

Immobilization of Ruthenium Benzylidene on Thermo-responsive Polymer : Methodology and Application

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Attachment of metal complex on polymer has direct implication for the development of novel catalyst with recyclability, reusability and water solubility in the context environmental concern. In this paper, we illustrate a simple strategy to immobilize ruthenium benzylidene organometallic complex on thermo-responsive polymer. For this, pyridine-substituted poly (N-isopropylacrylamide) has been synthesized by atom transfer radical polymerization from a suitable initiator. Then, ruthenium benzylidene has been conjugated by binding with pyridine part of the polymer. Polymer conjugated ruthenium benzylidene is shown to have thermo-responsive characteristic in water (soluble below lower critical solution temperature (LCST) but precipitates out above LCST in water). Hence it can act as smart catalyst for metathesis reaction in water. For instance, it can be used as homogeneous metathesis catalyst for allyl alcohol in aqueous medium below lower critical solution temperature (LCST), that can be recovered as heterogeneous catalyst above LCST and recycled again as homogeneous catalyst. This is the first example of water-soluble recyclable metathesis catalyst. It is further demonstrated that steric crowding in the ligand play an important role in the superior performance of the catalyst.

1. Introduction

Ruthenium benzylidene complexes are important as catalysts for the metathesis reaction [1-3]. Attachment of ruthenium benzylidene on different polymers [4, 5] is an integral part of research for the development of environmentally benign catalyst with water solubility and recyclability [6, 7].

Various polymers can be used to render water solubility [8]. For example, polyethylene glycols were conjugated with ruthenium benzylidene independently by Grubbs [9-11], Emrick [12, 13] and Raines [14]. Some of those compounds showed excellent catalytic activity for self metathesis, cross metathesis or ring opening metathesis polymerization reactions in water medium. Those developments paved the way to eliminate the usage of toxic organic solvents: an important parameter for green chemistry approach, successful biochemical reactions and cost effectiveness.

In most cases, recyclable metathesis catalysts were prepared by immobilizing them on polymer support. Recently we reported various methods of covalent or non covalent bond formation on flat or curved surfaces [15-17]. Hoveyda and others prepared recyclable ruthenium benzylidene by immobilizing it on porous sol-gel glass [18]. Yang et al [19] prepared recyclable supported catalyst by immobilizing it on mesoporous material. Kirschning and others anchored Grubbs III type catalyst onto polyvinyl pyridine [20], while Lee et al prepared silica-supported Hoveyda type catalyst [21]. Many of them are either not soluble in organic or aqueous medium; hence homogeneous catalysis – a prerequisite for high efficacy – still remains a challenge in either media with recyclable polymer supported catalyst [22]. In a recent review article, several aspects of homogeneous catalysis particularly resolving of heterogeneity problems have been discussed by Robert H. Crabtree [23].

It was recognized that, Poly(N-isopropylacrylamide) poly (NIPAM) is thermo-responsive in nature [24, 25]. Hence, contrary to the behaviour of most compounds in water, poly (NIPAM) becomes less soluble in water at elevated temperature. The temperature above which poly (NIPAM) undergoes from soluble to insoluble state in water is called Lower Critical Solution Temperature (LCST). By exploiting thermo-responsive nature of poly(NIPAM), several groups have prepared smart protein [26] or smart surface [27] after suitable conjugation. Those types of thermo-responsive polymers or conjugates have been also used for targeted drug delivery [28, 29], nanotechnology [30], etc. However, to the best of our knowledge, there is no example of ruthenium benzylidene with thermo-responsive tag, to use as homogeneous as well as recyclable metathesis catalyst in water.

We report in this paper a clear cut demonstration that ruthenium benzylidene complexes with poly (NIPAM) tag can be prepared in four simple steps to show thermo-responsive characteristics. Hence, it can be used as “smart” catalyst for metathesis reaction of allyl alcohol in aqueous medium with the advantages of both homogeneous and heterogeneous metathesis reaction.

