]	*dr*[c] [%]	*ee*[c] [%]
1	**P1-3a**	36	96	4.5:1	99
2	**P2-3b**	24	84	8:1	>99
3	**P3-3c**	30	86	6.4:1	98
4	**P4-3d**	36	81	6.4:1	98
5	**P5-3e**	24	75	5.5:1	99
6	**P6-3b**	36	63	10.5:1	94
7	**P7-3b**	36	67	11.3:1	96
8	**P8-6a**	24	59	1.1:1	64
9	**P9-6b**	24	73	5.9:1	>99

[a]At room temperature, asymmetric reactions involving **11** (0.50 mmol), **12** (0.55 mmol), and the polymeric catalyst (5 mol%) were conducted in 2.5 mL of CH_2Cl_2. [b]Isolated yield after purification by the column chromatography [c]Enantioselectivity (ee), as assessed by HPLC (flow rate: 1.0 mL/min on chiral cel OD-H).

Table 4: Asymmetric Michael addition[a] of β-ketoesters **11** to *trans*- β-nitrostyrene **12** using hyperbranched polymeric catalyst **P2-3b** in different solvents.

Entry	Solvent	Yield[b] [%]	*dr*[c] [%]	*ee*[c] [%]
1	CH_2Cl_2	84	8:1	>99
2	Acetone	60	6:1	98
3	MeOH	70	3.7:1	95
4	EtOAc	27	3.4:1	97
5	Hexene	81	7.9:1	97
6	THF	52	6.6:1	96

7	CH_3CN	55	4.9:1	98

[a]At room temperature, asymmetric reactions involving **11** (0.50 mmol), **12** (0.55 mmol), and the polymeric catalyst (5 mol%) were conducted in 2.5 mL of CH_2Cl_2. [b]Isolated yield after purification by the column chromatography [c]Enantioselectivity (ee), as assessed by HPLC (flow rate:1.0 mL/min on chiral cel OD-H).

Table 5: Enantioselective Michael addition[a] reaction resulted from the combination of different donors and acceptors using polymeric catalyst, **P2-3b**.

Entry	Michael donor	Michael acceptor	Product	Reaction time [h]	Yield[b] [%]	dr[c] [%]	ee[c] [%]
1	**14**	**12**	**18**	42	77	14.4:1	92
2	**11**	**15**	**19**	48	87	9.3:1	73
3	**11**	**16**	**20**	46	82	1.7:1	>99
4	**11**	**17**	**21**	38	89	13:1	99

[a]At room temperature, asymmetric reactions involving **11** (0.50 mmol), **12** (0.55 mmol), and the polymeric catalyst (5 mol%) were conducted in 2.5 mL of CH_2Cl_2. [b]Isolated yield after purification by the column chromatography [c]Enantioselectivity (ee), as assessed by HPLC (flow rate: 1.0 mL/min on chiral cel OD-H).

Table 6: Enantioselective Michael addition[a] of β-ketoesters **11** with *trans*- β-nitrostyrene **12** using different HBP **P2-3a** to look on recyclability performance.

Entry	Cycle	Reaction time [h]	Yield[b] [%]	*dr*[c] [%]	*ee*[c] [%]
1	fresh	24	84	8:1	>99
2	1	24	77	9.8:1	97
3	2	30	85	9.4:1	99
4	3	30	81	7.8:1	98
5	4	36	67	8.6:1	99

[a]At room temperature, asymmetric reactions involving **11** (0.50 mmol), **12** (0.55 mmol), and the polymeric catalyst (5 mol%) were conducted in 2.5 mL of CH_2Cl_2. [b]Isolated yield after purification by the column chromatography [c]Enantioselectivity (ee), as assessed by HPLC (flow rate: 1.0 mL/min on chiral cel OD-H).

Supporting Information

For

Preparation of a chiral hyperbranched polymer based on cinchona alkaloids and investigation of its catalytic activity in asymmetric reactions

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[Materials and General Considerations]

All solvents and reagents were brought from Sigma-Aldrich, Wako Pure Chemical Industries, Ltd., or Tokyo Chemical Industry (TCI) Co., Ltd. at the maximum available cleanness and were used as received. Pre-coated silica gel plates (Merck 5554, 60F254) was used for Thin-layer chromatography (TLC) to monitor various types of reactions progression. Column chromatography was conducted by using a silica gel column (Wakogel C-200, 100–200 mesh). Yanaco micro melting apparatus was used to record melting point and the average values of the analysed samples were taken. NMR spectra were recorded on JEOL JNM-ECS400 spectrometers and JEOL JNM-ECX500 spectrometers in CDCl3 or DMSO-d6 at room temperature operating at 400 MHz (1H), 500 MHz (1H) and 100 MHz (13C{1H}). For 1H NMR Tetramethylsilane (TMS) was used as an internal standard and chemical shifts were reported in parts-per-million (ppm). CDCl3 was used as standard for 13C NMR and the J values were reported in hertz. JEOL JIR-7000 Fourier transform (FT)-IR spectrometer was use to record IR spectra and reported in reciprocal centimeters (cm-1). High-resolution mass spectrometry (HRMS) electrospray ionization (ESI) spectra were recorded using Bruker micro TOF-Q II HRMS/MS instrument. High-performance liquid chromatography (HPLC) was run with a Jasco HPLC system constructed of a DG-980-50 three-line degasser, a HPLC pump (PU-980), a Jasco UV-975 UV detector for peak detection, and a column oven CO-2065 equipped with a chiral column (Chiralpak OD-H, Daicel) with hexane/2-propanol as the eluent at a flow rate of 1.0 mL/min at room temperature. Size-exclusion chromatography (SEC) was performed using a Tosoh HLC 8020 instrument with UV (254 nm) or refractive index detection. As a carrier solvent dimethylformamide (DMF) was used at a flow rate of 1.0 mL min-1 at 40 °C and two polystyrene gel columns of 10-µm bead size were used. The number average molecular weight (Mn) and molecular weight distribution (Mw/Mn) values were determined by using a calibration curve compared with polystyrene standards. The optical rotation was obtained by using a JASCO DIP-149 digital polarimeter using a 10-cm thermostatted microcell.

Synthesis of cinchona derived sulfonamide and ester dimers:

Synthesis of compound 3b

Cinchonidine amine 1 (1099.0 mg, 3.7456 mmol; 2 equiv or little excess), α,α'-m-xylene sulfonyl chloride 2 (545.0 mg, 1.7977 mmol), triethyl amine (522 µL, 3.7456 mmol) and magnetic stir bar taken in a 20 mL volumetric flask. Then dry CH_2Cl_2 10.0 mL added to the mixture and kept it at room temperature with stirring. The reaction progress was observe by TLC. After 24 hours CH_2Cl_2 was removed by rotary evaporator and then the crude compound was purified by silica gel (100–200 mesh) column chromatography using CH_2Cl_2: MeOH = 9:1 as an eluent to give the desired compound 3b in 48% yield as white solid. mp: 151-153 ºC. $[\alpha]_D^{26.4}$ = –7.53 (*c* 0.19 g/dL in DMF). ^{1}NMR (400 MHz, $CDCl_3$, 25 ºC) δ 8.95-8.92 (m, 2H), 8.23-8.28 (m, 2H), 8.10-8.12 (m, 2H), 7.68-7.45 (m, 2H), 7.50-7.63 (m, 4H), 7.32 (d, J=4.8, 1H), 7.02 (s, 1H), 6.83-6.92 (m, 2H), 6.59-6.92 (m, 2H), 6.59 (d, J=11.2, 1H), 5.54-5.22 (m, 2H), 4.85-4.99 (m, 4H), 4.58 (d, J=8.8, 1H), 3.58-3.77 (m, 4H), 3.14-3.24 (m, 4H), 2.86-3.02 (m, 2H), 2.68-2.77 (m, 4H), 2.28 (br, 2H), 1.57-1.69 (m, 6H), 1.25-1.31 (m, 2H), 0.74-0.92 (m, 2H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$, 25 °C) δ 150.3, 148.5, 145.9, 141.2, 132.3, 130.8, 130.4, 129.7, 128.9, 127.4, 124.9, 122.8, 120.0,

114.8, 60.7, 59.8, 55.5, 52.7, 40.4, 39.5, 27.6, 25.5 ppm. IR (KBr) *v* 3213, 2938, 2865, 1708, 1590, 1509, 1455, 1424, 1319, 1222, 1149, 1128, 988, 764 cm^{-1}. HRMS (ESI) calcd for $C_{46}H_{52}N_6O_4S_2$ $[M+Na]^+$: 817.02 found: 817.3606.

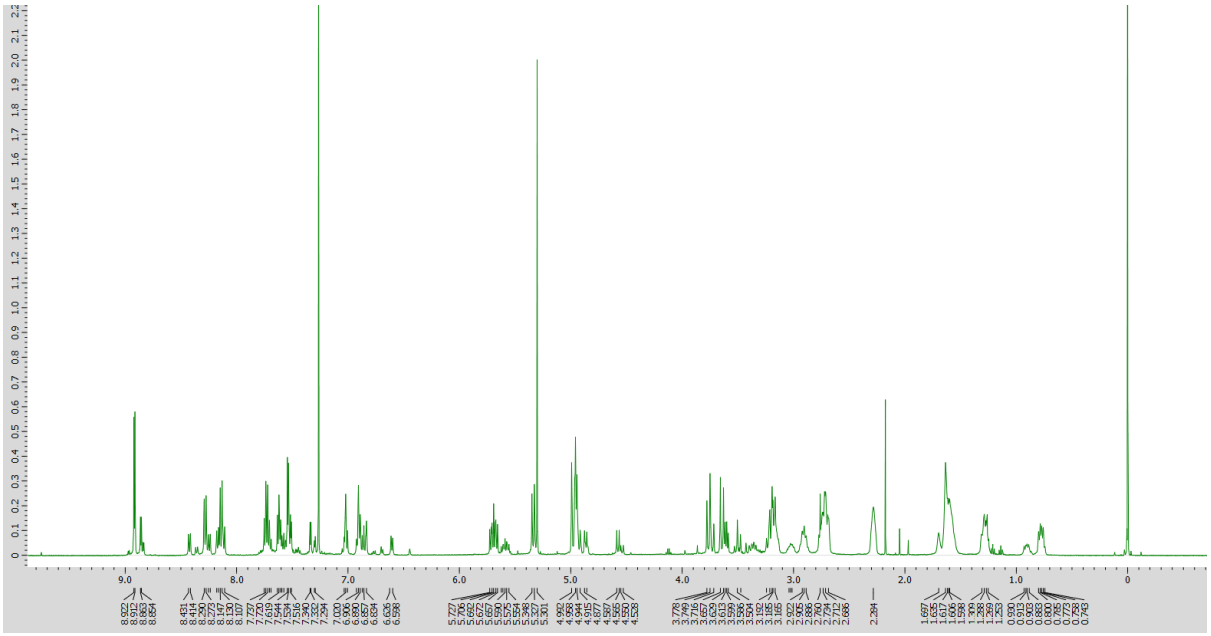


Figure S1: ^1H NMR of dimer 3b in $CDCl_3$

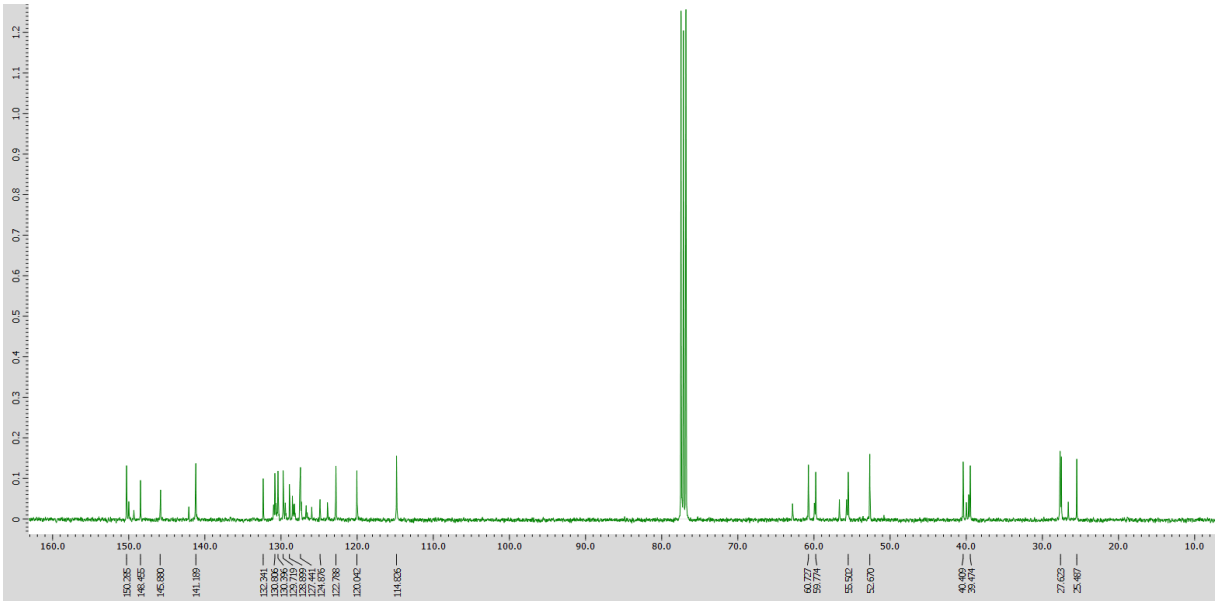
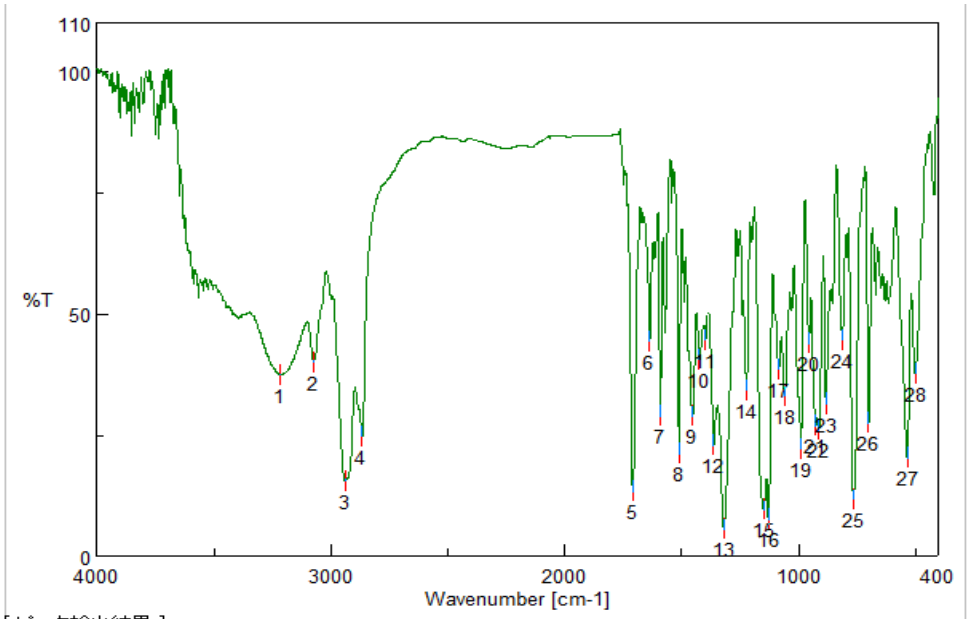


Figure S2: ^{13}C NMR of dimer 3b in $CDCl_3$



[ピーク検出結果]

No.	位置	強度	No.	位置	強度
1	3213.79	37.469	2	3073.98	40.0598
3	2938.98	15.6065	4	2885.7	24.7146
5	1708.62	13.3917	6	1636.3	44.3917
7	1590.99	28.9608	8	1509.03	21.1254
9	1455.03	28.9298	10	1424.17	40.614
11	1396.21	44.6586	12	1362.46	22.8491
13	1319.07	5.67499	14	1222.65	34.2302
15	1149.37	9.72735	16	1128.15	7.64053
17	1084.76	38.6258	18	1058.73	33.0375
19	988.339	22.1228	20	954.591	43.8139
21	926.628	26.9706	22	912.165	26.0255
23	882.274	31.433	24	812.849	44.6678
25	764.637	11.7713	26	700.034	27.504
27	534.185	20.3246	28	500.437	37.7514

Figure S3: IR spectra of 3b

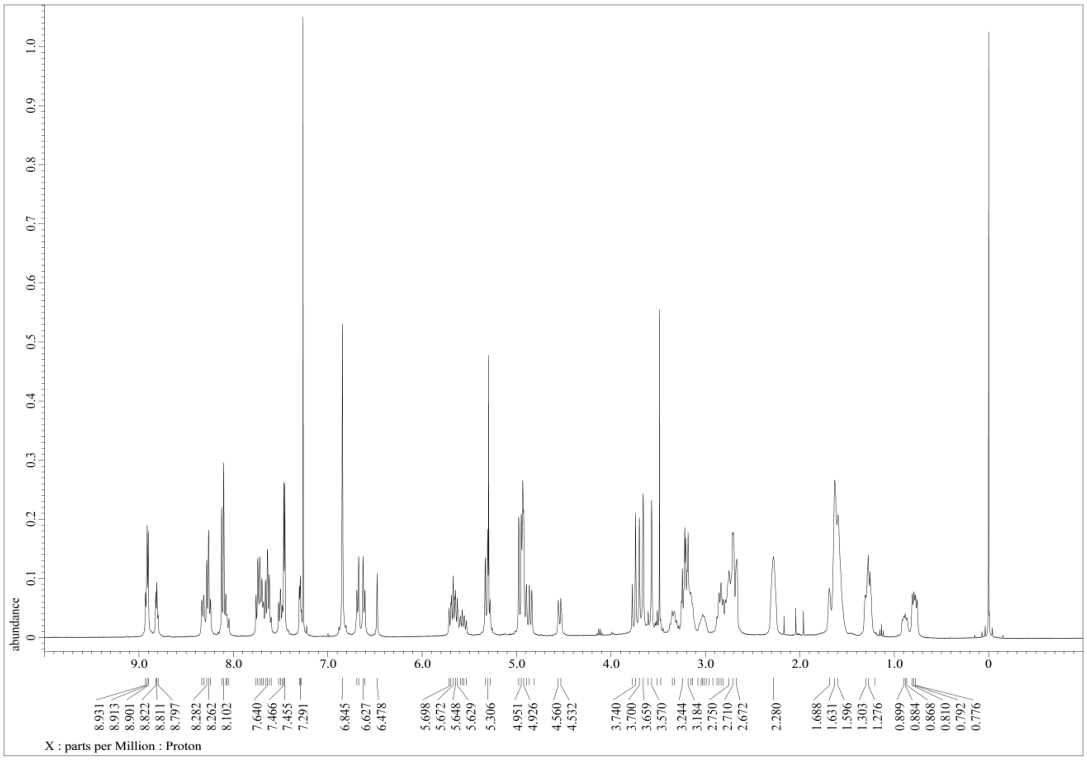


Figure S4: ^{1}H NMR of dimer 3c in $CDCl_3$

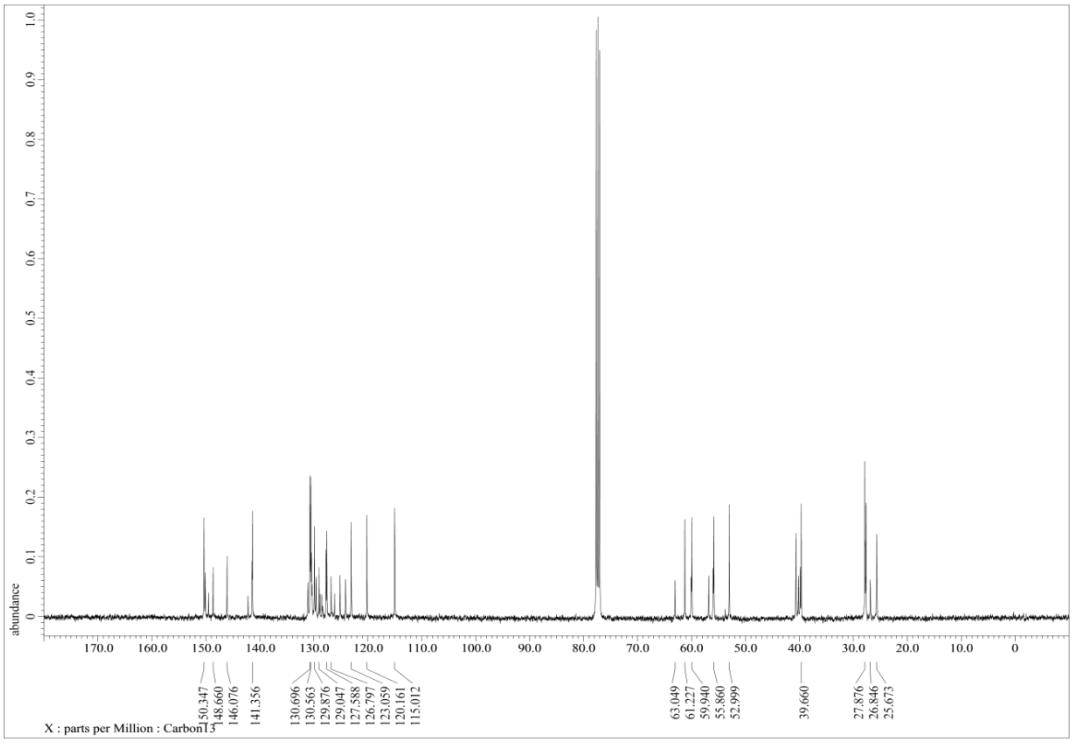
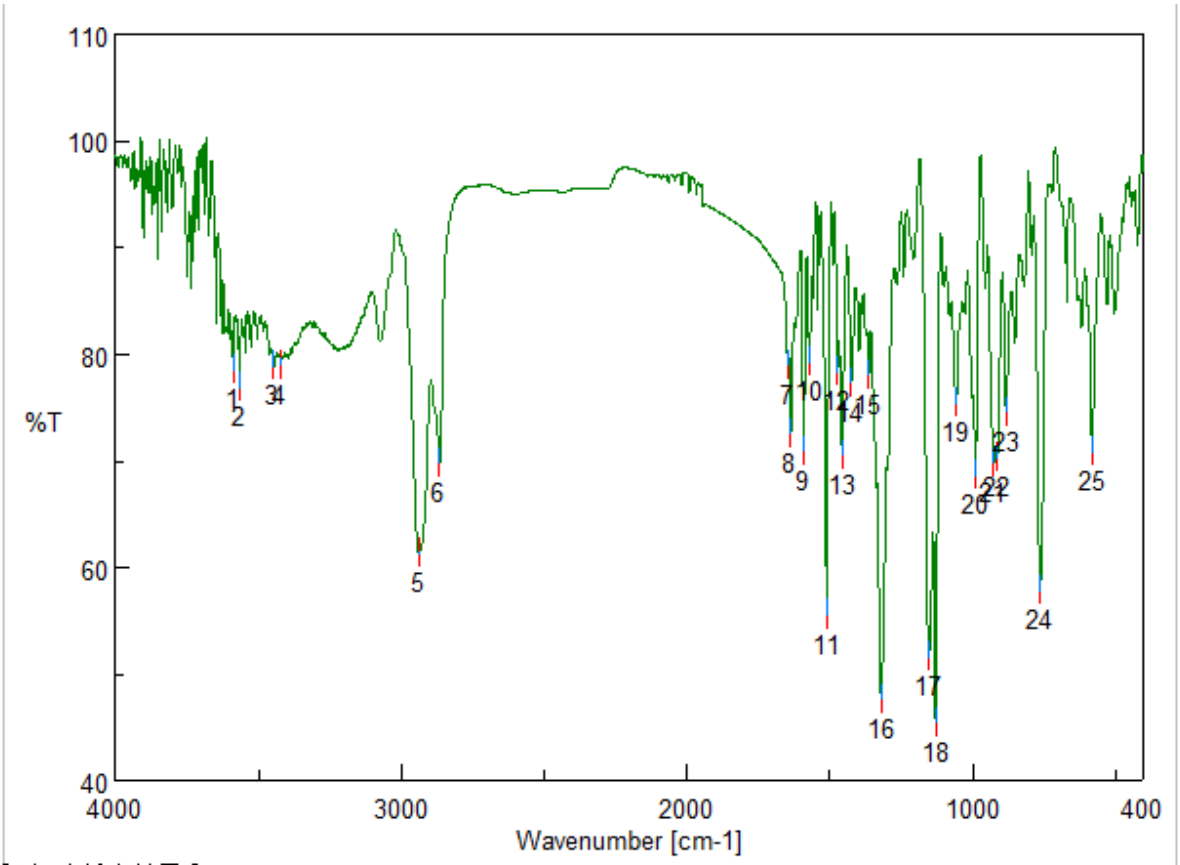