2. Results and Discussions

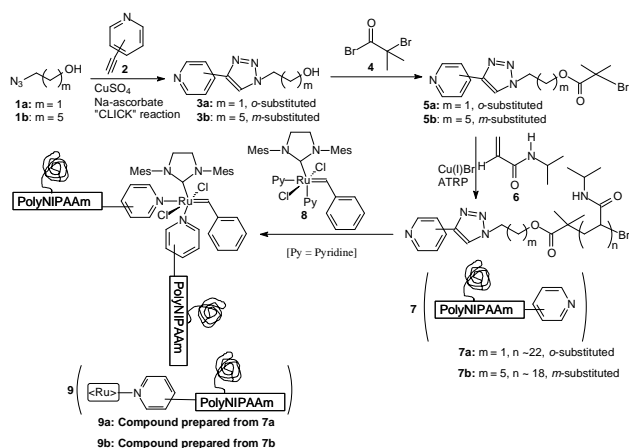
Scheme 1 depicts the synthesis of thermo-responsive ruthenium benzylidene compounds from azido alcohol. First, azidoethanol or azidohexanol was reacted with 2-ethynylpyridine or 3-ethynylpyridine, respectively to obtain the triazole **3a** or **3b** respectively. The products were purified by column chromatography using a mixture of methanol and dichloromethane. Disappearance of peak at $\sim 2090\text{ cm}^{-1}$ in IR and appearance of triazole ring proton signal at 7.7-7.8 ppm in both cases confirmed the success of this “click” reaction. The triazole compounds were esterified with 2-bromoisobutyrylbromide to form the suitable initiator for Atom Transfer Radical Polymerization (ATRP) **5a** or **5b**.

Both the compounds **5a** or **5b** were purified by column chromatography to obtain pale yellow solid compounds. In ^1H NMR spectra, two methyl groups ($2\times\text{CH}_3$) appeared as singlet in the region 1-2 ppm and the carbonyl carbon appeared at around 170 ppm, in ^{13}C NMR spectroscopy. The carbonyl stretching absorption appears as a sharp peak at $\sim 1730\text{ cm}^{-1}$ in IR.

Our initial attempts to perform the ATRP reaction of N-isopropylacrylamide (NIPAM) using either initiators in common solvents like toluene, methanol or DMSO were not successful. The successful ATRP reaction was achieved by using a solvent mixture of methanol and water along with a catalyst system of copper (I) bromide and bipyridine. Thorough degassing of the solvent with nitrogen prior to the polymerization reaction is also crucial for its success. The degree of polymerization was controlled by changing the initiator to monomer ratio. A higher degree of polymerization for *ortho*-substituted compound was desirable to impart the steric crowding close to the metal centre (*vide supra*). An initial purification of the polymer was achieved by reprecipitation from diethyl ether and tetrahydrofuran mixture. The trace amount of copper was removed by the quick filtering of the polymer through a pad of silica gel using methanol as solvent. The disappearance of peak at 5-6 ppm confirmed the absence of monomer while the appearance of new broad peaks between 1-2 ppm confirmed the success of polymerization to obtain pyridine-poly(NIPAM) compounds **7a** or **7b**. In ^{13}C NMR (ESI), the characteristic signal for amide carbon was observed at 170 – 180 ppm. The degree of polymerization (Scheme 1) was confirmed from the end group analysis by ^1H NMR and GPC traces.

The pyridine-poly(NIPAM) compound **7a** or **7b** was reacted with $[(\text{H}_2\text{IMes})(\text{pyridine})_2(\text{Cl})_2\text{Ru}=\text{CHPh}]$ (**8**) to obtain the poly(NIPAM)-tagged ruthenium benzylidene compound **9a** or **9b**. We presumed that, two units of pyridine are attached to provide a more stable 18 electron species as reported by Grubbs and Emrick[12, 31] separately for pyridine-based ruthenium benzylidene complexes. ^1H NMR spectra further indicated an attachment of multiple pyridine units.

The compounds were purified by flash column chromatography under nitrogen to obtain deep green colour compound. Complete removal of starting material (**8**) was achieved by repeated removal of solvent, under high vacuum in three cycles. Complete disappearance of starting material **8** was also confirmed by TLC and ^1H NMR. A characteristic new singlet for benzylidene proton at ~ 19 ppm in ^1H NMR for **9a** or **9b** further confirmed the success of the reaction. The ruthenium loading in comparison to pyridine moieties were calculated by comparing the ratio of integration of benzylidene proton (one proton) at ~ 19 ppm and methyl protons (6 protons) of N-isopropyl groups at ~ 1 ppm.



Scheme 1. Synthesis of thermoresponsive ruthenium benzylidene compounds. Highlighted table summarises conversion of self metathesis reactions of different substrates using catalyst **9a**.

Both compounds **9a** and **9b** showed thermoresponsive characteristics in water. While both the compounds were soluble in water below 36°C , a rapid phase separation and precipitation occurs upon heating above 38°C from water medium. This specific property was exploited to perform the homogeneous catalysis below 36°C in water and heterogeneous catalytic recovery from water above 38°C .

Our initial attempt to perform metathesis reaction using catalyst **9b** was not successful. However, metathesis reaction in acidified D_2O for various substrates using catalyst **9a** was successful. In this case, 95%, 73% and 60 % conversion was observed for self metathesis of allyl alcohol, 3-buten-1-ol, and Ring Opening Metathesis Polymerization (ROMP) of PEGylated oxanorbornene in acidified D_2O respectively.

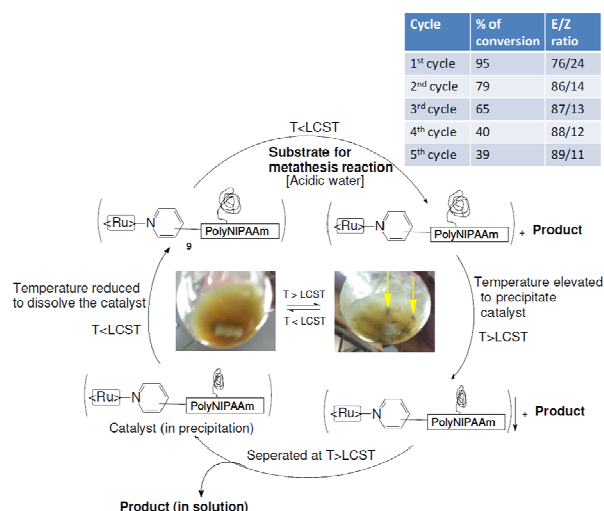
Scheme 2 summarizes the strategy of recycle of catalysts in deuterated water medium using a model substrate allyl alcohol. We have chosen allyl alcohol particularly because the substrate is usually challenging for metathesis reaction in water and very few reports along the line existed [11]. First, allyl alcohol and catalyst **9a** was dissolved in degassed D_2O at pH 1.0 below 36°C and stirred under nitrogen atmosphere for 24 h. The reaction mixture was heated above 38°C to get the green colour precipitation (Scheme 2, picture on the right). The product, which is in solution and the catalyst (mod), which is in the precipitation, was separated and the catalyst was recycled again by dissolving in D_2O for the catalytic reaction of allyl alcohol. Scheme 2, highlighted table, summarises the result of % of conversion of allyl alcohol in different cycles. Reduction of the metathesis reaction was also observed with the increase in the number of cycles. This may be attributed to the leaching out of some of the metal complex after reaction or slight change in catalytic structures. Inductively Coupled Plasma (ICP) experiments were performed to study the leaching phenomenon. In this case, ruthenium metal content of catalyst **9a** and **9b** before and after reaction were determined using ICP experiments. A decrease in ruthenium concentration (from diluted solution) was observed for both cases – in case of **9a**, a decrease from 6.1 ppm to 2.3 ppm and in case of **9b**, a decrease from 8.9 ppm to 3.1 ppm, to confirm the leaching. Further, we compared the ruthenium content in solution for “after the first cycle” and “after the third” cycle. We found only a slight change between “after the first cycle” and “after the 3rd cycle”, indicating that most of leaching phenomenon occurred during the first cycle

of reaction.

The higher activity of the catalyst **9a** than **9b** may be attributed to the greater steric crowding[32] of the ligands due to (i) higher degree of polymerization ($n \sim 22$ vs $n \sim 18$) (ii) shorter chain length of the linker ($m=1$ vs $m=5$) and (iii) closer proximity in the aromatic substitution (*ortho* vs *meta*) leading to easier dissociation of the ligand. The catalytic activity of metathesis reaction, effected by such type of steric factors was also observed by other authors.