Figure S5: ^{13}C NMR of dimer 3c in $CDCl_3$



[ピーク検出結果]

No.	位置	強度	No.	位置	強度
1	3586.95	78.525	2	3566.7	76.9042
3	3446.17	78.871	4	3421.1	78.9623
5	2938.98	61.3688	6	2865.7	69.8506
7	1645.95	79.0335	8	1636.3	72.6064
9	1590.99	70.953	10	1568.81	79.315
11	1509.03	55.6188	12	1472.38	78.3734
13	1456.96	70.615	14	1424.17	77.3894
15	1382.46	78.1294	16	1319.07	47.6858
17	1152.26	51.6392	18	1129.12	45.4831
19	1057.76	75.4655	20	988.339	68.6339
21	925.664	69.8245	22	912.165	70.3051
23	882.274	74.5663	24	763.673	57.8827
25	580.469	70.865			

Figure S6: IR spectra of 3c

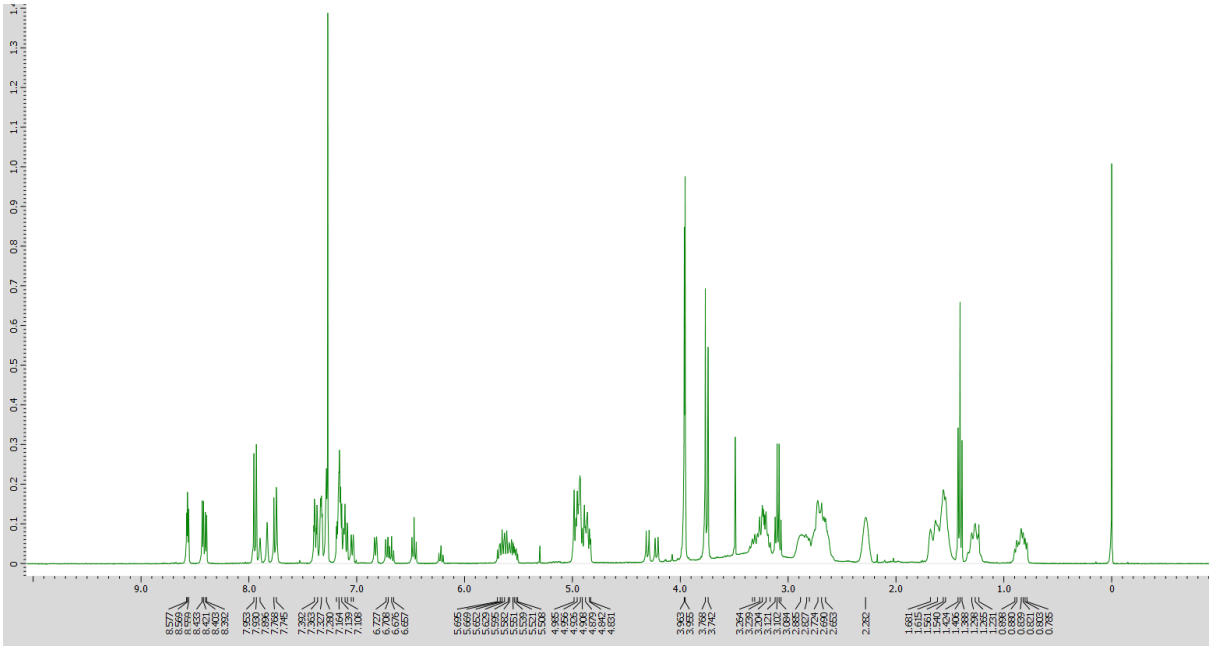


Figure S7: ^{1}H NMR of dimer 3d in $CDCl_3$

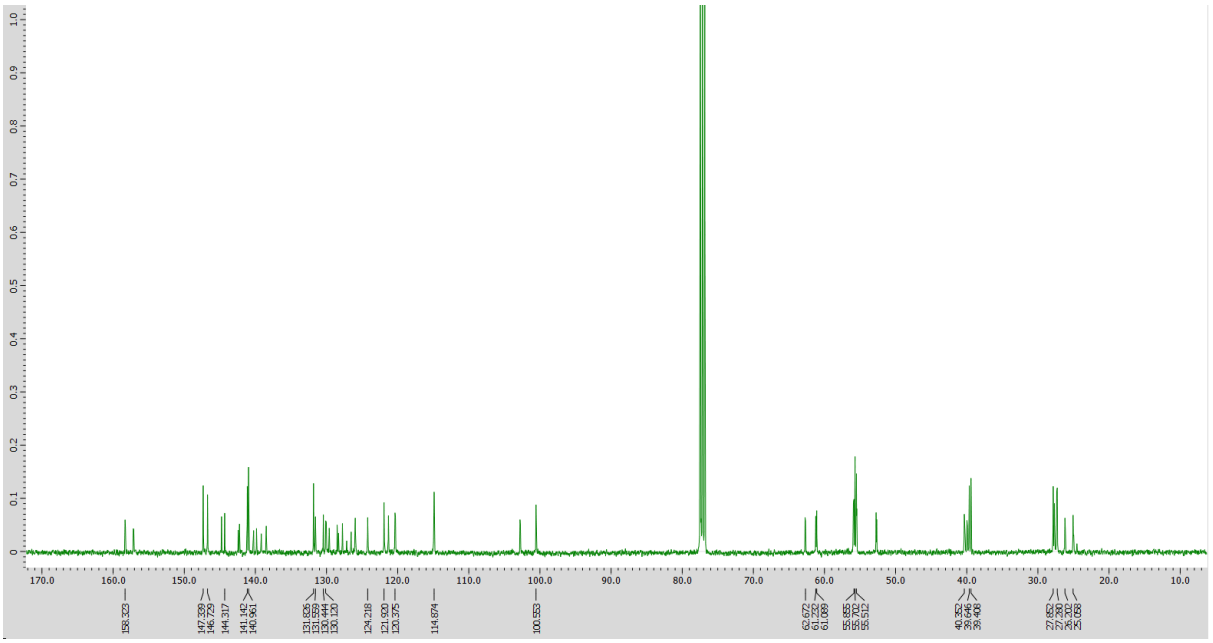
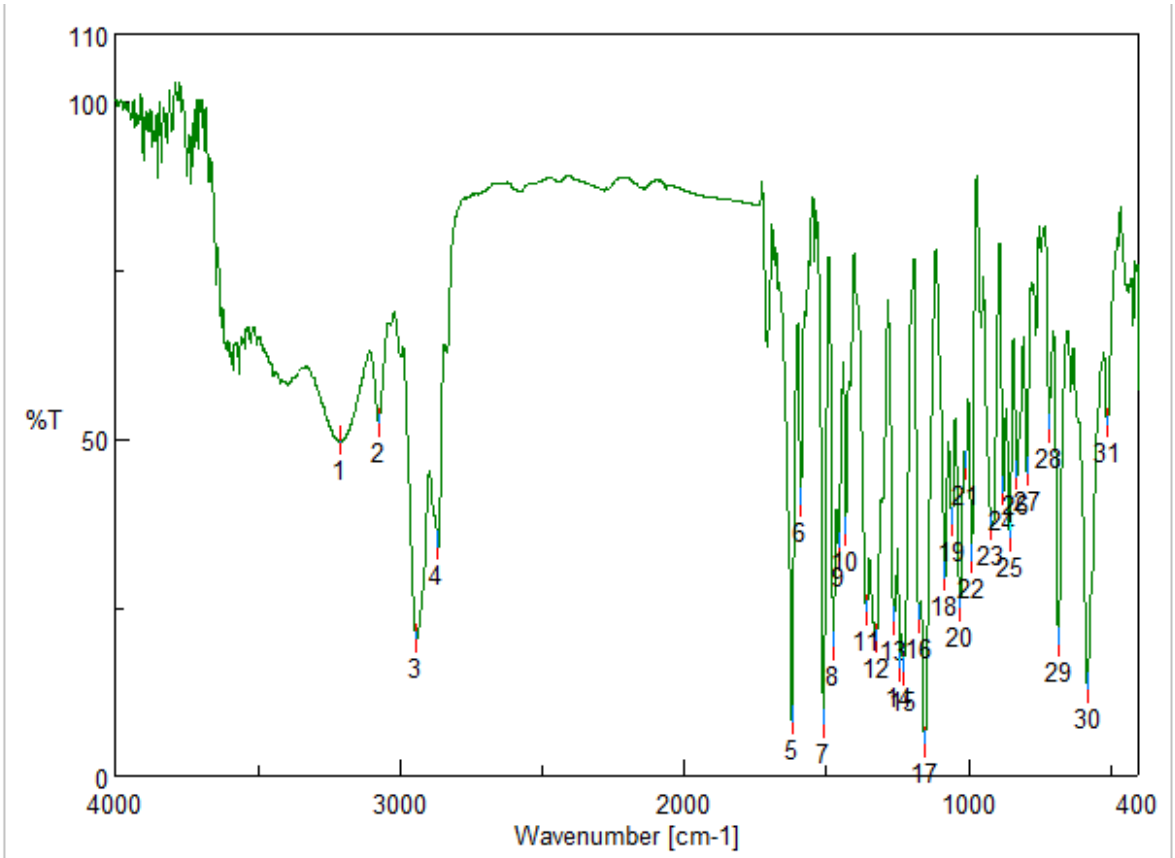


Figure S8: ^{13}C NMR of dimer 3d in $CDCl_3$



[ピーク検出結果]

No.	位置	強度	No.	位置	強度
1	3208.97	49.5825	2	3074.94	52.3647
3	2941.88	20.4648	4	2865.7	34.0954
5	1620.88	8.21066	6	1590.02	40.4174
7	1509.03	7.73583	8	1474.31	19.2547
9	1456.96	33.9789	10	1432.85	36.187
11	1359.57	24.5354	12	1324.86	20.2929
13	1263.15	23.0663	14	1240.97	16.133
15	1228.43	15.5937	16	1174.44	23.2886
17	1153.22	4.98806	18	1082.83	29.5454
19	1058.73	37.5941	20	1029.8	25.0471
21	1010.52	45.8911	22	988.339	32.0735
23	918.914	37.0126	24	877.452	42.1244
25	855.275	35.4195	26	829.241	44.4481
27	794.528	45.0958	28	716.425	51.5053
29	683.642	19.649	30	580.469	13.0113
31	511.044	52.2411			

Figure S9: IR spectra of 3d

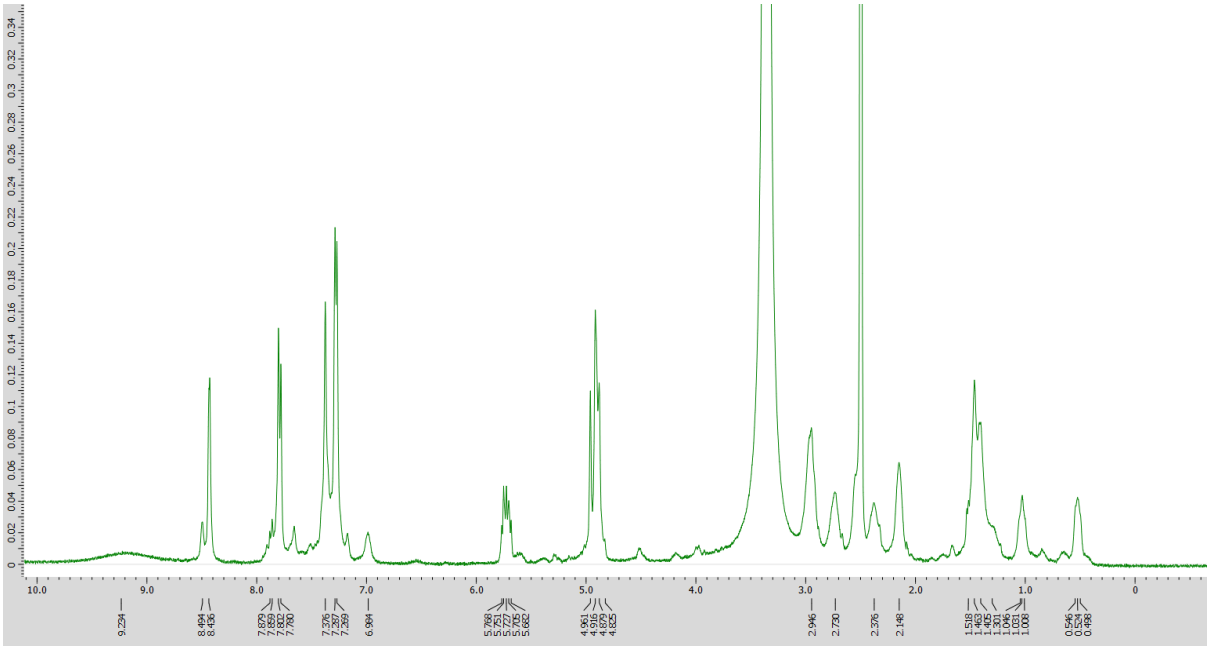


Figure S10: ^{1}H NMR of dimer 3e in DMSO-d_6

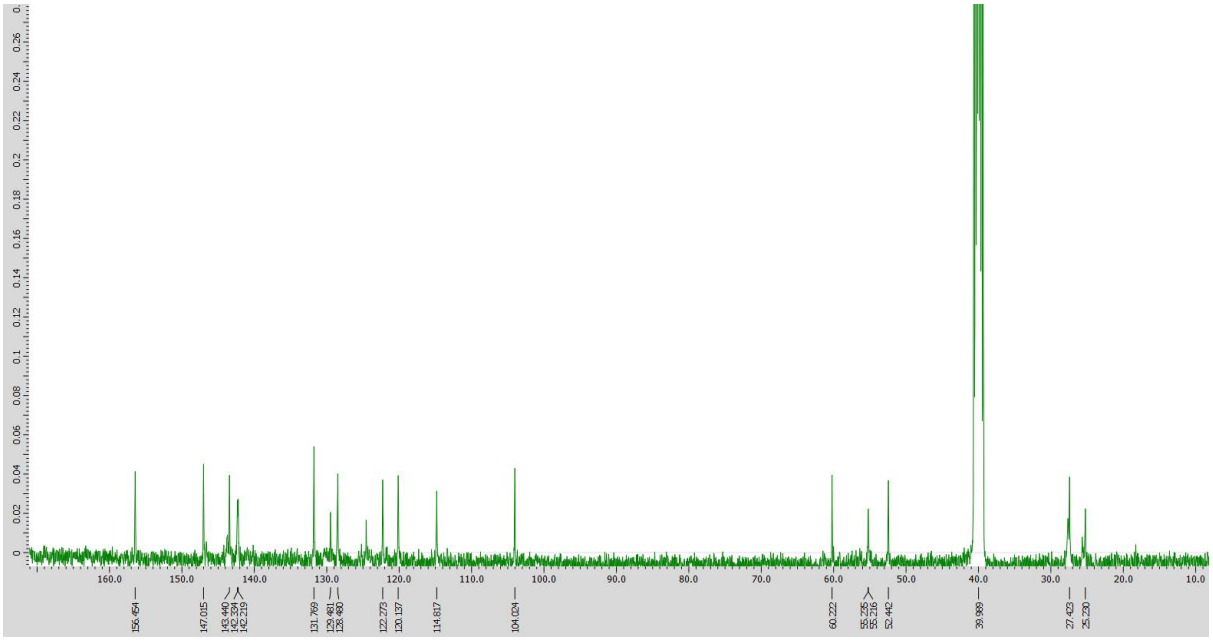
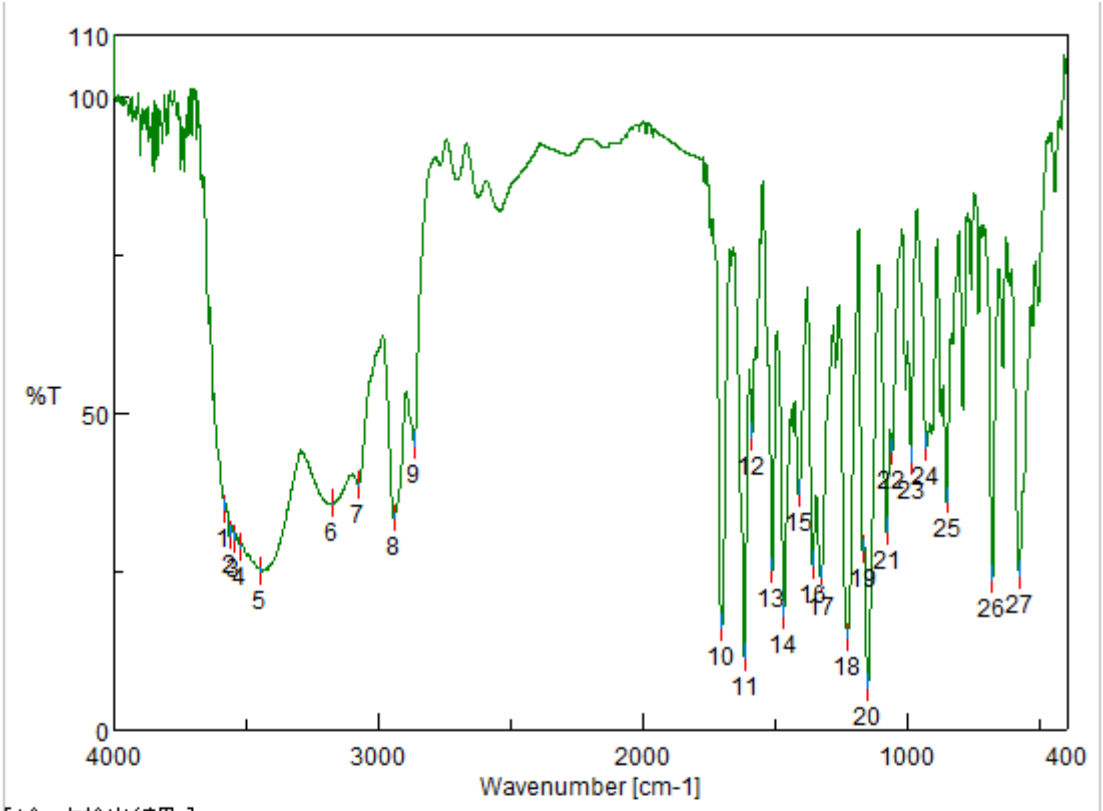


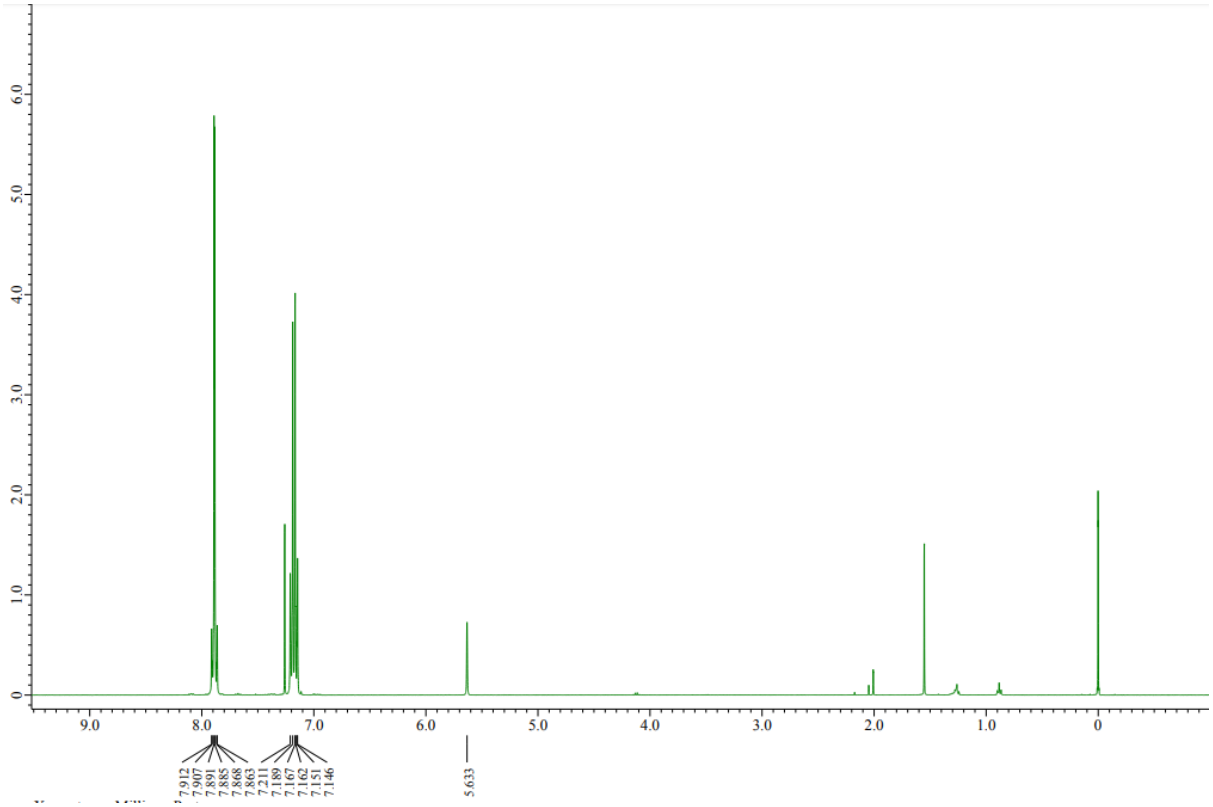
Figure S11: ^{13}C NMR of dimer 3e in DMSO-d_6



[ピーク検出結果]

No.	位置	強度	No.	位置	強度
1	3585.98	34.8344	2	3565.74	30.618
3	3544.52	29.9143	4	3524.27	28.6967
5	3445.21	24.9694	6	3178.11	35.6925
7	3079.76	38.5185	8	2943.8	33.3677
9	2867.63	44.9596	10	1705.73	16.1445
11	1619.91	11.1572	12	1591.95	46.1869
13	1514.81	25.0878	14	1471.42	17.8453
15	1415.49	37.2523	16	1361.5	25.9528
17	1329.68	23.856	18	1230.36	14.5117
19	1173.47	28.3401	20	1153.22	6.40884
21	1082.83	31.1976	22	1061.62	43.8179
23	989.304	42.3098	24	932.414	44.4809
25	855.275	36.1296	26	682.677	23.5699
27	581.433	24.2523			

Figure S12: IR spectra of 3e



FigureS13: ^{1}H NMR of dimer 9b in $CDCl_3$

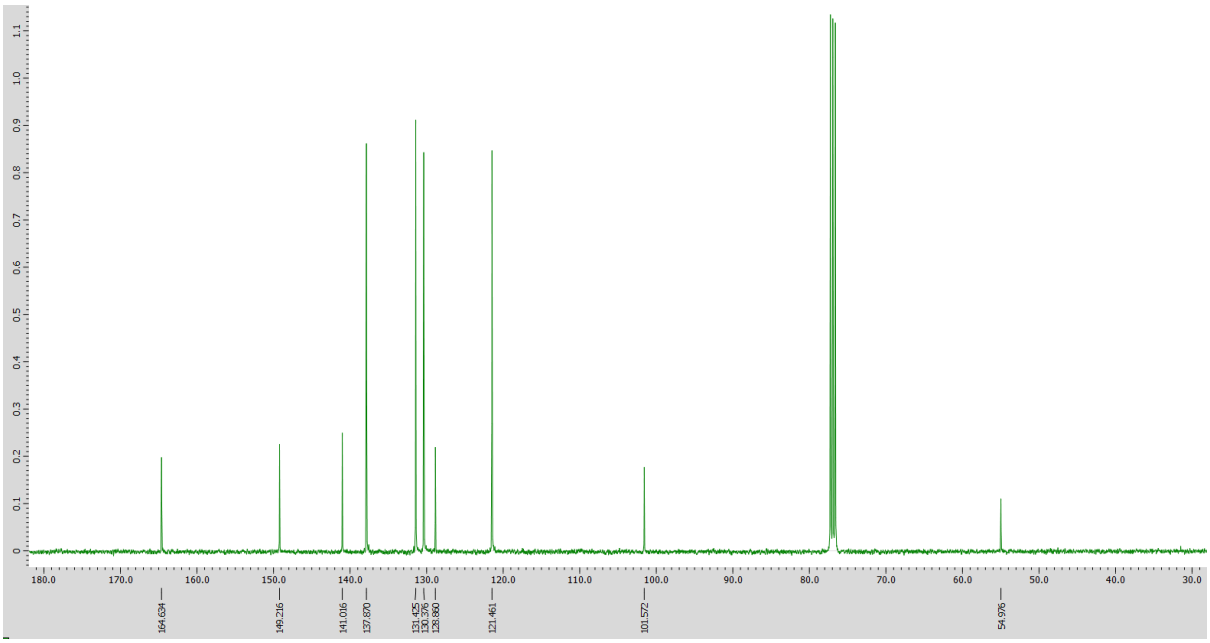


Figure S14: ^{13}C NMR of dimer 9b in $CDCl_3$

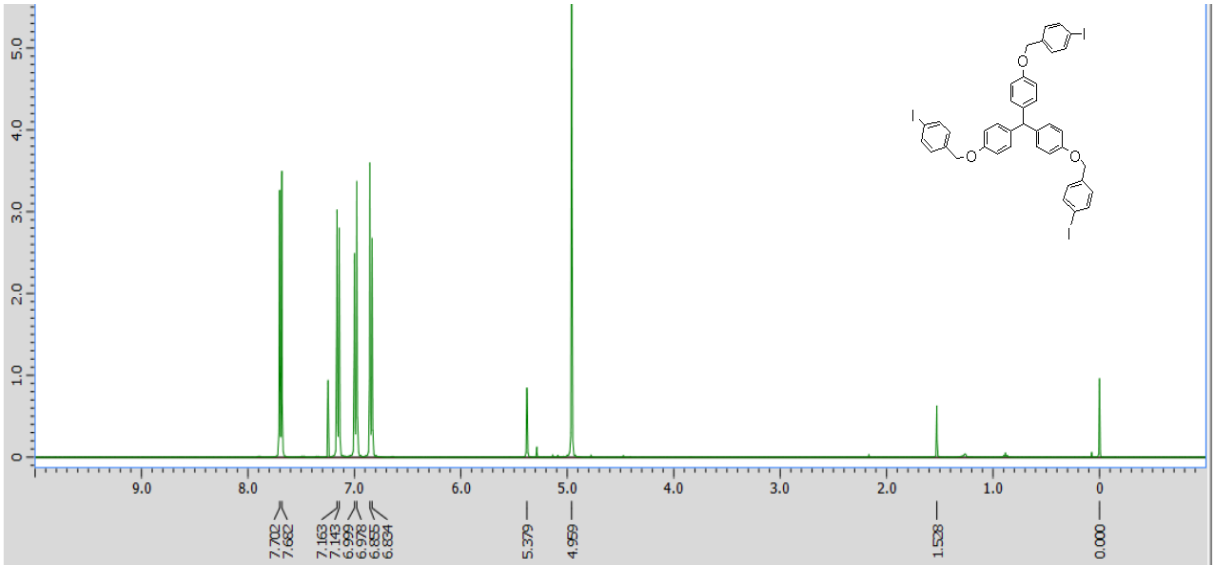


Figure S15: ^{1}H NMR of dimer 9c in $CDCl_3$

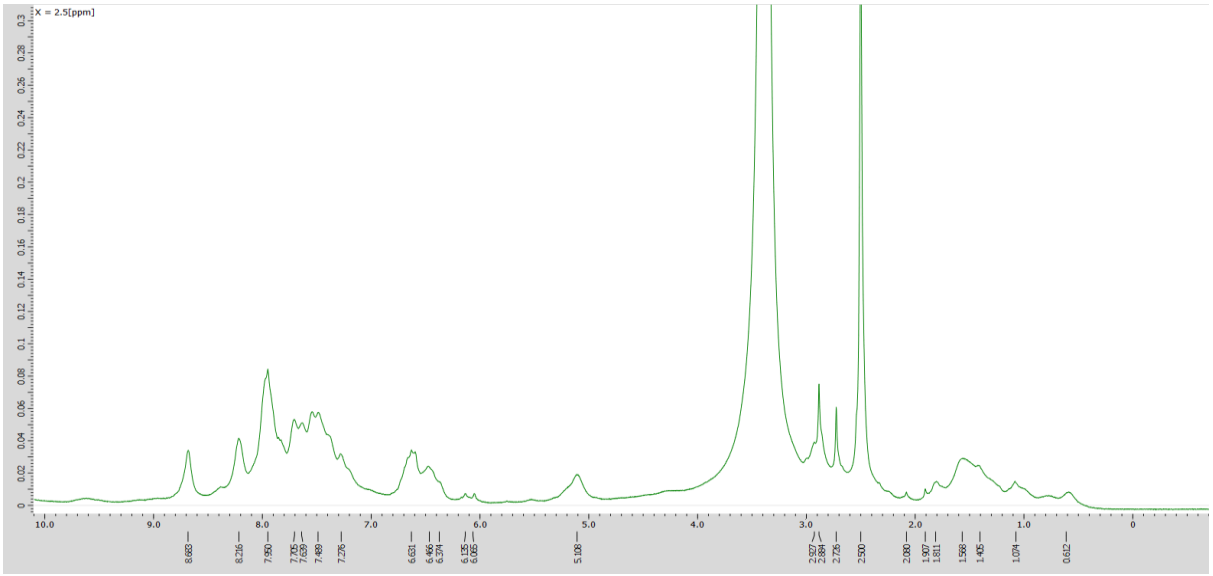
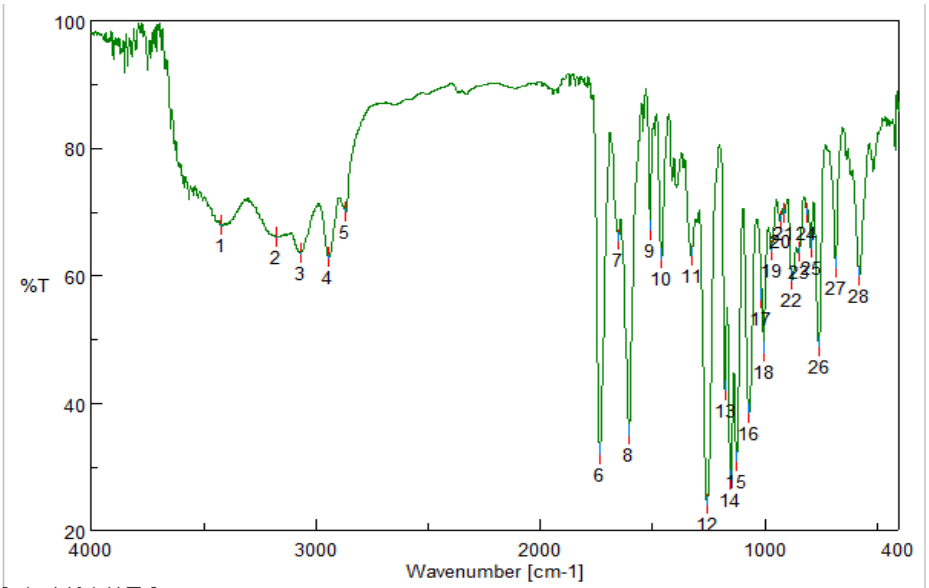


Figure S16: ^{1}H NMR of polymer P1-3a in DMSO-d_6



[ピーク検出結果]

No.	位置	強度	No.	位置	強度
1	3421.1	67.7696	2	3178.11	66.0801
3	3067.23	63.4316	4	2942.84	62.8435
5	2865.7	70.0645	6	1733.69	31.996
7	1652.7	65.5369	8	1604.48	35.0179
9	1509.03	67.0836	10	1458.89	62.5968
11	1327.75	63.1756	12	1257.36	24.1271
13	1177.33	42.0062	14	1151.29	27.9218
15	1125.26	30.9054	16	1069.33	38.3881
17	1015.34	56.313	18	1004.73	47.9455
19	970.983	63.8266	20	931.45	68.582
21	912.165	69.7471	22	877.452	59.2455
23	849.49	63.6317	24	812.849	69.7326
25	794.528	64.2975	26	758.852	48.9234
27	683.642	61.2829	28	577.576	59.9945

Figure S17: IR spectra of polymer P1-3a

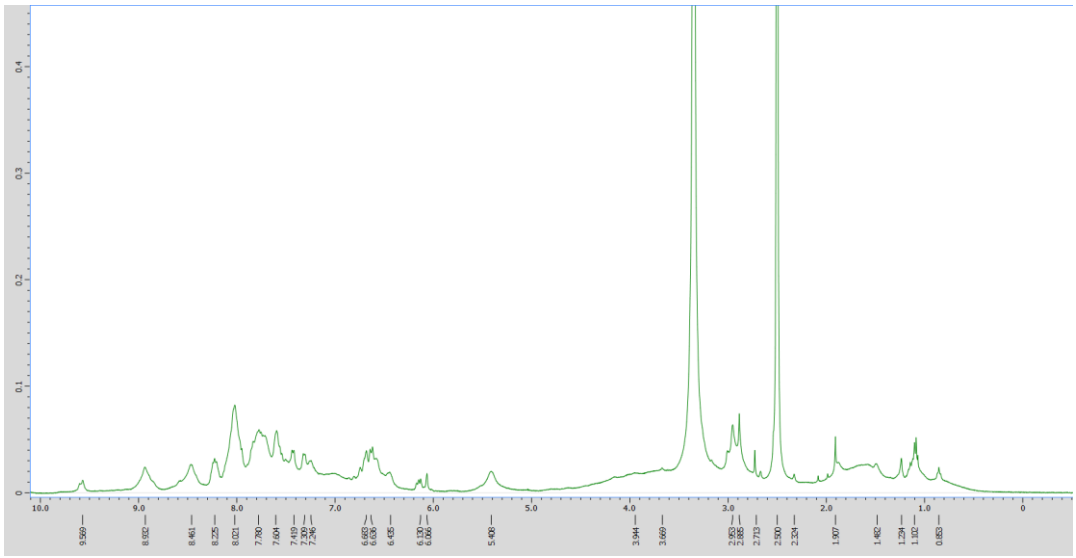
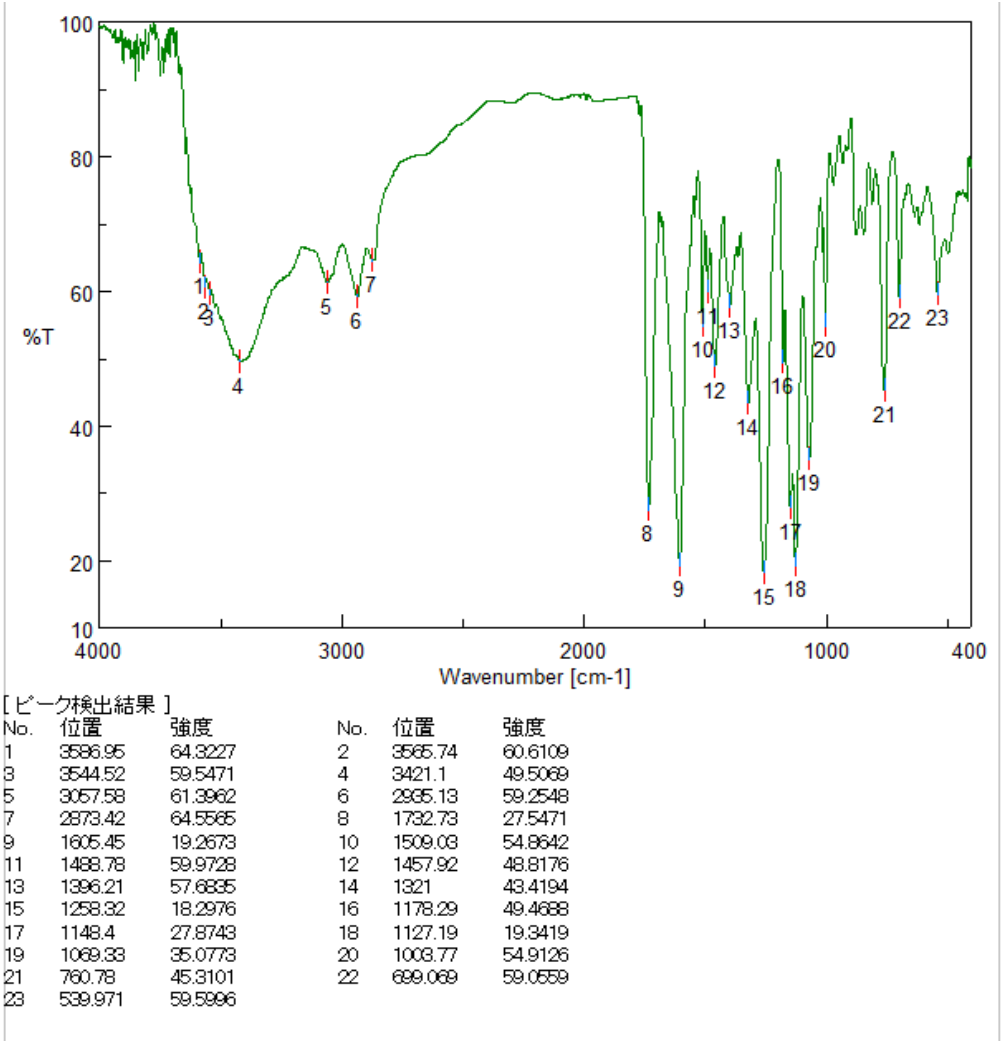


Figure S18: ^{1}H NMR of polymer P2-3b in DMSO-d_6



[ピーク検出結果]

No.	位置	強度	No.	位置	強度
1	3586.95	64.3227	2	3565.74	60.6109
3	3544.52	59.5471	4	3421.1	49.5069
5	3057.58	61.3962	6	2935.13	59.2548
7	2873.42	64.5565	8	1732.73	27.5471
9	1605.45	19.2673	10	1509.03	54.8642
11	1488.78	59.9728	12	1457.92	48.8176
13	1396.21	57.6835	14	1321	43.4194
15	1258.32	18.2976	16	1178.29	49.4688
17	1148.4	27.8743	18	1127.19	19.3419
19	1069.33	35.0773	20	1008.77	54.9126
21	760.78	45.3101	22	699.069	59.0559
23	539.971	59.5996			

Figure S19: IR spectra of polymer P2-3b

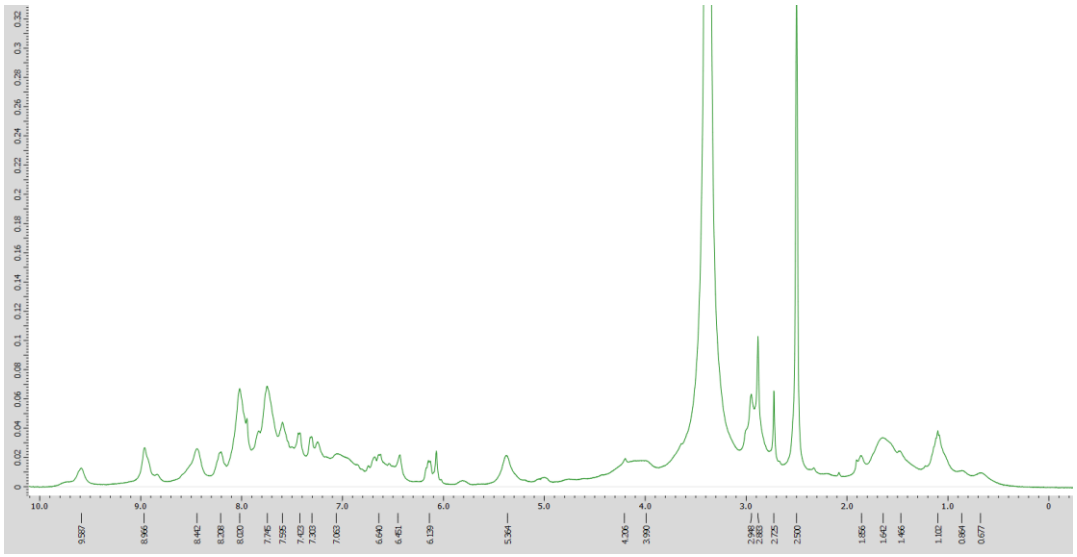
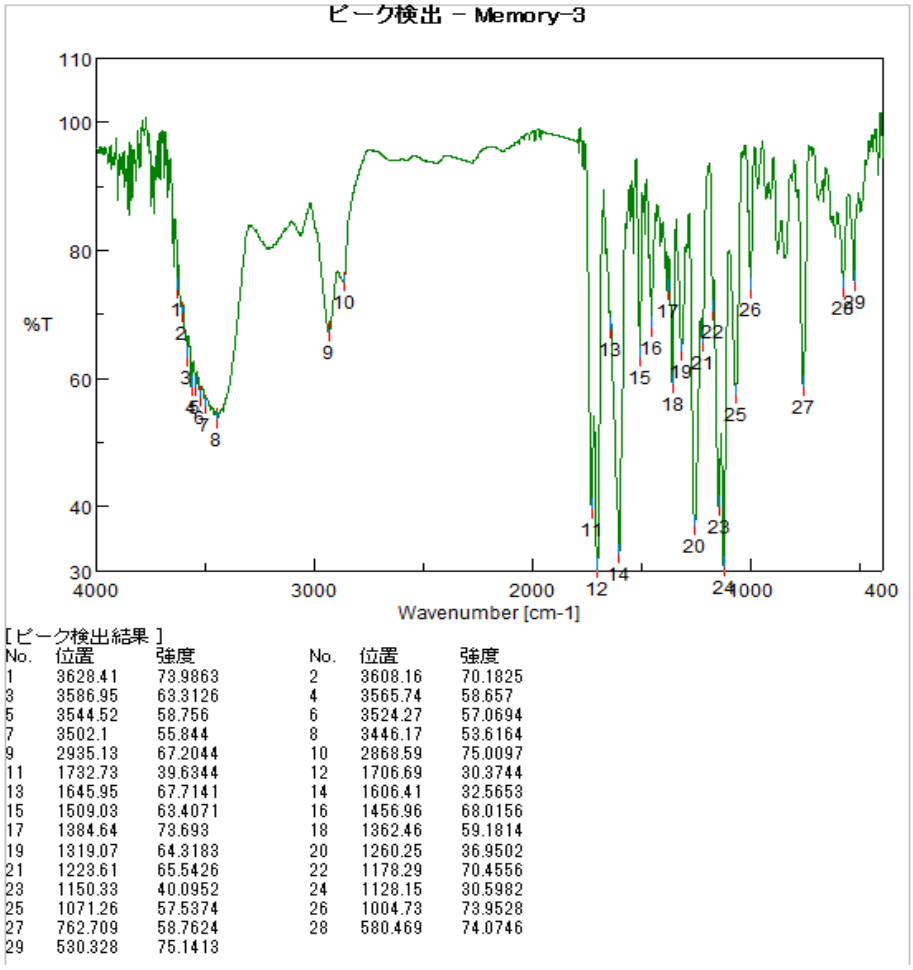