The turn over number (TON) for the reaction of allyl alcohol in the first cycle and second cycle was 38 and 26 respectively. The decrease in the turn over number may be due to the leaching of polymer bearing pyridines from metal complexes.

Although in many homogeneous catalysis, use of only a 0.02-0.05 mol% of catalyst was enough for decent conversion, use of 3-5 mol% of catalysts are common for supported catalyst.[33]



Scheme 2. Strategy for the recycle of the catalyst: catalysis in homogeneous medium (left side figure inside the circle) and recovery from the heterogeneous medium (right side figure inside the circle). Yellow arrows clearly indicate the green colour precipitation which appeared only on heating above LCST. The highlighted table (inset) indicates % of conversion of allyl alcohol in acidified D_2O for allyl alcohol using catalyst **9a**.

Although thermoresponsive ruthenium compound was precipitated out conveniently from the solution, minute amount of contamination of ruthenium with the product in solution was still observed. However, EDAX experiment suggested almost a 10 fold decrease in ruthenium contamination, after the temperature induced precipitation. We observed decrease of ruthenium concentration further by a simple filtration through a small bed of silica gel easily. Depending on the application area, ruthenium concentration can be decreased further by using a larger silica/alumina pad.

3. Experimental

3.1. Materials and Instrumentations

Reactions were performed in dry round bottom flask under nitrogen atmosphere. 6-Bromo-1-hexanol, 2-bromoethanol, 3-ethynylpyridine, 2-ethynylpyridine, 2-bromo-2-methylpropionyl bromide, anhydrous dichloromethane(DCM), N-isopropylacrylamide (NIPAM), 2,2'-bipyridine (BiPy), copper(I)bromide(CuBr), deuterated water(D_2O), deuterated chloroform ($CDCl_3$), Grubbs' second generation catalyst was purchased from Sigma-Aldrich and used as received. Sodium azide, sodium L(+) ascorbate (s d fine-chem Limited), pyridine (SISCO Research Laboratories Pvt. Ltd), copper sulphate, triethyl amine, ethanol, methanol (Himedia-laboratories pvt.ltd) was used as received. Thin-layer chromatography was performed on Merck 60 F254 precoated silica gel aluminium sheets, visualized by exposure to UV (254 nm) or stained by iodine vapour. Column chromatography was performed on silica gel (60-120 mesh) under nitrogen or air flash. NMR spectra were recorded at 500 MHz with JEOL ECA-500 spectrometer or on 400 MHz with Bruker Avance - III spectrometer. The following terminology was used for the NMR signals, s: singlet, d: doublet, t: triplet, q: quartet, m: multiplet, br: broad. High-resolution mass spectra were obtained using a Qt of Micro YA263 instrument. Infra red spectra were recorded using ABB MB3000 spectrometer. GPC experiments were performed to measure the molecular weights using JASCO gel permeation chromatograph (GPC), MX-2080-+31 fitted with PL gel 5 μ m Mixed-C columns, 300 X 7.5 mm and refractive index (RI) detector, in tetrahydrofuran with a flow rate at 1 mL min^{-1} at 30 °C.

3.2. Synthesis of triazoles (3a, 3b)

[General procedure A]

2-(4-(pyridin-2-yl)-1H-1,2,3-triazol-1-yl)ethanol (3a)

In a 25 ml two neck round bottom flask, 2-ethynyl pyridine, **2a** (1030 mg, 10 mmol) was mixed with 10 ml of absolute ethanol and 5 ml of distilled water under nitrogen atmosphere. To this solution, was added the mixture of copper sulphate (249.68 mg, 1mmol),