Figure S20: ^{1}H NMR of polymer P3-3c in DMSO-d_6



[ピーク検出結果]

No.	位置	強度	No.	位置	強度
1	3628.41	73.9863	2	3608.16	70.1825
3	3586.95	63.3126	4	3565.74	58.657
5	3544.52	58.756	6	3524.27	57.0694
7	3502.1	55.844	8	3446.17	53.6164
9	2935.13	67.2044	10	2868.59	75.0097
11	1732.73	39.6344	12	1706.69	30.3744
13	1645.95	67.7141	14	1606.41	32.5653
15	1509.03	63.4071	16	1456.96	68.0156
17	1384.64	73.693	18	1362.46	59.1814
19	1319.07	64.3183	20	1260.25	36.9502
21	1223.61	65.5426	22	1178.29	70.4556
23	1150.33	40.0952	24	1128.15	30.5982
25	1071.26	57.5374	26	1004.73	73.9528
27	762.709	58.7624	28	580.469	74.0746
29	530.328	75.1413			

Figure S21: IR spectra of polymer P3-3c

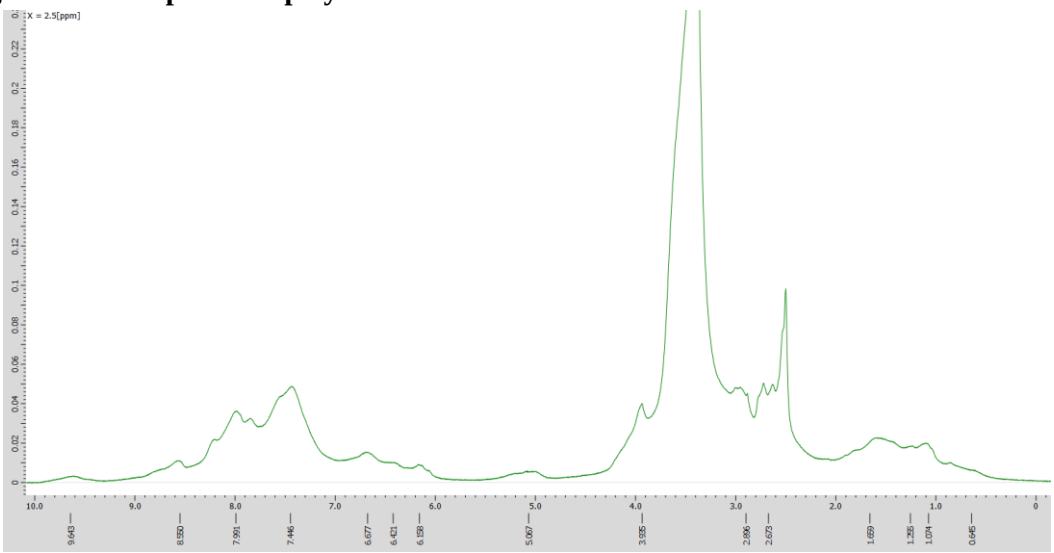
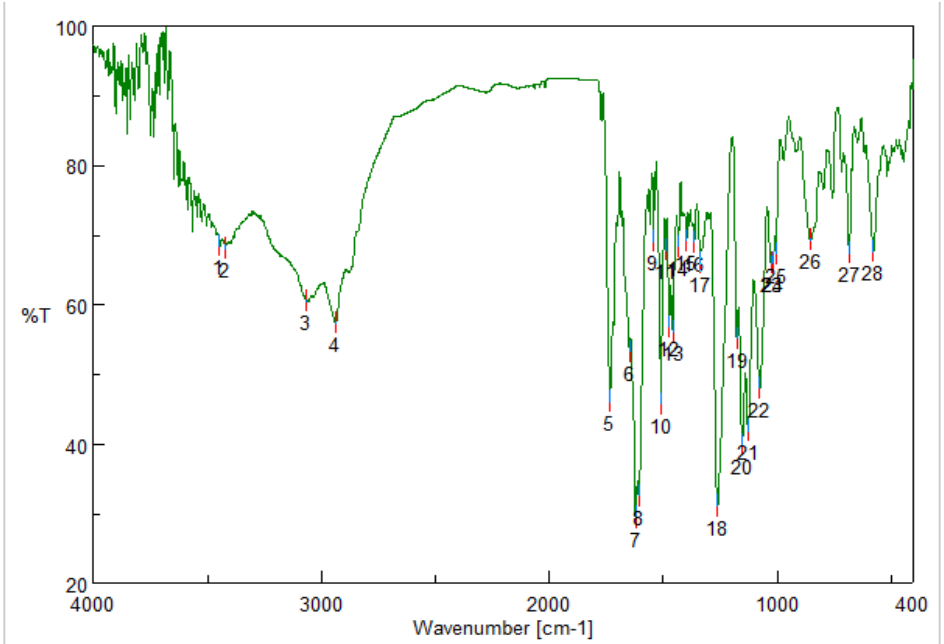


Figure S22: ^{1}H NMR of polymer P4-3d in DMSO-d_6



[ピーク検出結果]

No.	位置	強度	No.	位置	強度
1	3446.17	68.4717	2	3420.14	68.0903
3	3065.3	60.5185	4	2937.06	57.4165
5	1732.73	46.0636	6	1646.91	53.3167
7	1620.88	29.4895	8	1607.38	32.5417
9	1541.81	69.1186	10	1508.06	45.7343
11	1488.78	67.794	12	1473.35	56.8753
13	1456.96	56.1294	14	1434.78	68.3822
15	1396.21	69.2113	16	1362.46	69.0345
17	1338.36	65.9918	18	1261.22	31.1567
19	1177.33	55.1806	20	1152.26	39.8981
21	1127.19	41.8249	22	1075.12	48.1059
23	1026.91	65.9319	24	1017.27	66.0805
25	1005.7	67.3496	26	854.311	69.2463
27	683.642	67.373	28	576.612	67.6449

Figure S23: IR spectra of polymer P4-3d

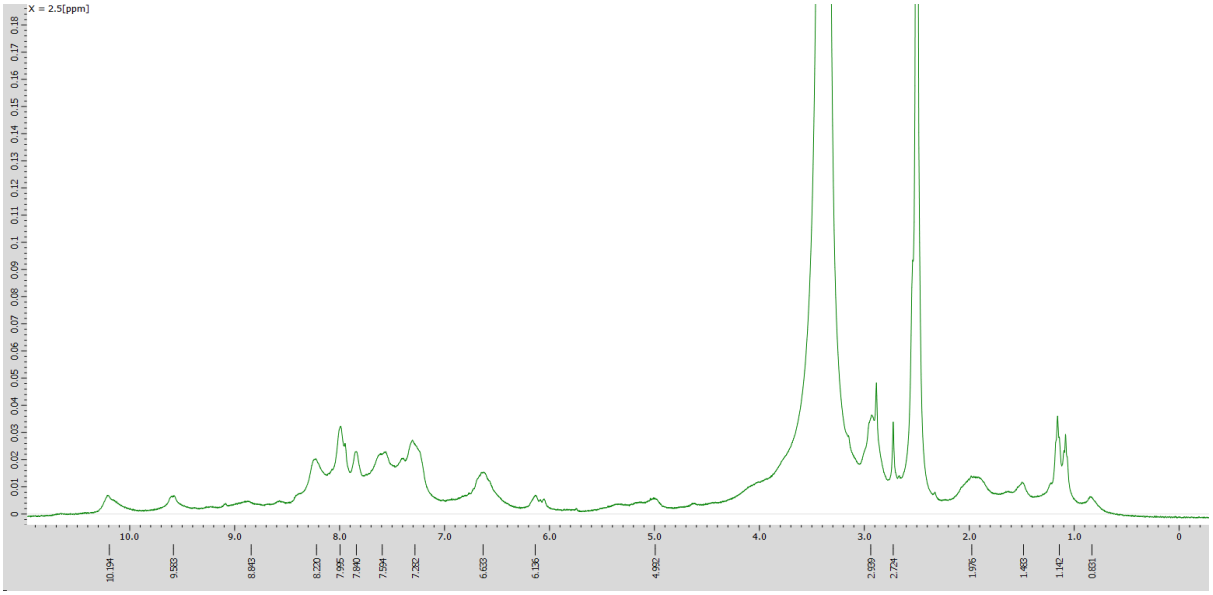
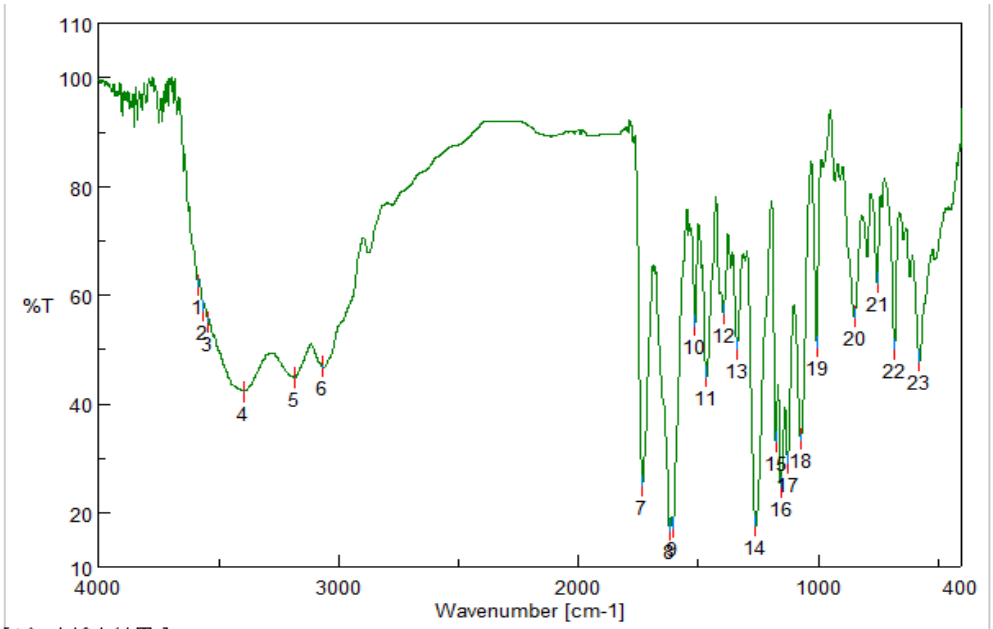


Figure S24: ^{1}H NMR of polymer P5-3e in DMSO-d_6



[ピーク検出結果]

No.	位置	強度	No.	位置	強度
1	3585.98	61.706	2	3565.74	57.0699
3	3544.52	55.0293	4	3393.14	42.2434
5	3181.01	44.7771	6	3064.33	46.7667
7	1731.76	24.9644	8	1618.95	16.7325
9	1606.41	17.2409	10	1513.85	54.4132
11	1465.63	44.9814	12	1395.25	56.5266
13	1338.36	50.0629	14	1260.25	17.6333
15	1177.33	33.0557	16	1154.19	24.6477
17	1126.22	29.0535	18	1071.26	33.381
19	1005.7	50.4369	20	847.561	55.8764
21	753.066	62.1382	22	681.713	49.9889
23	576.612	47.8593			

Figure S25: IR spectra of polymer P5-3e

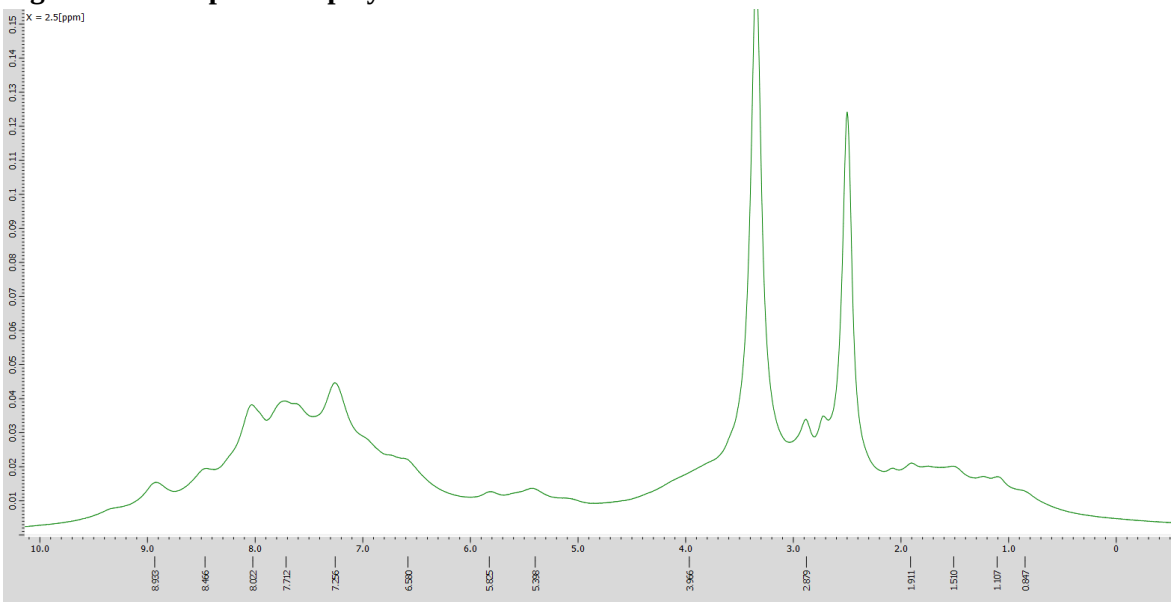
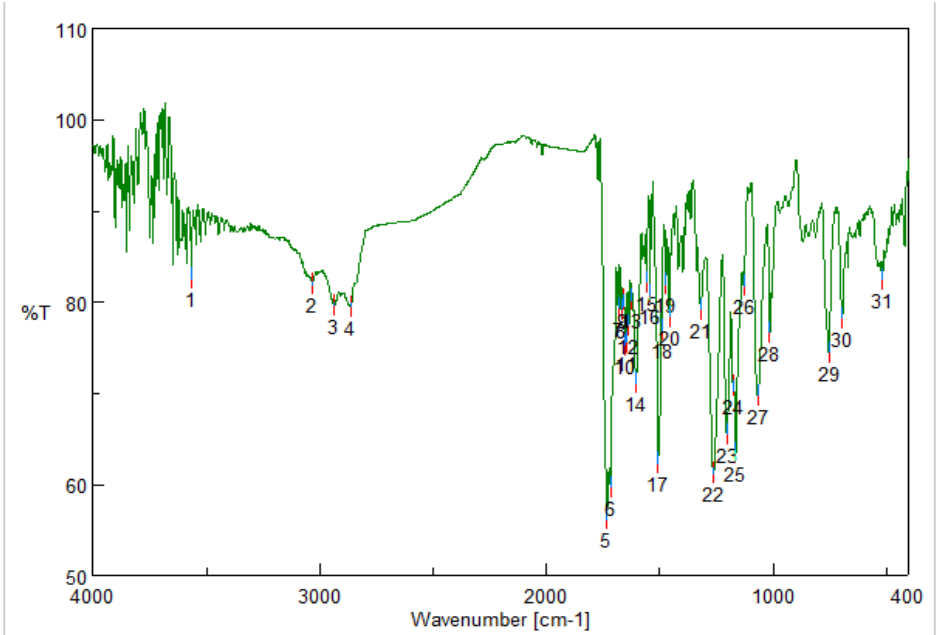


Figure S26: ^{1}H NMR of polymer P6-3b in DMSO-d_6



[ピーク検出結果]

No.	位置	強度	No.	位置	強度
1	3566.7	82.5654	2	3032.51	81.917
3	2933.2	79.6236	4	2863.77	79.4472
5	1732.73	56.2194	6	1717.3	59.7382
7	1683.55	79.3715	8	1669.09	79.2056
9	1661.37	80.2369	10	1652.7	75.2569
11	1646.91	75.587	12	1636.3	77.4434
13	1623.77	80.235	14	1604.48	71.1516
15	1558.2	82.1455	16	1541.81	80.7667
17	1507.1	62.302	18	1489.74	76.9377
19	1473.35	81.9714	20	1456.96	78.3857
21	1318.11	79.22	22	1262.18	61.2393
23	1203.36	65.5457	24	1176.36	70.7721
25	1164.79	63.404	26	1129.12	81.7984
27	1067.41	69.8071	28	1014.37	76.6994
29	754.031	74.4674	30	695.212	78.2319
31	517.798	82.5215			

Figure S27: IR spectra of polymer P6-3b

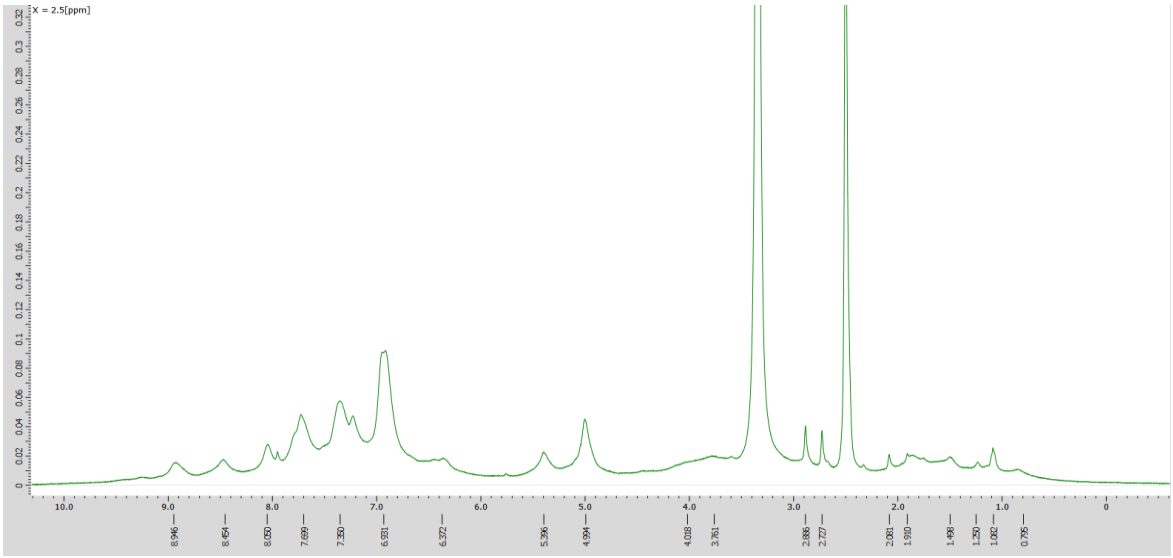
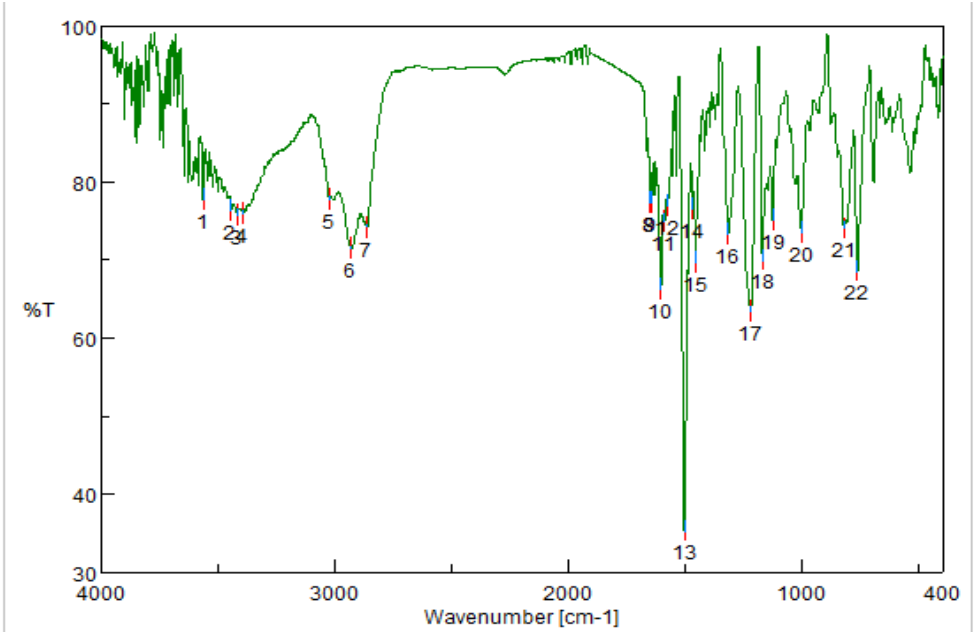


Figure S28: ^{1}H NMR of polymer P7-3b in DMSO-d_6



[ピーク検出結果]

No.	位置	強度	No.	位置	強度
1	3565.74	77.7366	2	3446.17	76.2632
3	3420.14	75.703	4	3393.14	75.9664
5	3023.84	77.6844	6	2931.27	71.4329
7	2864.74	74.1691	8	1652.7	77.2748
9	1646.91	77.3135	10	1606.41	66.1887
11	1590.99	74.9188	12	1576.52	76.9432
13	1506.13	35.234	14	1472.38	76.5018
15	1456.96	69.6829	16	1317.14	73.2987
17	1222.65	63.3961	18	1172.51	69.9431
19	1128.15	75.1965	20	1004.73	73.4484
21	822.491	74.0003	22	764.637	68.5418

Figure S29: IR spectra of polymer P7-3b

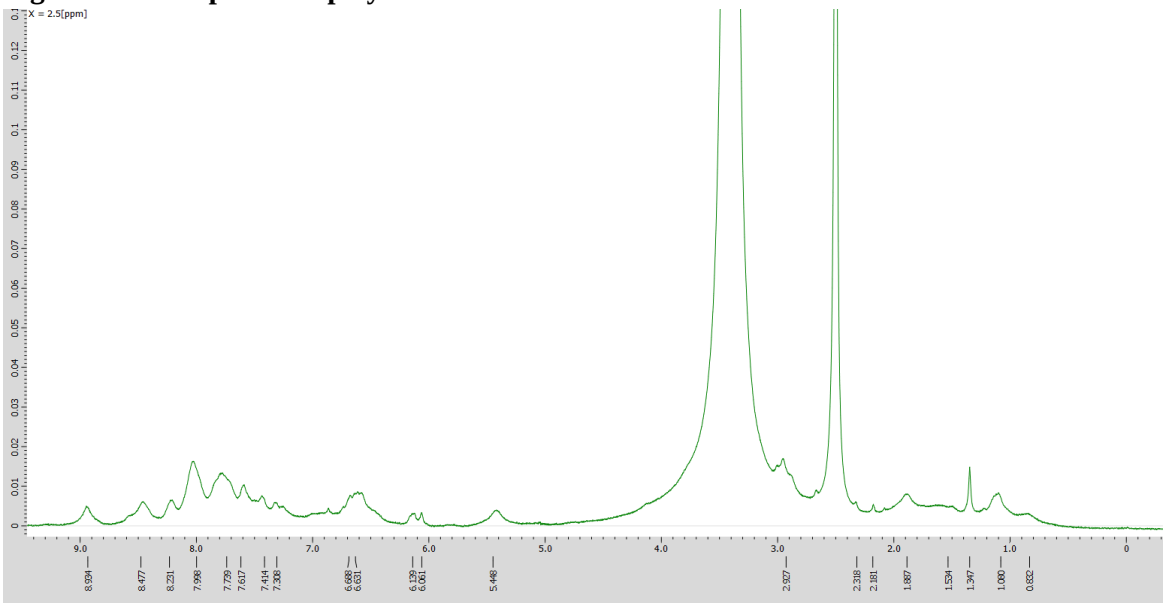
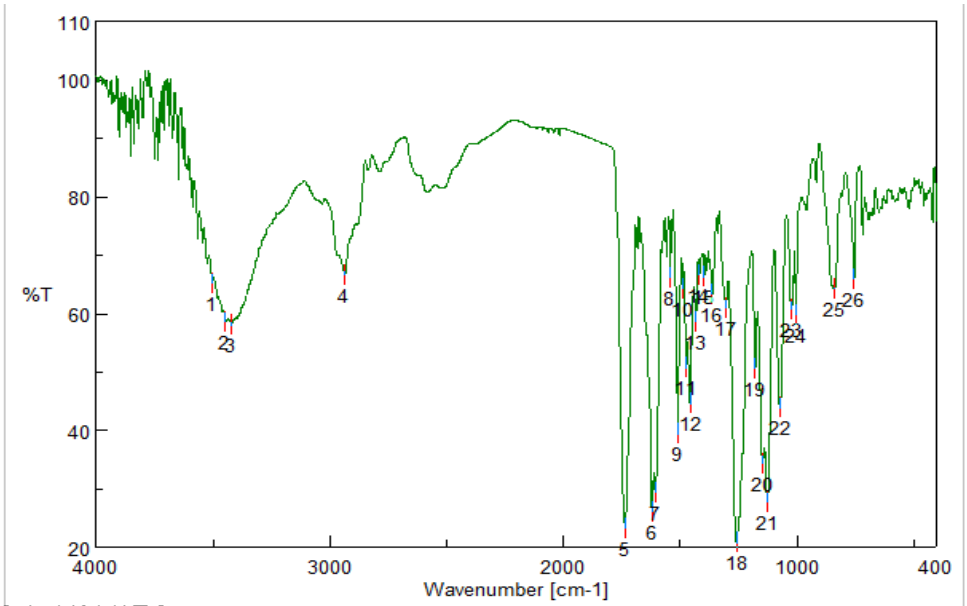


Figure S30: ^{1}H NMR of polymer P8-6a in DMSO-d_6



[ピーク検出結果]

No.	位置	強度	No.	位置	強度
1	3502.1	65.2045	2	3446.17	58.5591
3	3420.14	58.0403	4	2935.13	66.65
5	1733.69	23.3414	6	1619.91	26.1609
7	1606.41	29.4278	8	1540.85	66.1575
9	1508.06	39.4946	10	1488.78	64.236
11	1473.35	50.795	12	1456.96	44.6228
13	1433.82	58.5953	14	1417.42	66.6641
15	1396.21	66.2635	16	1382.46	63.289
17	1304.61	61.0188	18	1258.32	20.8306
19	1178.29	50.5778	20	1146.47	34.3433
21	1126.22	27.7531	22	1072.23	43.9901
23	1024.02	60.765	24	1003.77	59.7663
25	838.883	64.2868	26	754.995	65.911

Figure S31: IR spectra of polymer P8-6a

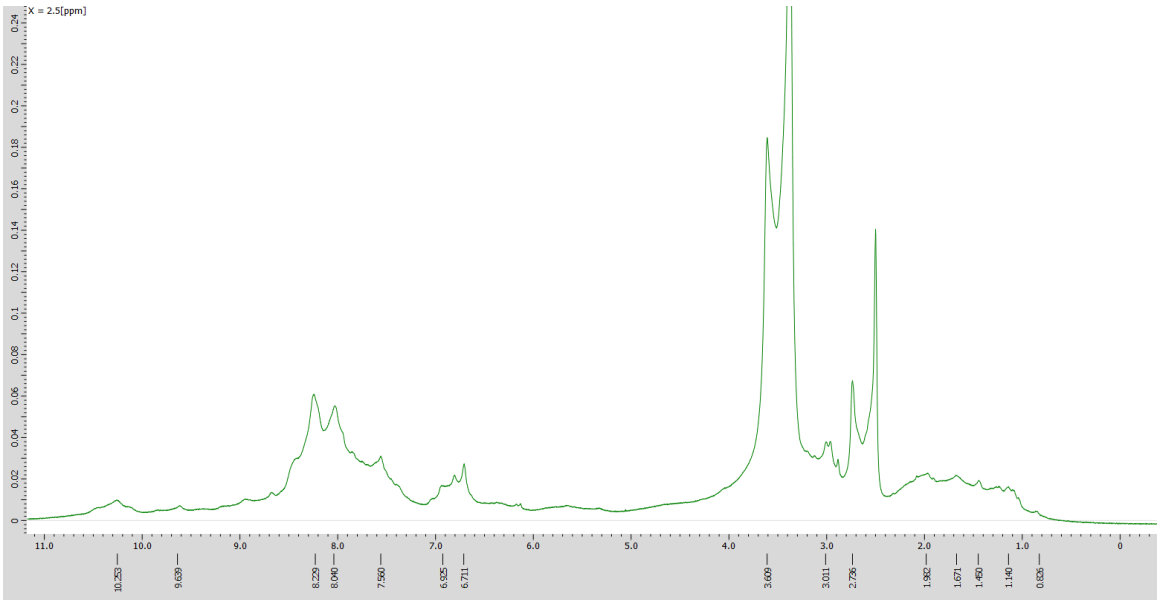
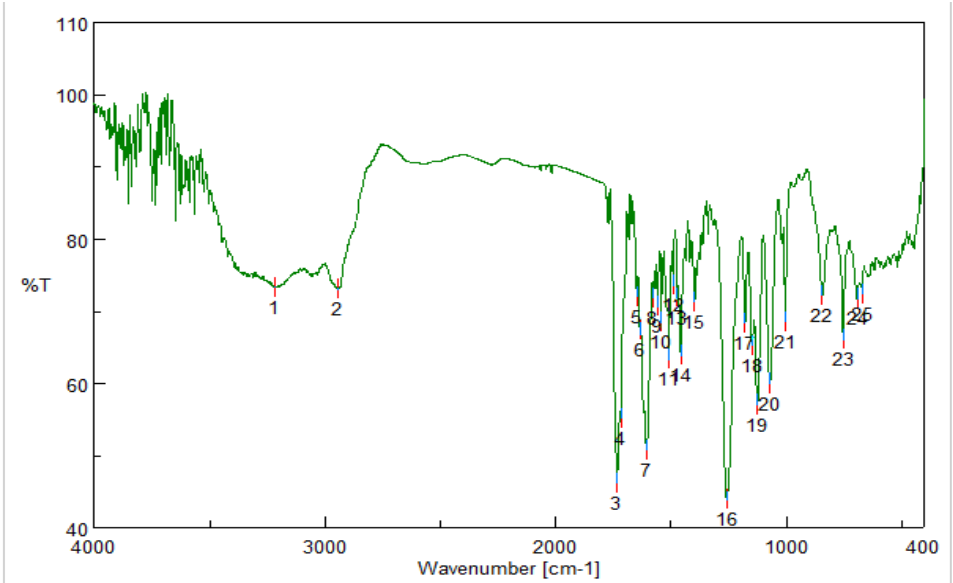


Figure S32: ^{1}H NMR of polymer P9-6b in DMSO-d_6



[ピーク検出結果]

No.	位置	強度	No.	位置	強度
1	3218.61	73.3237	2	2945.73	73.0754
3	1732.73	46.2031	4	1717.3	55.1865
5	1646.91	72.0886	6	1635.34	67.429
7	1605.45	50.8348	8	1576.52	71.9081
9	1558.2	70.6861	10	1540.85	68.4574
11	1508.06	63.3714	12	1488.78	73.6452
13	1472.38	71.8966	14	1456.96	63.8989
15	1396.21	71.3279	16	1258.32	43.9585
17	1178.29	68.3731	18	1148.4	65.2614
19	1124.3	57.0735	20	1070.3	60.0034
21	1003.77	68.5698	22	843.704	72.1965
23	753.066	66.1188	24	692.32	71.7868
25	669.178	72.3715			

Figure S33: IR spectra of polymer P9-6b

HPLC data of the products obtained from Enantioselective Michael Addition of Methyl 2-oxocyclopentanecarboxylate, 11 to *trans*-β-Nitrostyrene, 12

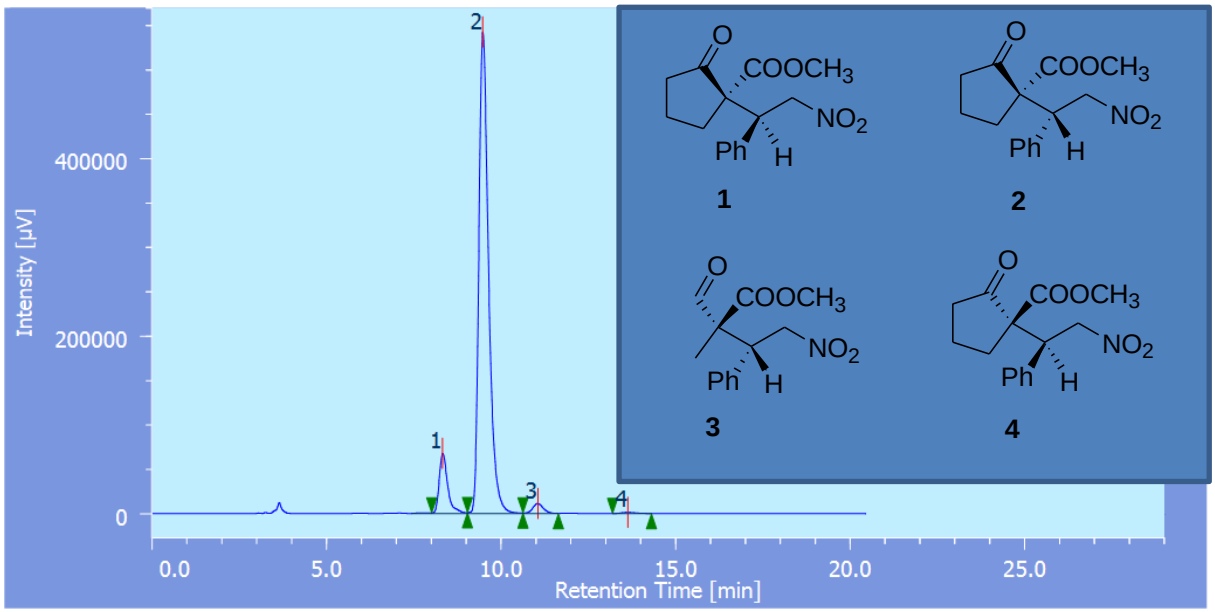


Figure S34: HPLC chromatogram of asymmetric compound, 13

Table 2, entry 1

99% *ee*

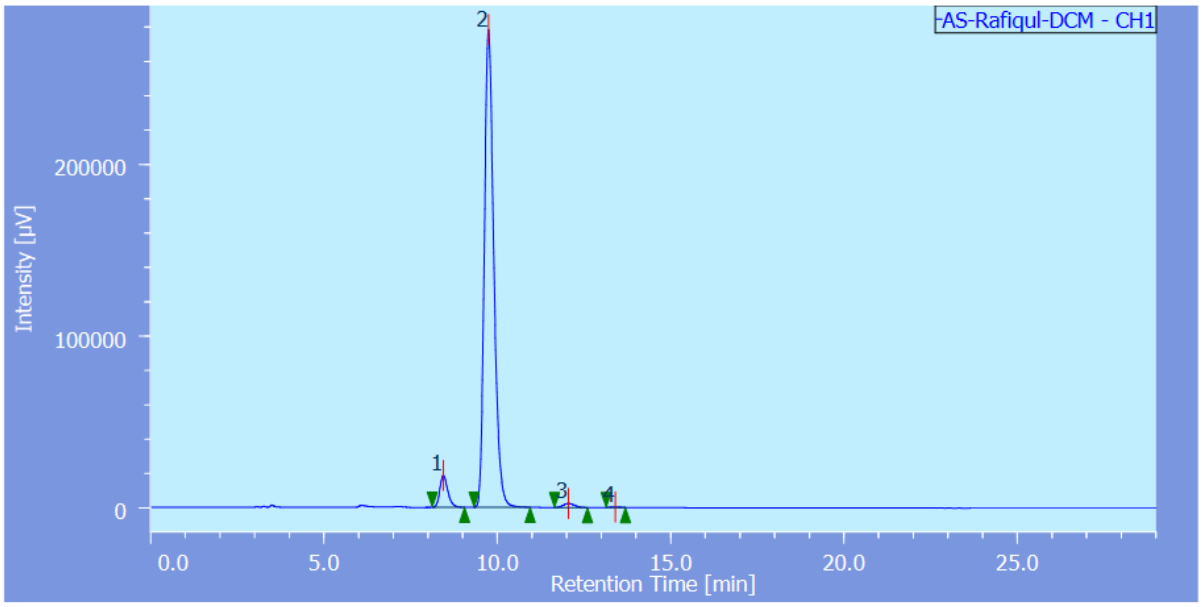


Figure S35: HPLC chromatogram of asymmetric compound, 13

Table 2, entry 2

99% *ee*

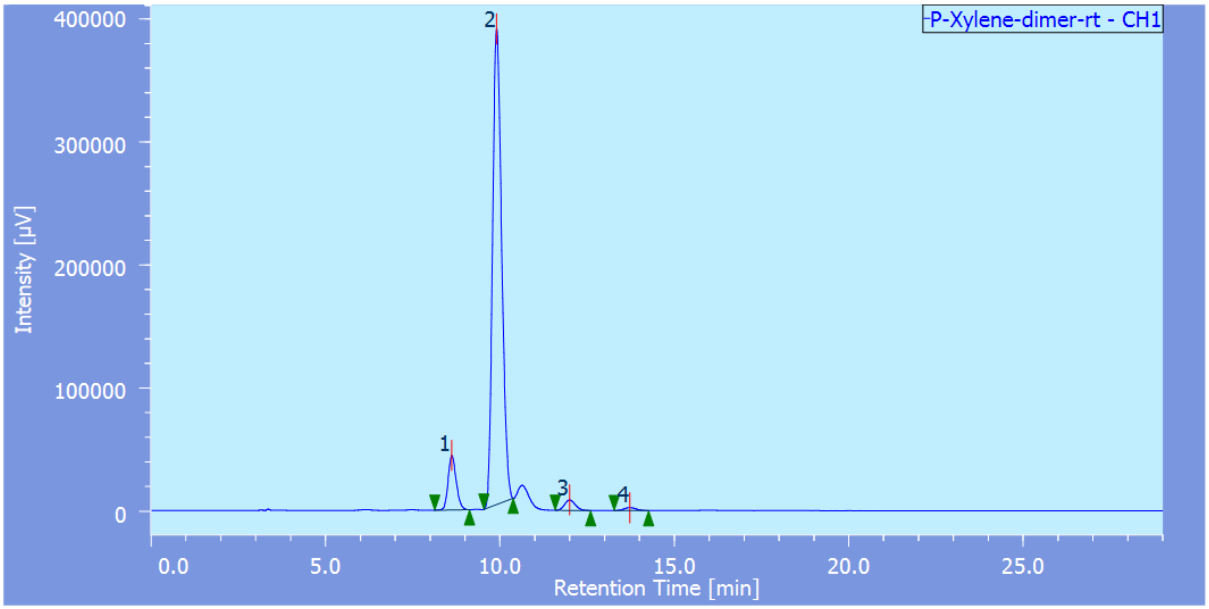


Figure S36: HPLC chromatogram of asymmetric compound, 13

Table 2, entry 3

98% *ee*

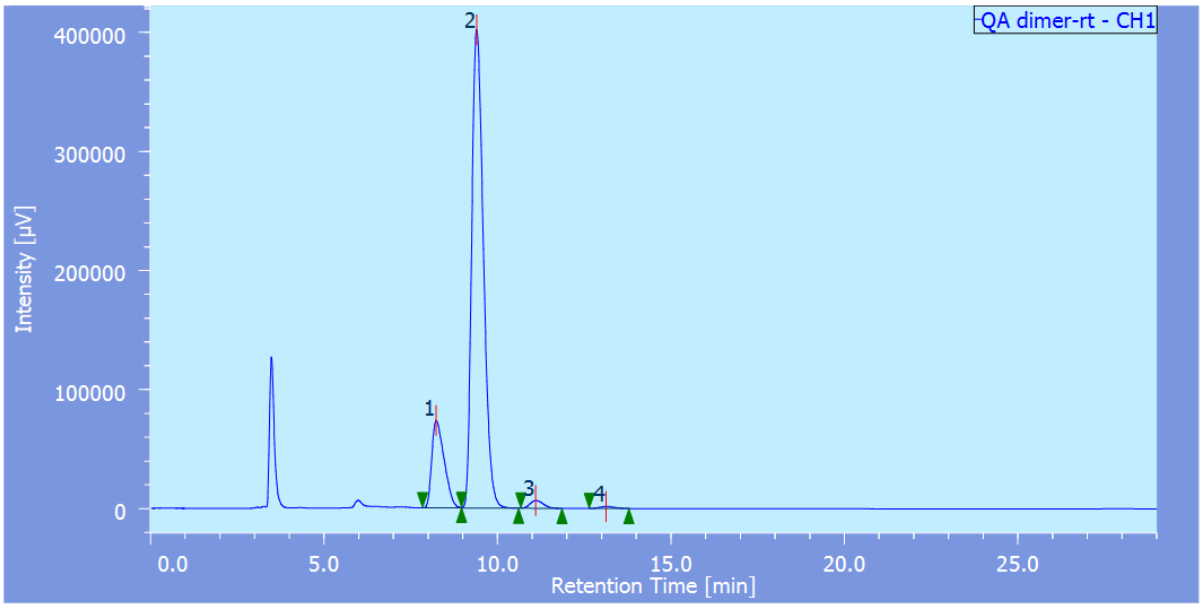


Figure S37: HPLC chromatogram of asymmetric compound, 13
Table 2, entry 4
99% *ee*

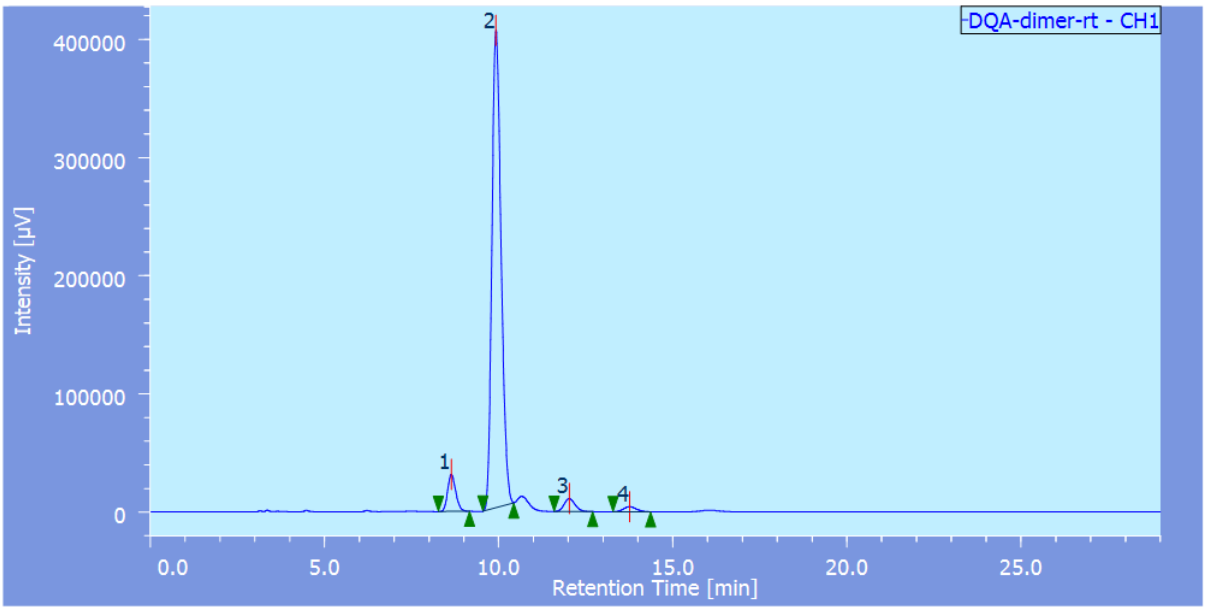


Figure S38: HPLC chromatogram of asymmetric compound, 13
Table 2, entry 5
97% *ee*