and sodium L (+) ascorbate (396 mg, 2 mmol) and stirred for 1 min. The colour of the reaction mixture was turned to brown yellow. To it, 2-azido ethanol, **1a** (3.77gm) was added, and purged with nitrogen gas. Stirring was continued another 18 hours at room temperature under nitrogen atmosphere. During that time, the colour of the reaction mixture changed to yellow turbidity. The mixture was filtered and concentrated by using rotavapor. This was purified by silica gel chromatography (5% methanol in dichloromethane) to obtain 1329.40 mg of **3a** (70%): pale yellow solid (m.p. = 103 °C); ¹H NMR (500 MHz, CDCl₃) δ (ppm): 8.44 (d, *J* = 5 Hz, 1H, ortho -CH), 8.29 (s, 1H, meta -CH), 8.05 (d, *J* = 10 Hz, 1H, para -CH), 7.74 (t, *J*₁ = 10 Hz, *J*₂ = 5 Hz, 1H, triazole -CH), 7.20 (t, *J*₁, *J*₂ = 5 Hz, 1H, meta -CH), 4.54 (t, *J*₁, *J*₂ = 5 Hz, 2H, N-CH₂), 4.12 (t, *J*₁, *J*₂ = 5 Hz, 2H, O-CH₂), 3.81-2.38 (br s, 1H, alcohol OH); ¹³C NMR (100 MHz, CDCl₃) δ (ppm): 149.8, 148.9, 147.3(aromatic -CH), 137.2, 123.5(alkene -CH), 122.8, 120.3(aromatic -CH), 60.9, 53.0(aliphatic -CH); IR (KBr): 3232, 3134, 2856, 1603, 1571, 1420, 1239, 1155, 1085, 1032, 785, 727 cm⁻¹; HRMS, calcd for C₉H₁₀N₄O (M+Na⁺) 213.0752, found 213.0752.

6-(4-(pyridin-3-yl)-1H-1,2,3-triazol-1-yl)hexan-1-ol (**3b**)

Following the general procedure A, 3-ethynyl pyridine, **2b** (1030.4 mg, 10 mmol) was converted to 1703 mg of **3b** (69%): pale yellow solid (m.p. = 61 °C); ¹H NMR (500 MHz, CDCl₃) δ (ppm): 8.94 (s, 1H, ortho -CH), 8.49 (d, *J* = 5 Hz, 1H, ortho -CH), 8.16 (d, *J* = 10 Hz, 1H, para -CH), 7.86 (s, 1H, triazole -CH), 7.32 (dd, *J*₁, *J*₂ = 5 Hz, 1H, meta -CH), 4.38 (t, *J*₁, *J*₂ = 5 Hz, 2H, N-CH₂), 3.59 (t, *J*₁, *J*₂ = 5 Hz, 2H, O-CH₂), 2.76 (br s, 1H, alcohol OH), 1.95-1.89 (m, 2H, meta N-CH₂), 1.55-1.50 (m, 2H, meta O-CH₂), 1.43-1.31 (m, 4H, para O-CH₂, N-CH₂); ¹³C NMR (100 MHz, CDCl₃) δ (ppm): 149.0, 146.8(aromatic -CH), 144.5(alkene -CH), 133.0, 126.9(aromatic -CH), 123.8(alkene-CH), 119.9(aromatic -CH), 62.2, 50.4, 32.3, 30.2, 26.1, 25.1(aliphatic -CH); IR (KBr): 3395, 3327, 3109, 2933, 2858, 1463, 1220, 1052, 812, 709 cm⁻¹; HRMS, calcd for C₁₃H₁₈N₄O (M+H⁺) 247.1559, found 247.1552.

3.3. Synthesis of esters (**5a**, **5b**)

[General procedure B]

2-(4-(pyridin-2-yl)-1H-1,2,3-triazol-1-yl)ethyl 2-bromo-2-methylpropanoate (**5a**)