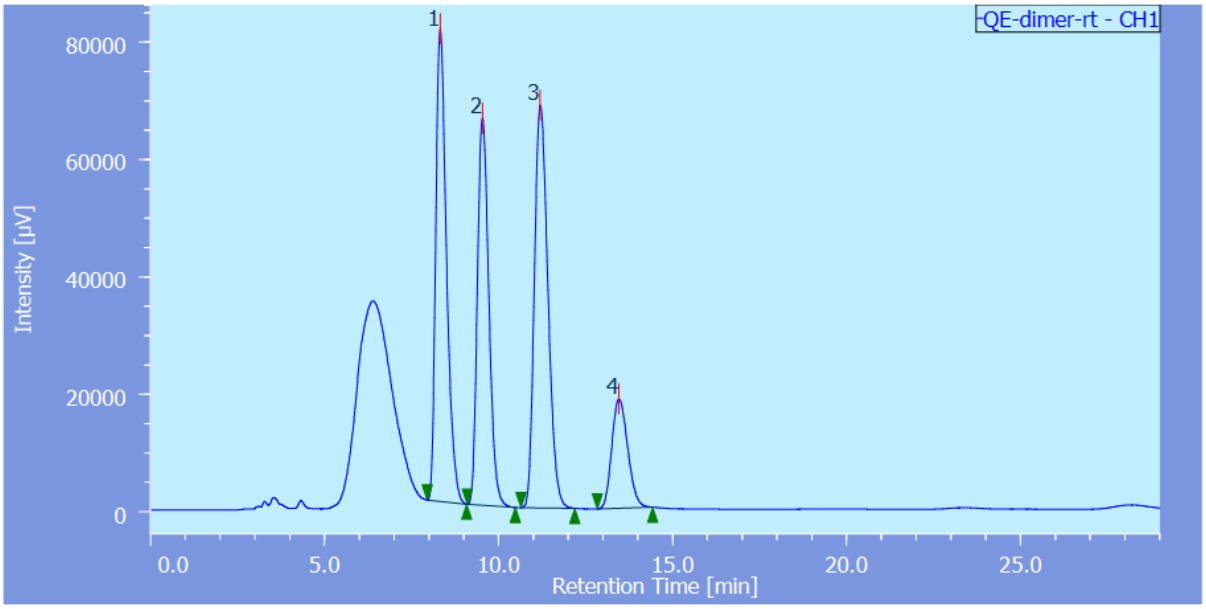


Figure S39: HPLC chromatogram of asymmetric compound, 13
Table 2, entry 6
44% *ee*

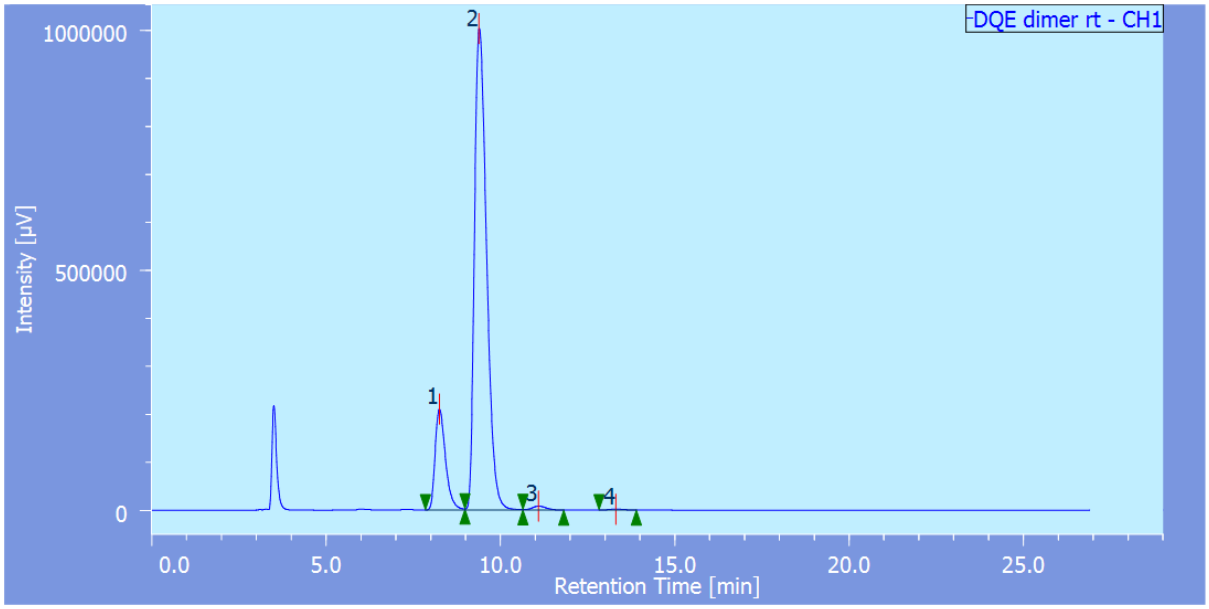


Figure S40: HPLC chromatogram of asymmetric compound, 13
Table 2, entry 7
99% *ee*

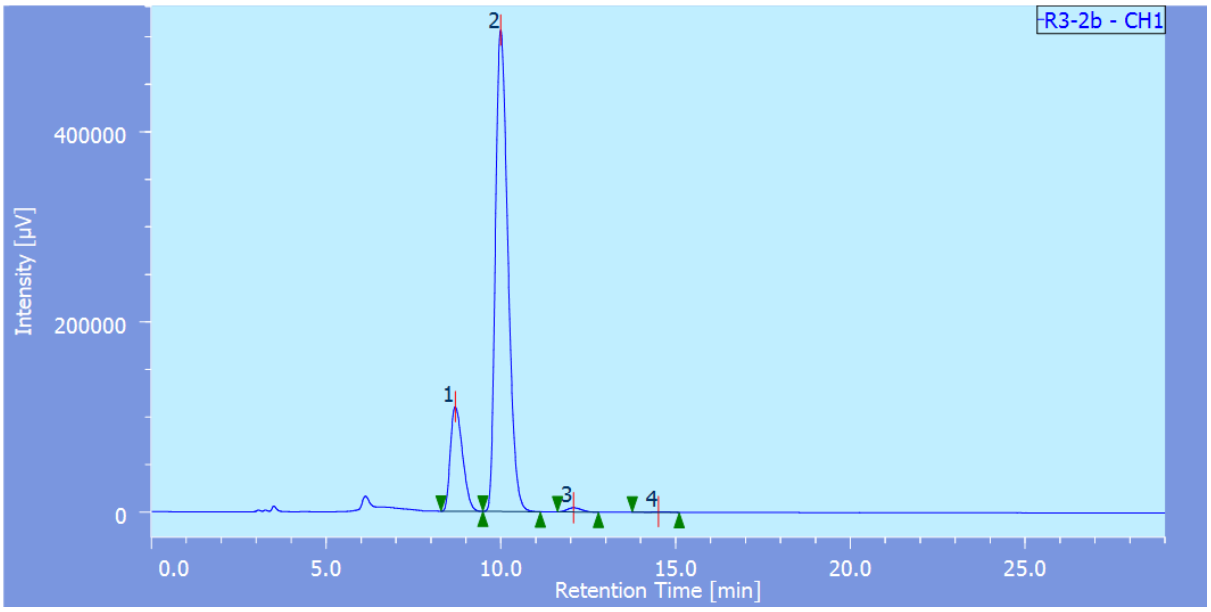


Figure S41: HPLC chromatogram of asymmetric compound, 13
Table 3, entry 1
99% *ee*

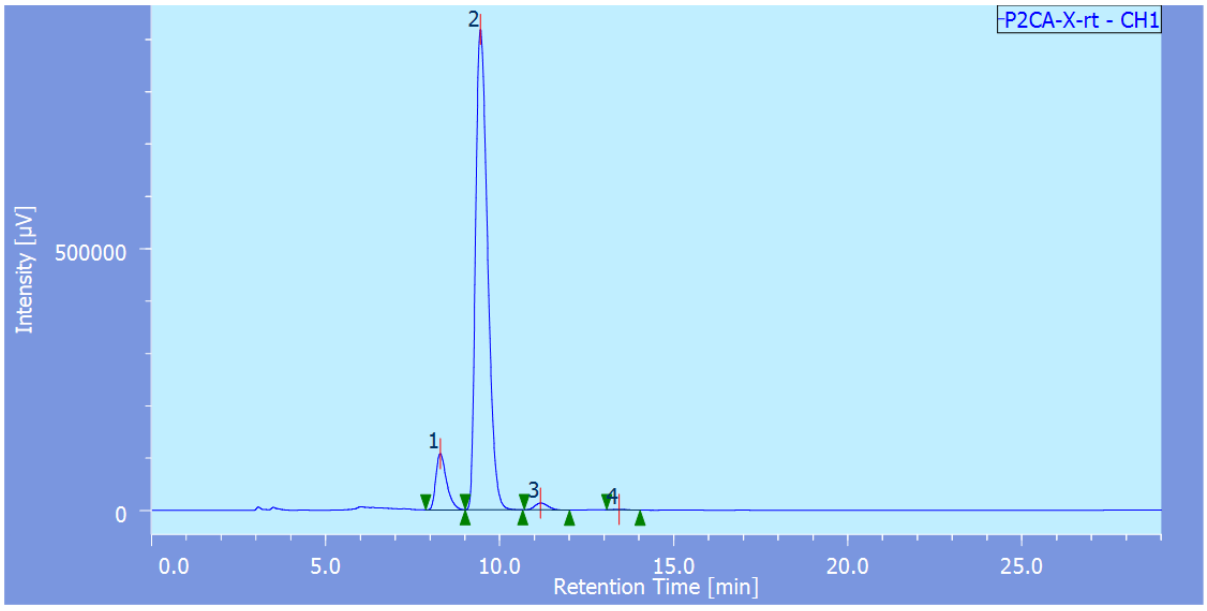


Figure S42: HPLC chromatogram of asymmetric compound, 13
Table 3, entry 2
>99% *ee*

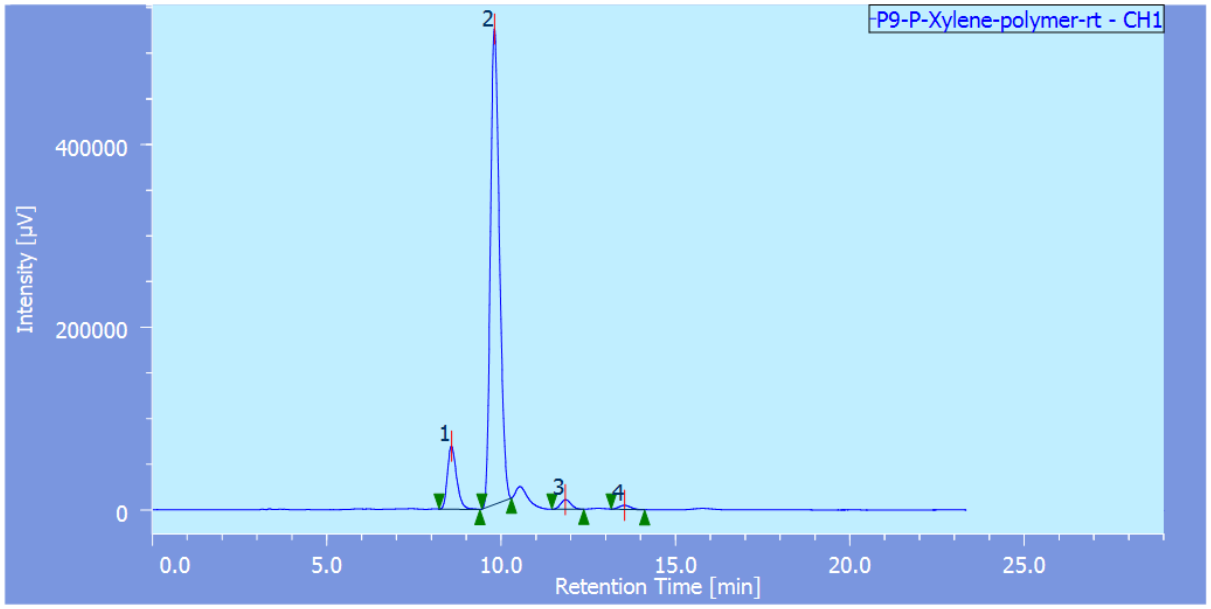


Figure S43: HPLC chromatogram of asymmetric compound, 13
Table 3, entry 3
98% *ee*

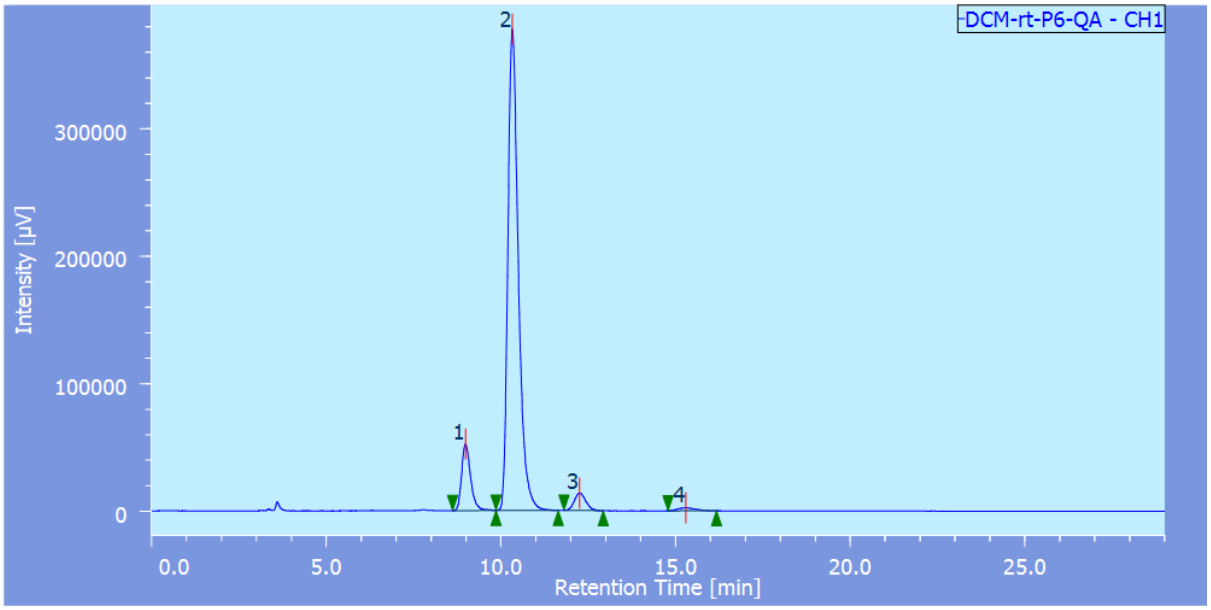


Figure S44: HPLC chromatogram of asymmetric compound, 13
Table 3, entry 4
98% *ee*

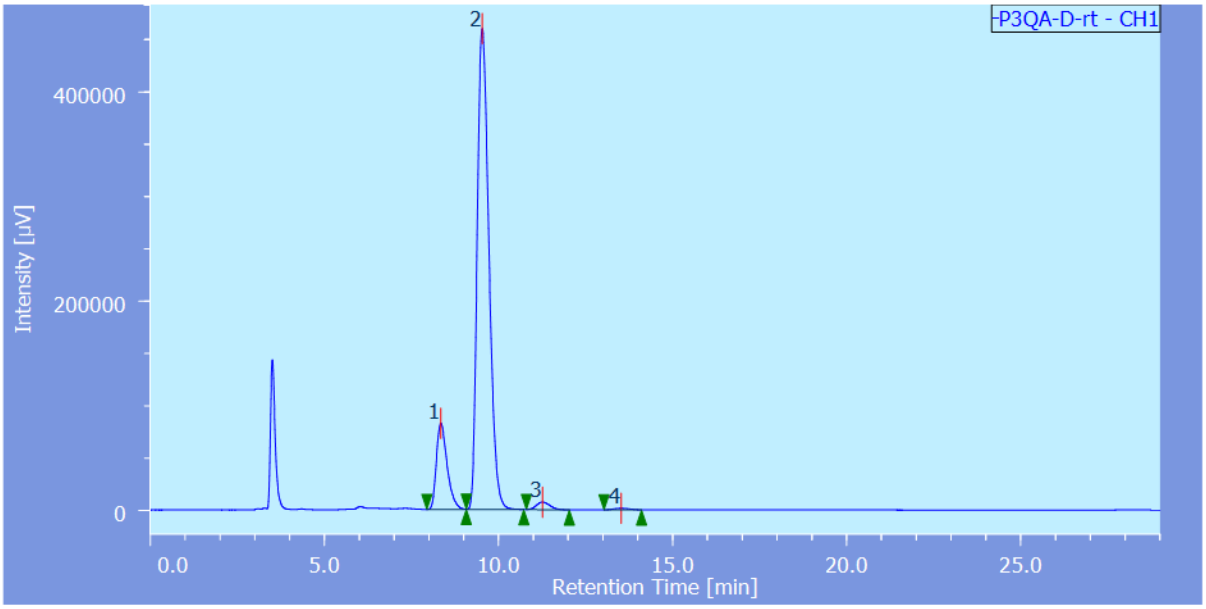


Figure S45: HPLC chromatogram of asymmetric compound, 13
Table 3, entry 5
99% *ee*

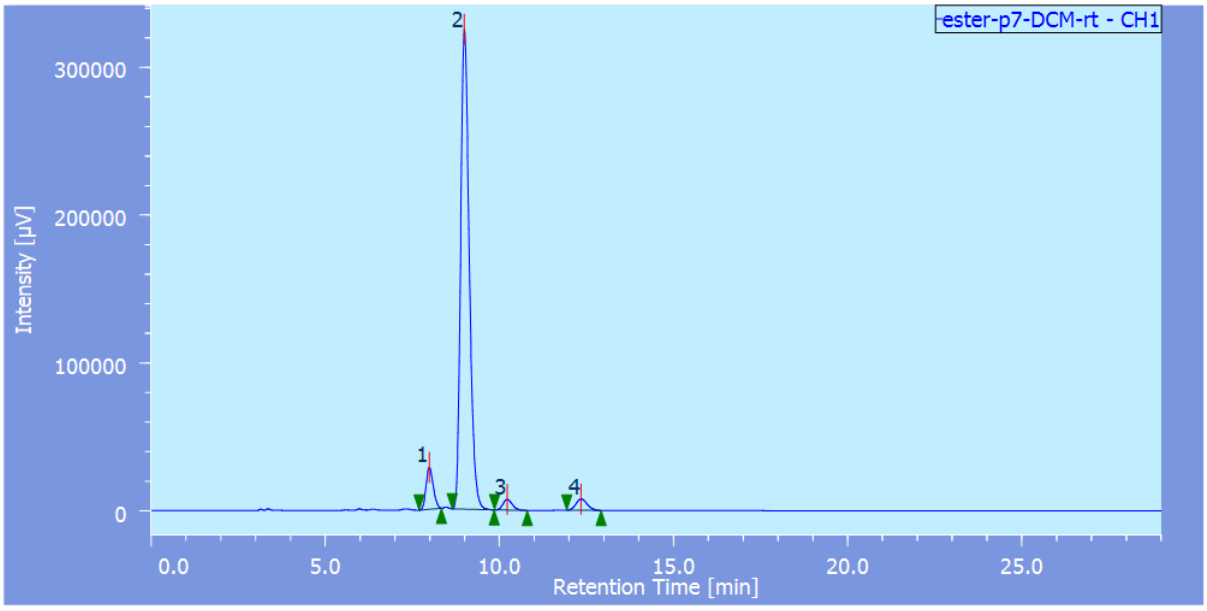


Figure S46: HPLC chromatogram of asymmetric compound, 13
Table 3, entry 6
94% *ee*

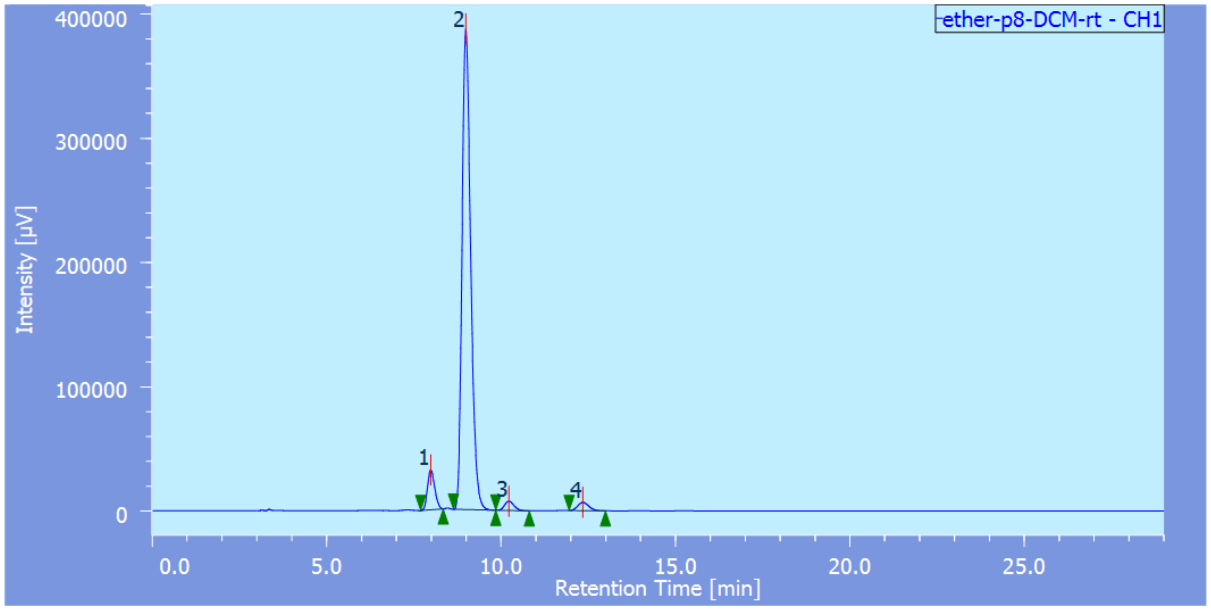


Figure S47: HPLC chromatogram of asymmetric compound, 13
Table 3, entry 7
96% *ee*

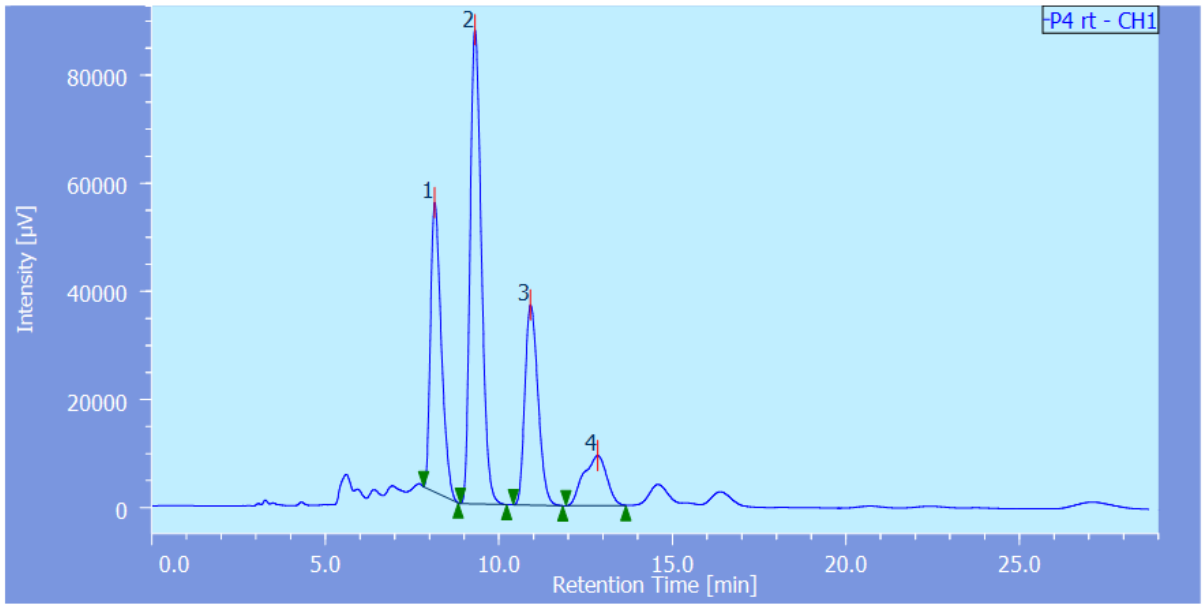


Figure S48: HPLC chromatogram of asymmetric compound, 13
Table 3, entry 8
64% *ee*

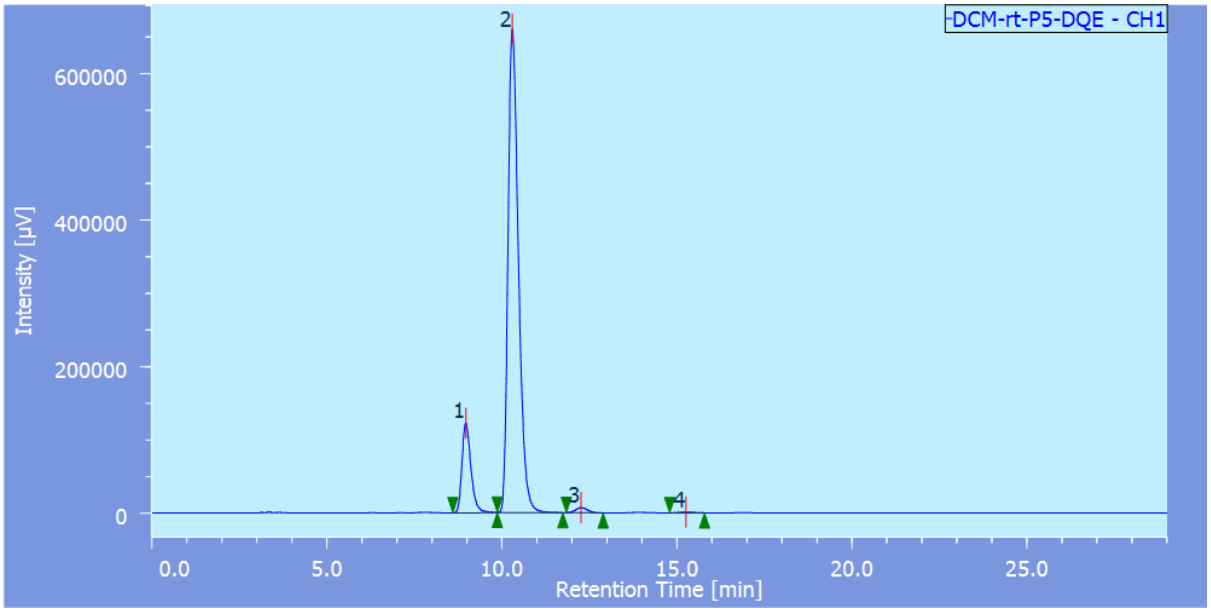


Figure S49: HPLC chromatogram of asymmetric compound, 13
Table 3, entry 9
>99% *ee*

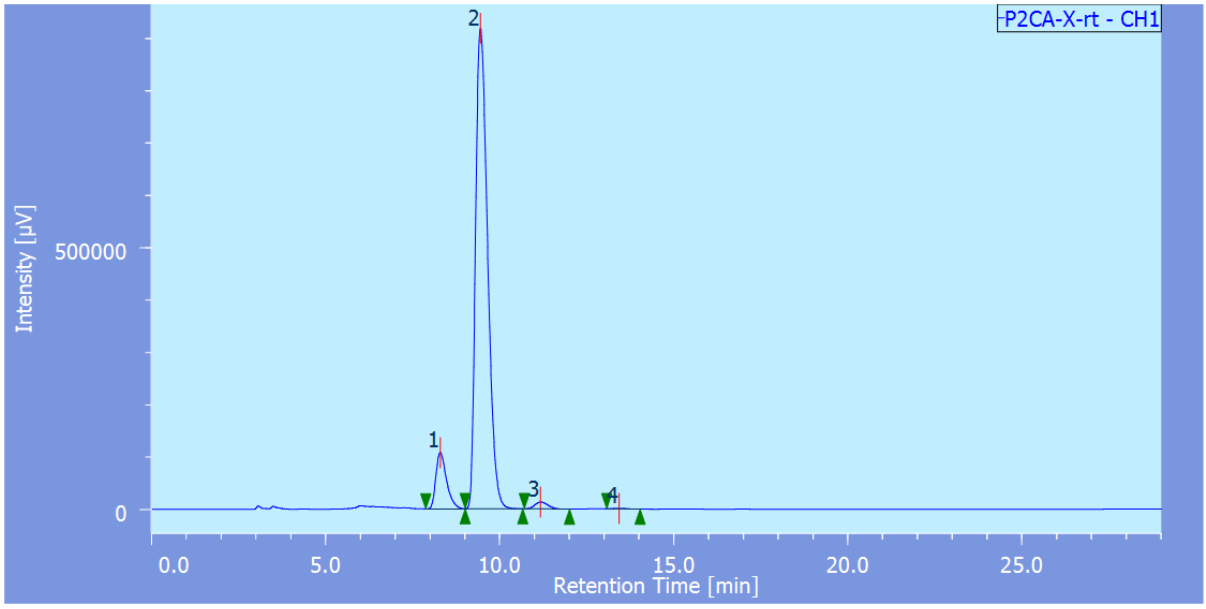


Figure S50: HPLC chromatogram of asymmetric compound, 13
Table 4, entry 1
>99% *ee*

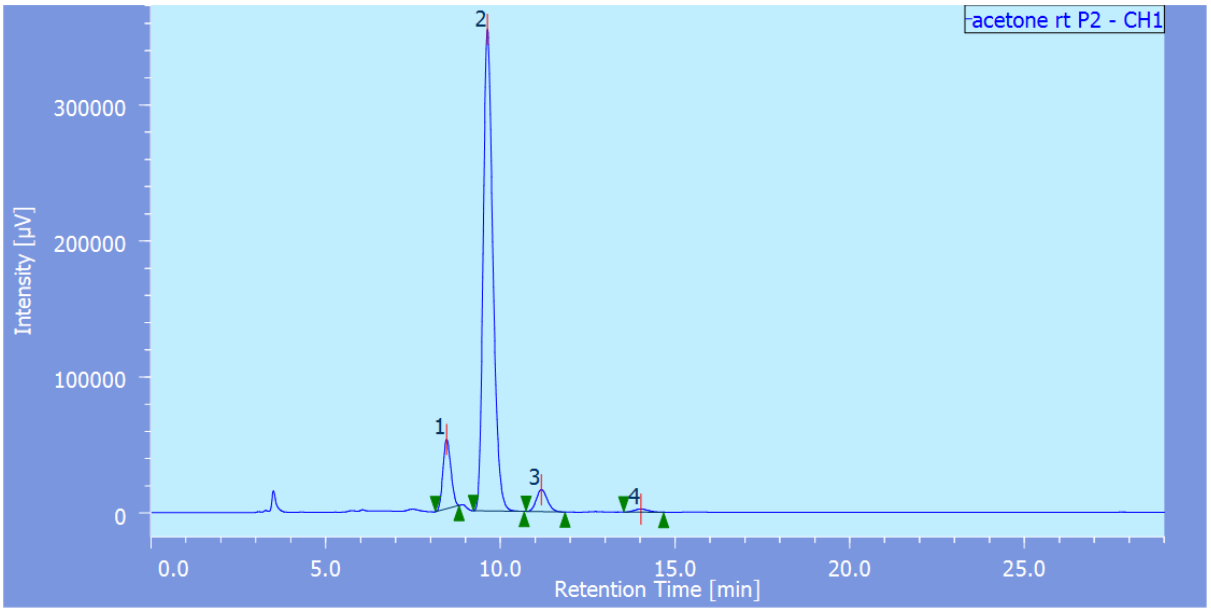


Figure S51: HPLC chromatogram of asymmetric compound, 13
Table 4, entry 2
98% *ee*

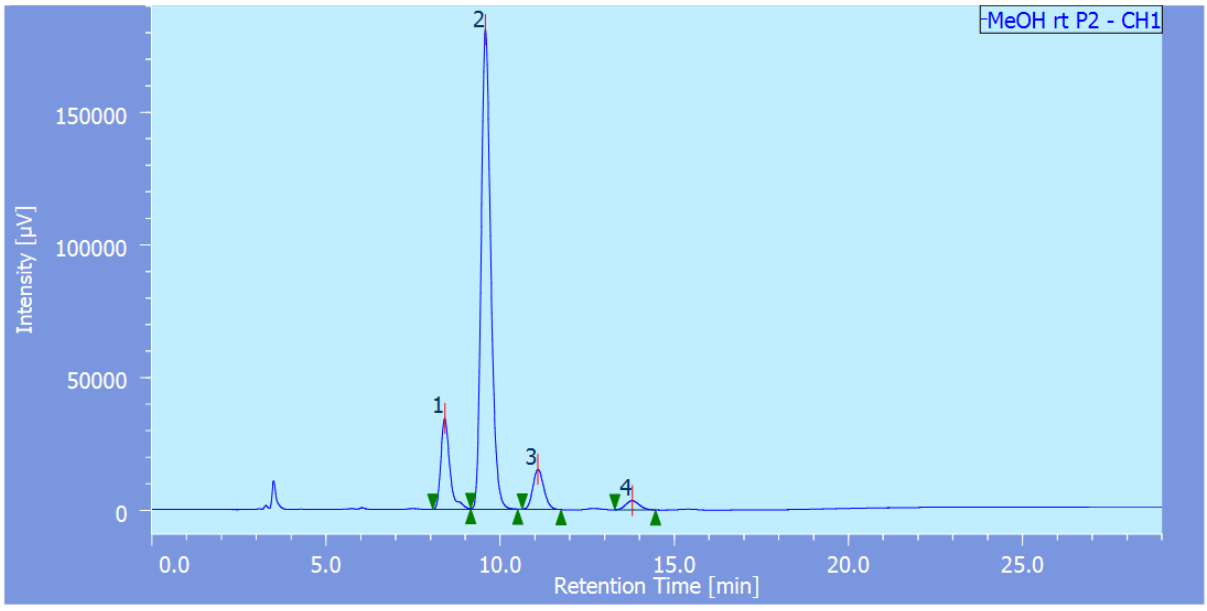


Figure S52: HPLC chromatogram of asymmetric compound, 13
Table 4, entry 3
95% *ee*

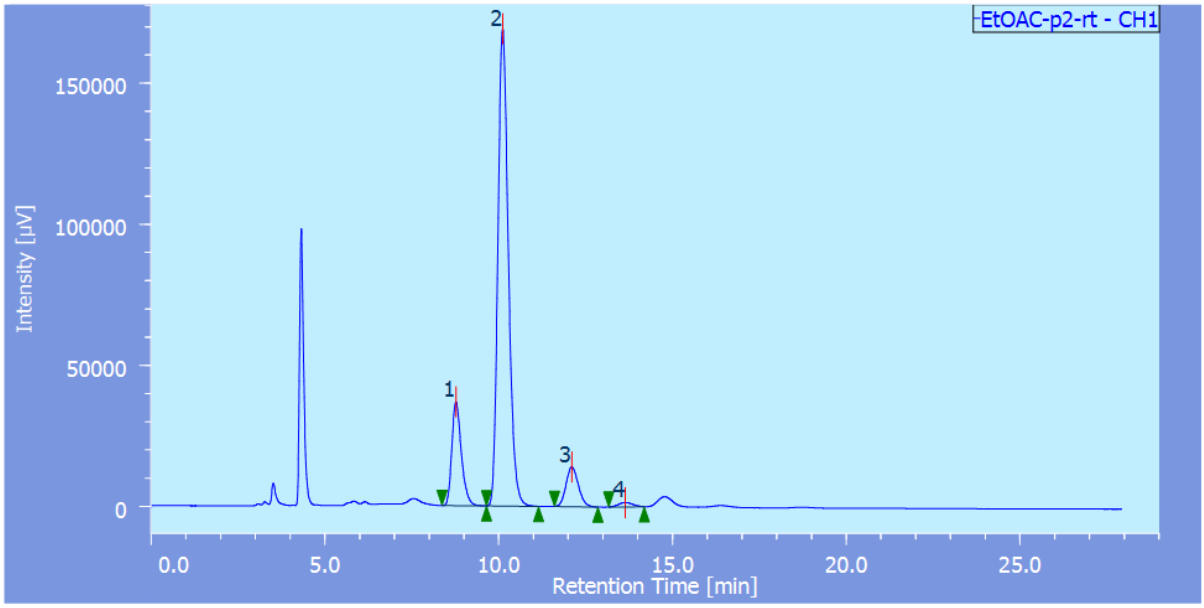


Figure S53: HPLC chromatogram of asymmetric compound, 13
Table 4, entry 4
97% *ee*

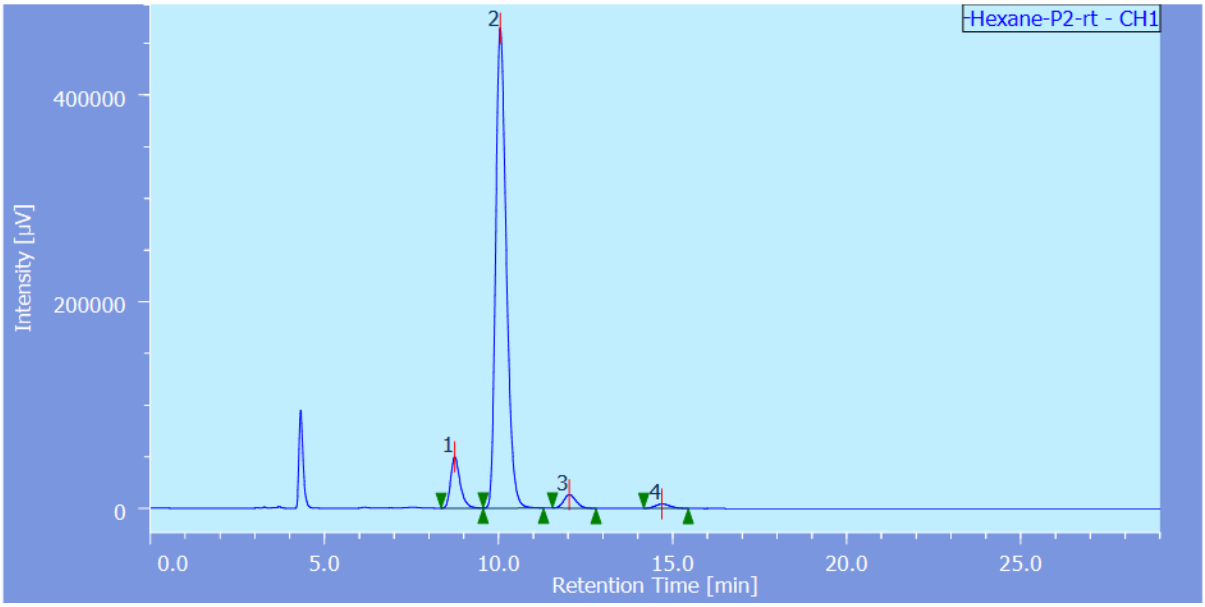


Figure S54: HPLC chromatogram of asymmetric compound, 13
Table 4, entry 5
97% *ee*

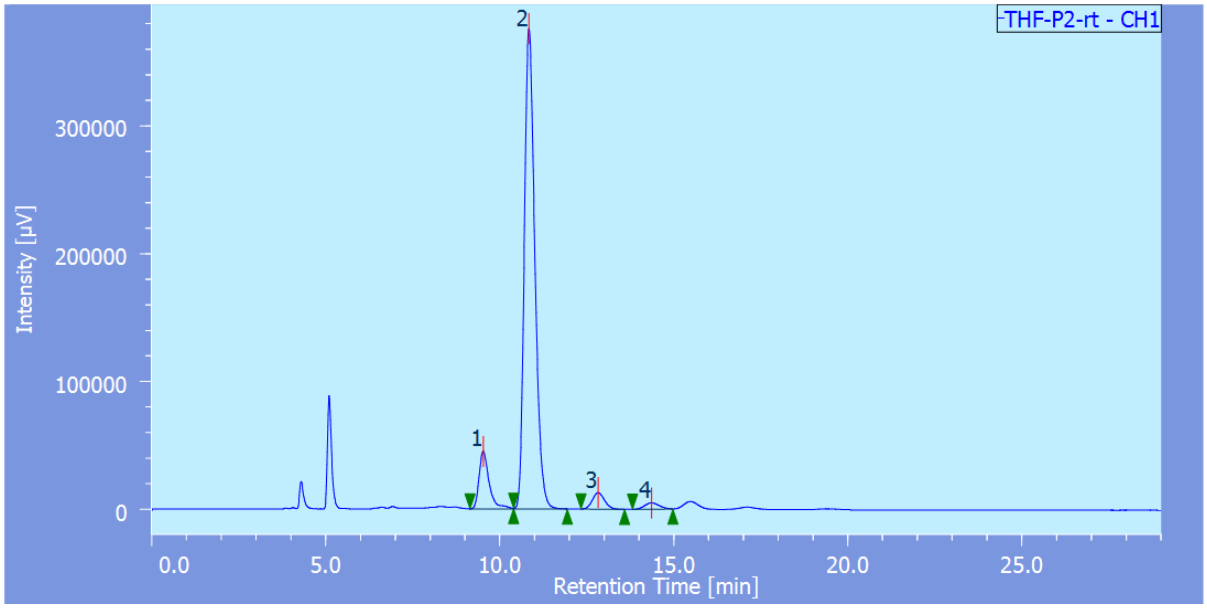


Figure S55: HPLC chromatogram of asymmetric compound, 13
Table 4, entry 6
96% *ee*

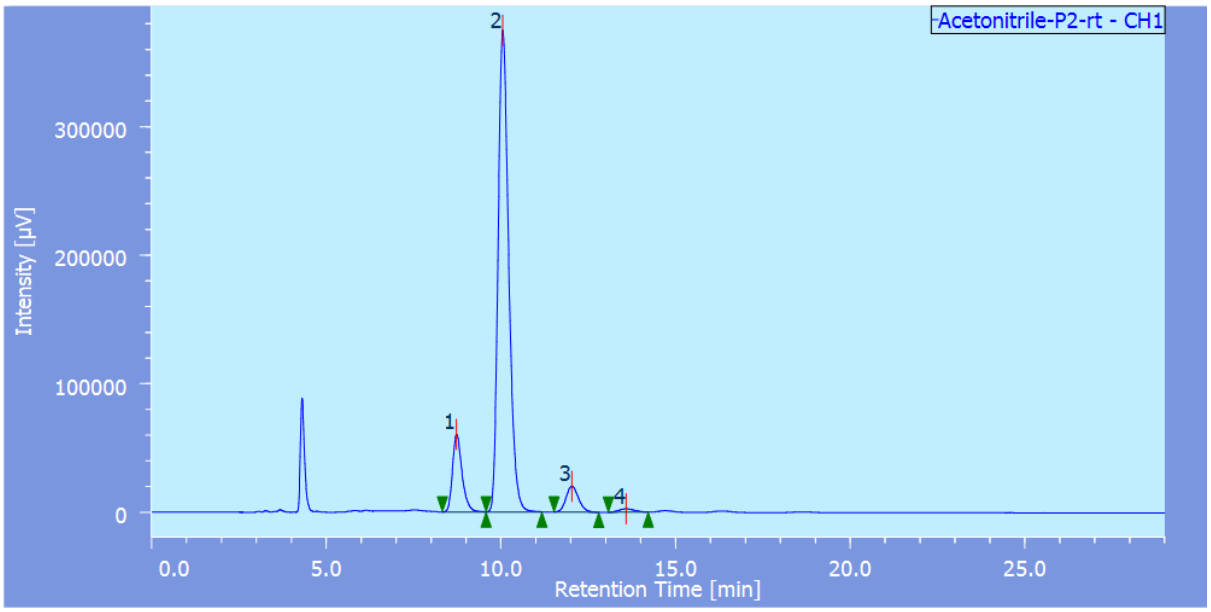


Figure S56: HPLC chromatogram of asymmetric compound, 13
Table 4, entry 7
98% *ee*