In a 25 ml two neck round bottom flask, 2-(4-(pyridin-2-yl)-1H-1,2,3-triazol-1-yl)ethanol (**3a**) (760.8 mg, 4 mmol) was dissolved in 15 ml of anhydrous dichloromethane. The reaction mixture was cooled to 0 °C and added tri-ethyl amine (0.6968ml, 5mmol), followed by 2-Bromo-2 methylpropionyl bromide (0.6180ml, 5mmol) in a drop wise manner. The stirring was continued at 0 °C for another two hours under nitrogen atmosphere, and then it was allowed to come to 25 °C. The stirring was continued for another 24 hours at 25 °C. The reaction mixture was mixed with 25 ml dichloromethane, washed with water for 3-times and dried over by sodium sulphate. Concentration *in vacuo* provided light yellow oil. It was purified by column chromatography using 1-3% methanol in dichloromethane to obtain 1234 mg of **5a** (91%): pale yellow solid (m.p. = 90.8 °C); ¹H NMR (400 MHz, CDCl₃) δ (ppm): 8.59 (d, *J* = 4 Hz, 1H, ortho -CH), 8.30 (s, 1H, meta -CH), 8.18 (d, *J* = 8 Hz, 1H, para -CH), 7.80 (t, *J*₁, *J*₂ = 8 Hz, 1H, triazole -CH), 7.25 (t, *J*₁ = 8 Hz, *J*₂ = 4 Hz, 1H, meta -CH), 4.76 (t, *J*₁, *J*₂ = 4 Hz, 2H, O-CH₂), 4.64 (t, *J*₁, *J*₂ = 4 Hz, 2H, N-CH₂), 1.90 (s, 6H, 2CH₃); ¹³C NMR (100 MHz, CDCl₃) δ (ppm): 171.2 (-C=O), 149.9, 149.4, 148.5(aromatic -CH), 137.0, 123.0(alkene -CH), 122.8, 120.3(aromatic -CH), 63.7, 55.0, 49.0, 30.6(aliphatic -CH); IR (KBr): 3144, 3007, 2967, 1732, 1603, 1572, 1473, 1278, 1151, 787 cm⁻¹; HRMS, calcd for C₁₃H₁₅BrN₄O₂ (M+H⁺) 339.0457, found 339.0451.

6-(4-(pyridin-3-yl)-1H-1,2,3-triazol-1-yl)hexyl 2-bromo-2-methylpropanoate (**5b**)

Following the general procedure B, 6-(4-(pyridin-3-yl)-1H-1,2,3-triazol-1-yl)hexan-1-ol (**3b**) (984 mg, 4 mmol) was converted to 845 mg of **5b** (54%): pale yellow solid (m.p. = 73 °C); ¹H NMR (400 MHz, CDCl₃) δ (ppm): 8.96 (s, 1H, ortho -CH), 8.51 (d, *J* = 4 Hz, 1H, ortho -CH), 8.16 (d, *J* = 8 Hz, 1H, para -CH), 7.87 (s, 1H, triazole -CH), 7.32 (dd, *J*₁, *J*₂ = 4 Hz, 1H, meta -CH), 4.39 (t, *J*₁ = 8 Hz, *J*₂ = 4 Hz, 2H, N-CH₂), 4.12 (t, *J*₁, *J*₂ = 8 Hz, 2H, O-CH₂), 1.99-1.91 (m, 2H, meta N-CH₂), 1.88 (s, 6H, 2CH₃), 1.69-1.62 (m, 2H, meta O-CH₂), 1.47-1.34 (m, 4H, para O-CH₂, N-CH₂); ¹³C NMR (100 MHz, CDCl₃) δ (ppm): 171.6(-C=O), 149.0, 146.9(aromatic -CH), 144.6(alkene -CH), 133.0, 126.8(aromatic -CH), 123.7(alkene -CH), 119.9(aromatic -CH), 65.6, 56.0, 50.3, 30.7, 30.1, 28.1, 26.0, 25.2(aliphatic -CH); IR (KBr): 3133, 2935, 1730, 1441, 1280, 1171, 1050, 810 cm⁻¹; HRMS, calcd for C₁₇H₂₃BrN₄O₂ (M+H⁺) 395.1083, found 395.1078.

3.4. Synthesis of NIPAM polymers (**7a**, **7b**)

[General procedure C]

2-substituted pyridine-based NIPAM polymer (**7a**)

In a 25 ml two neck round bottom flask, N-isopropylacrylamide (565.8 mg, 5 mmol), dissolved in 2 ml degassed water and 2-(4-(pyridin-2-yl)-1H-1,2,3-triazol-1-yl)ethyl 2-bromo-2-methylpropanoate (81.40 mg, 0.24 mmol), dissolved in 0.2 ml degassed methanol was mixed together. To it, copper bromide (17.16 mg, 0.12 mmol), 2,2'-bipyridine (56.22 mg, 0.36mmol) was added and stirred at ambient temperature for 18 h. Solvent was removed and the brown colour compound was dissolved in minimal amount of tetrahydrofuran and added to the stirring solution of di-ethylether to get a blue colour precipitation. Reprecipitation from THF-diethyl ether followed by purification through a small pad of silica gel (methanol) to obtain 131.6 mg of compound **7a**: white powder; ¹H NMR (400 MHz, CDCl₃) δ (ppm): 3.86 (s), 1.19-2.16 (br, m), 1.11 (s); IR (KBr): 3436, 2974, 2935, 1643 1549, 1461, 1385, 1169, 1110, 619 cm⁻¹; GPC (THF) M_n=2802 g/mol, M_w = 3475 g/mol, PDI = 1.24.