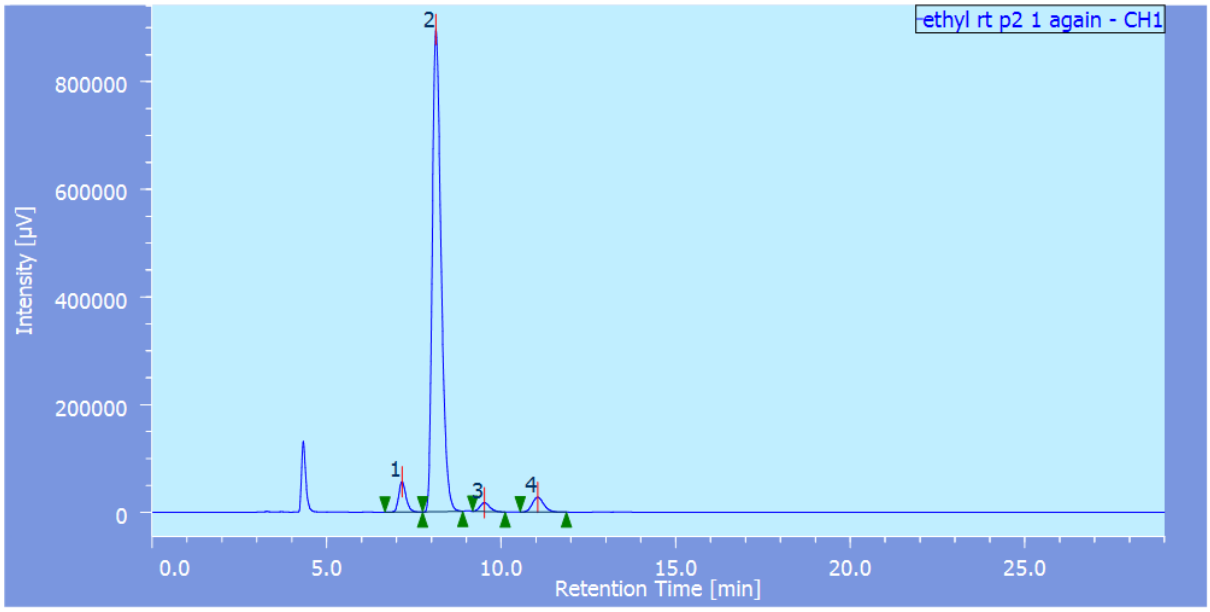


Figure S57: HPLC chromatogram of asymmetric compound, 18

Table 5, entry 1

92% *ee*

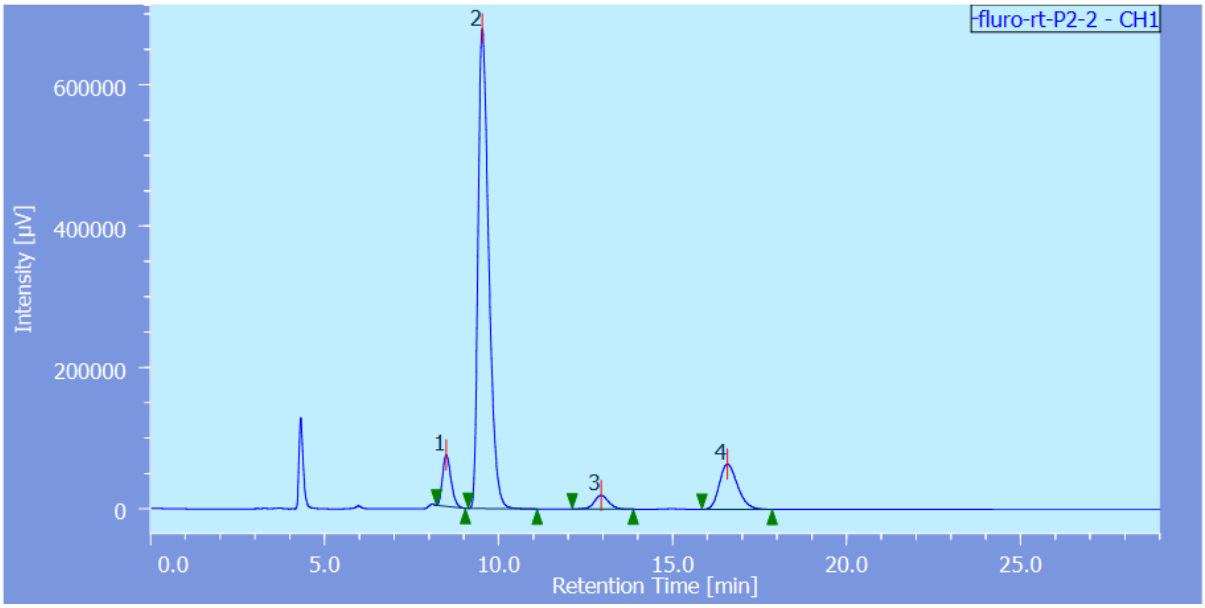


Figure S58: HPLC chromatogram of asymmetric compound, 19

Table 5, entry 2

73% *ee*

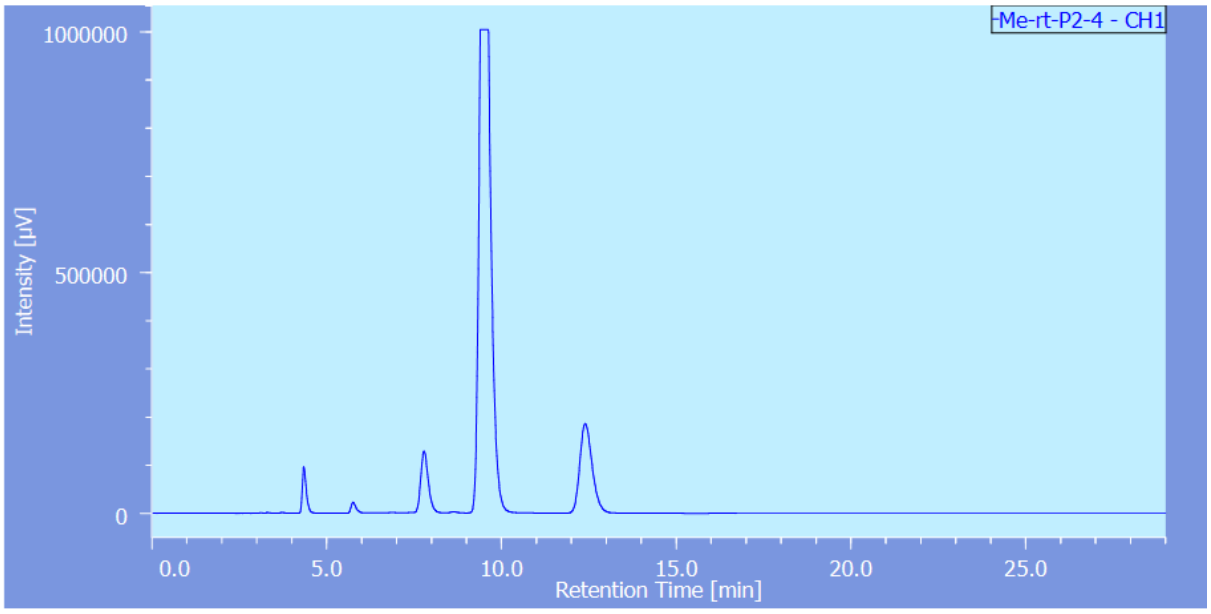


Figure S59: HPLC chromatogram of asymmetric compound, 20
Table 5, entry 3
>99% *ee*

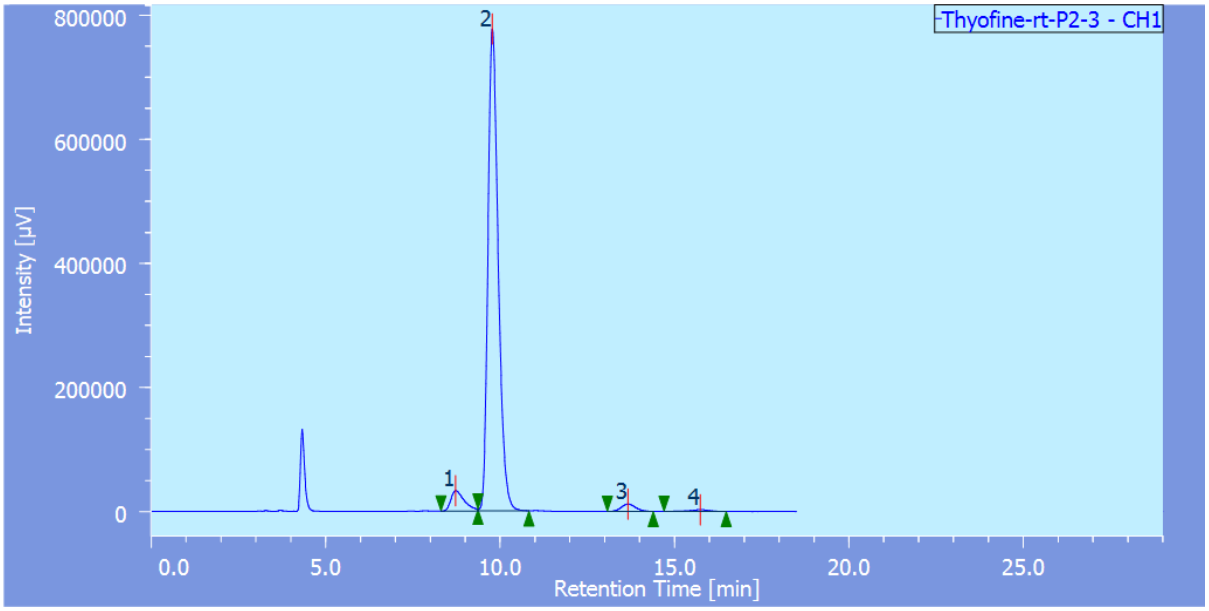


Figure S60: HPLC chromatogram of asymmetric compound, 21
Table 5, entry 4
99% *ee*

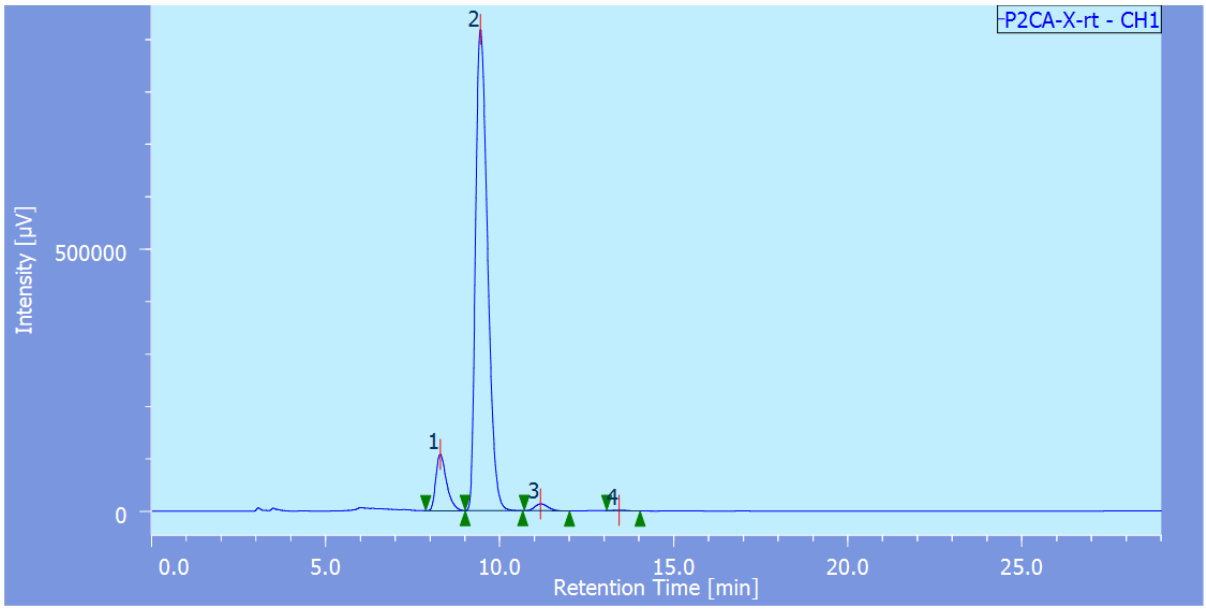


Figure S61: HPLC chromatogram of asymmetric compound, 13
Table 6, entry 1, fresh
>99% *ee*

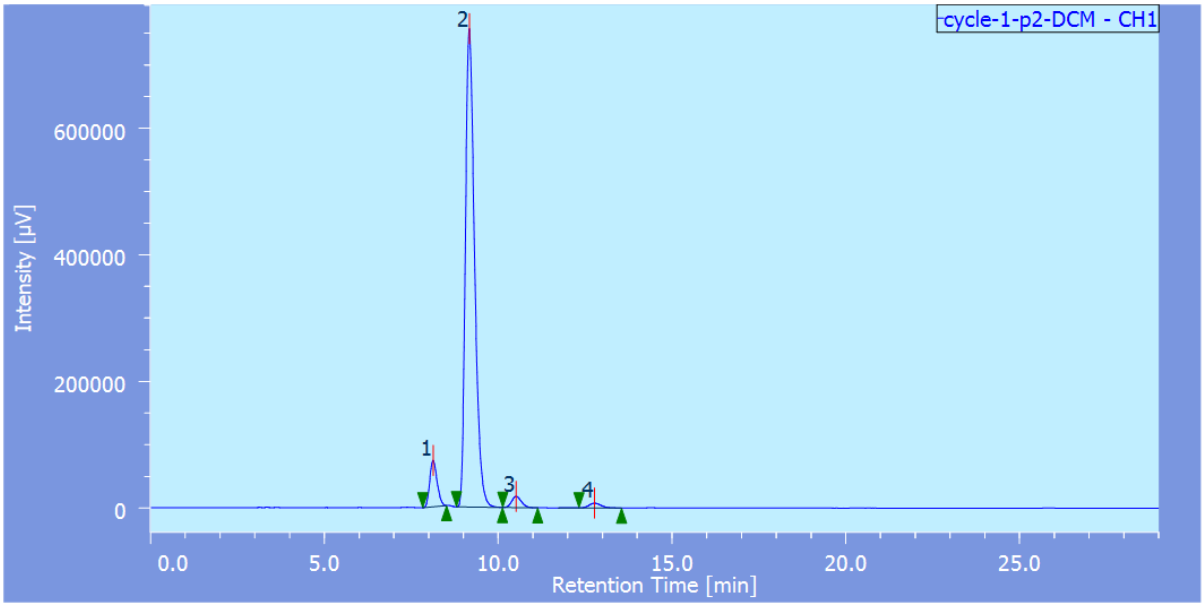


Figure S62: HPLC chromatogram of asymmetric compound, 13
Table 6, entry 2, cycle 1
97% *ee*

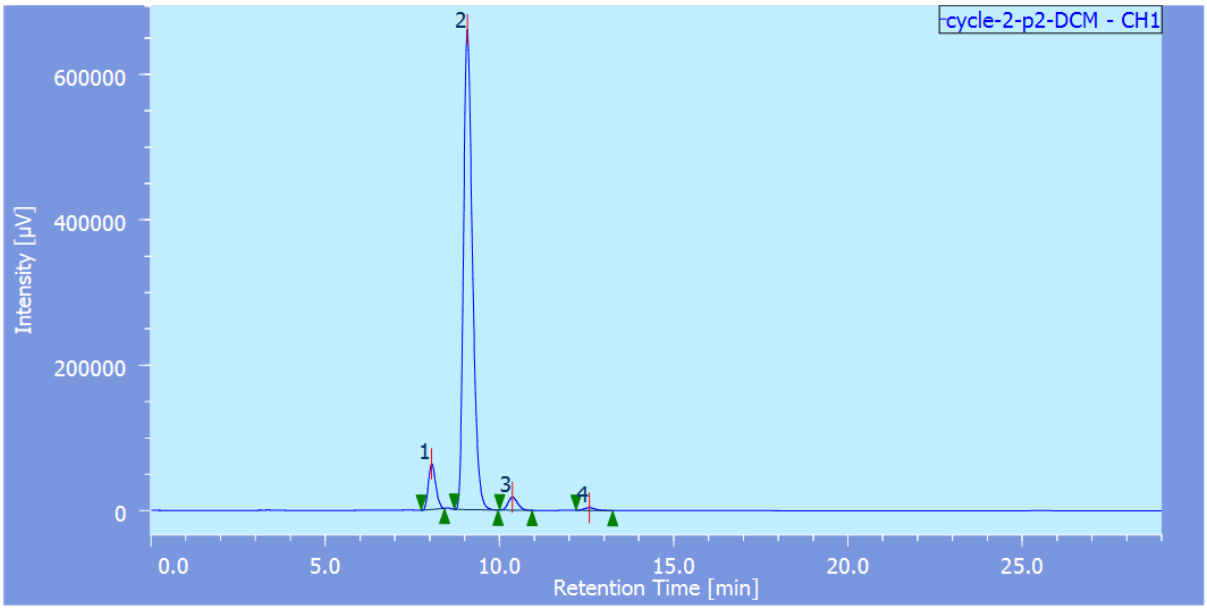


Figure S63: HPLC chromatogram of asymmetric compound, 13
Table 6, entry 3, cycle 2
99% *ee*

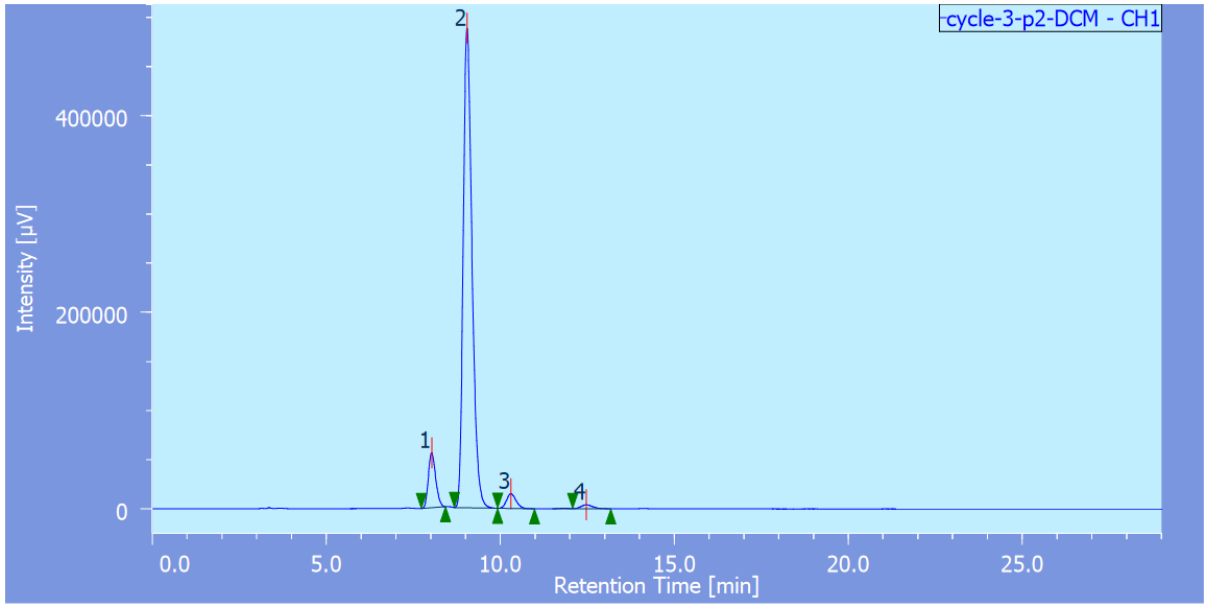


Figure S64: HPLC chromatogram of asymmetric compound, 13
Table 6, entry 4, cycle 3
98% *ee*

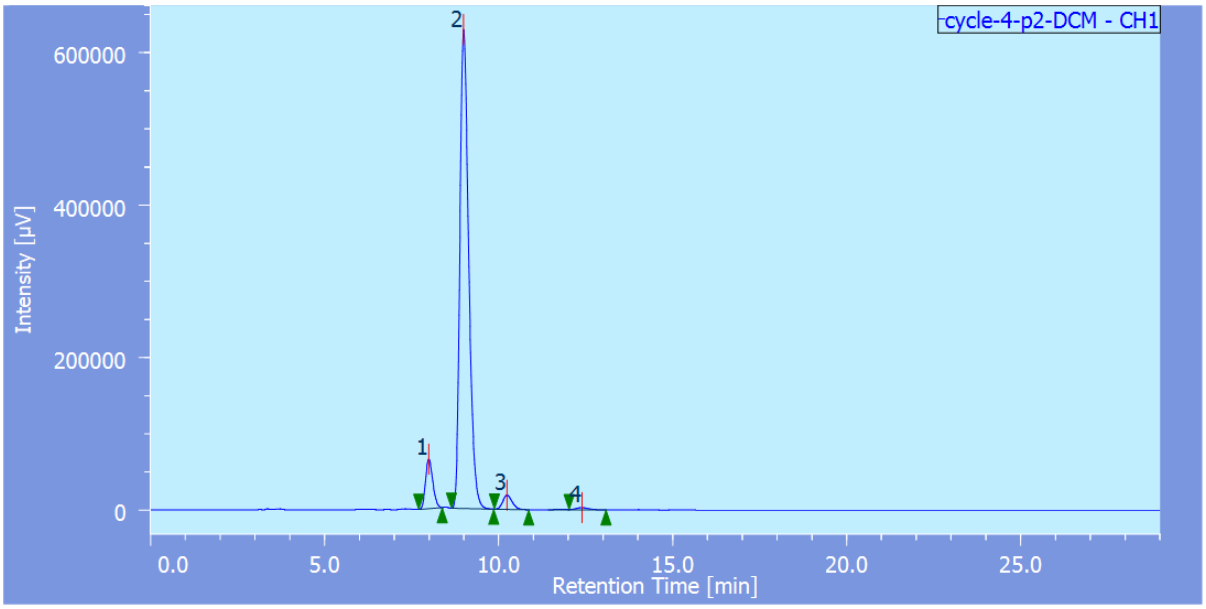


Figure S65: HPLC chromatogram of asymmetric compound, 13
Table 6, entry 5, cycle 4
99% *ee*