3-substituted pyridine-based NIPAM polymer (**7b**)

Following the general procedure C, 6-(4-(pyridin-3-yl)-1H-1,2,3-triazol-1-yl)hexyl 2-bromo-2-methylpropanoate, **5b** (94.58 mg, 0.24 mmol) was reacted with N-isopropylacrylamide (565.8 mg, 5 mmol) to obtain 197.4 mg of **7b**: white powder; ¹H NMR (400

MHz, CDCl₃) δ (ppm): 3.80 (s), 1.17-2.09 (br, m), 1.05 (s); ¹³C NMR (125 MHz, CDCl₃) δ (ppm): 174.3(-C=O), 42.3, 41.2, 31.8, 29.5, 29.2, 22.4, 14.0(aliphatic -CH); IR (KBr): 3443, 2974, 2934, 1645, 1550, 1461, 1385, 1168, 1129, 620 cm⁻¹; GPC (THF) M_n=2441 g/mol, M_w = 3340 g/mol, PDI = 1.36.

3.5. Preparation of poly (NIPAM)-based ruthenium benzylidene compounds (9a, 9b)

[General procedure D]

o-substituted ruthenium benzylidene compound (9a)

In a clean 25 ml two neck round bottom flask, (50 mg, 0.0178 mmol) of the 2-substituted pyridine-based NIPAM polymer (7a), (30 mg, 0.0412 mmol) of [(H₂IMes)(pyridine)₂(Cl)₂Ru=CHPh] in anhydrous dichloromethane (6 ml) was taken and then stirred for 30 min. All the solvent was removed under vacuum pump, again anhydrous dichloromethane was added and stirred for 30 min again. Solvent was removed and the process was repeated for 3 times. Finally all the solvent was removed and column chromatography was performed to obtain 2-substituted polyNIPAM-tagged ruthenium benzylidene complex (62.51 mg, 0.0101 mmol) **9a** as green powder; ¹H NMR (500 MHz, CDCl₃) δ (ppm): 19.15 (s, 1H, Ru=CHPh), 10.01 (s), 5.88-7.96 (br, m), 5.28 (s), 3.97 (s), 3.06 (br, s), 1.12-2.64 (br, m); ¹³C NMR (125 MHz, CDCl₃) δ (ppm): 174.3(-C=O), 159.2, 158.2, 129.6, 128.5, 126.1, 123.1, 69.9, 42.2, 41.2, 35.5, 29.5, 29.2, 20.9, 17.9, 13.9.

m-substituted ruthenium benzylidene compound (9b)

Following the general procedure D, 3-substituted pyridine-based NIPAM polymer (7b) (200 mg, 0.0819 mmol) was reacted with (30 mg, 0.0412 mmol) of (H₂IMes)(pyridine)₂(Cl)₂Ru=CHPh to obtain (201.8 mg, 0.0370 mmol) of **9b** as green powder; ¹H NMR (500 MHz, CDCl₃) δ (ppm): 19.12 (s, 1H, Ru=CHPh), 9.98 (s), 8.54 (s), 7.94-5.73 (br, m), 5.26 (s), 4.96-2.82 (br, m), 2.67-0.63 (br, m); ¹³C NMR (125 MHz, CDCl₃) δ (ppm): 173.3(-C=O), 156.8, 136.5, 134.0, 129.2, 128.9, 128.7, 128.5, 128.4, 127.9, 127.6, 126.8, 122.3, 41.3, 40.2, 30.8, 28.6, 21.6, 20.0, 17.2, 13.1.

3.6. Typical procedure of metathesis reaction of allyl alcohol using the catalyst 9a followed by recycle of the catalyst

In a 10 ml two-neck round bottom flask, catalyst 9a (22mg), allyl alcohol (8 mg) and acidified degassed D₂O (1 ml) was mixed together and stirred under nitrogen at 34 °C for 24 h. The reaction vessel was then placed under water bath at 38 °C for 10 minute. A deep green colour precipitation was visible almost instantly. The solution was decanted to obtain the product mixed with trace amount of reactant. ¹H NMR analysis was used to calculate the conversion percentage. The precipitation (containing the catalyst) was dissolved in degassed D₂O and mixed with allyl alcohol to perform the metathesis reaction again. The process was repeated for 5-6 cycles.

4. Conclusions

We have synthesized thermoresponsive metathesis catalysts for the first time by conjugating ruthenium benzylidene with poly (N-Isopropylacrylamide) tag. For this, "click" reaction, esterification, atom transfer radical polymerization and substitution reactions were performed sequentially. The compounds showed phase separation rapidly at 36-38 °C in water. Hence the homogeneous metathesis reaction with recyclability was conveniently performed for self metathesis of allyl alcohol below 36 °C in water and was recovered from the reaction medium above 38 °C. While the recyclability of the catalyst should be useful for cost reduction, ability of the easy removal of catalyst should be advantageous for its adaptation to the biological systems [34]. The methodology can be extended to other thermoresponsive metathesis catalysts (such as Hoveyda-Grubbs type [35]). We are currently pursuing research in that direction.

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Appendix A. Supplementary material

Supplementary data related to this article can be found at <http://dx.doi.org/10.1016/XXXXXXX>

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Supporting Information

Immobilization of Ruthenium Benzylidene on Thermoresponsive Polymer : Methodology and Application†

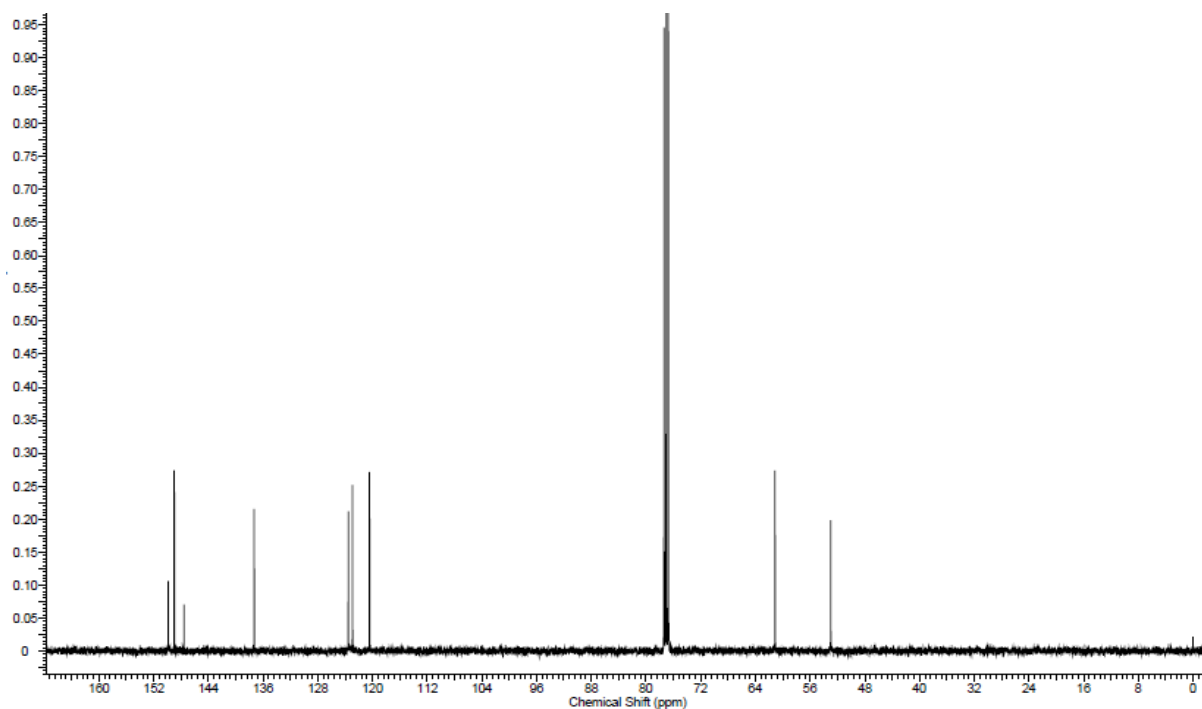
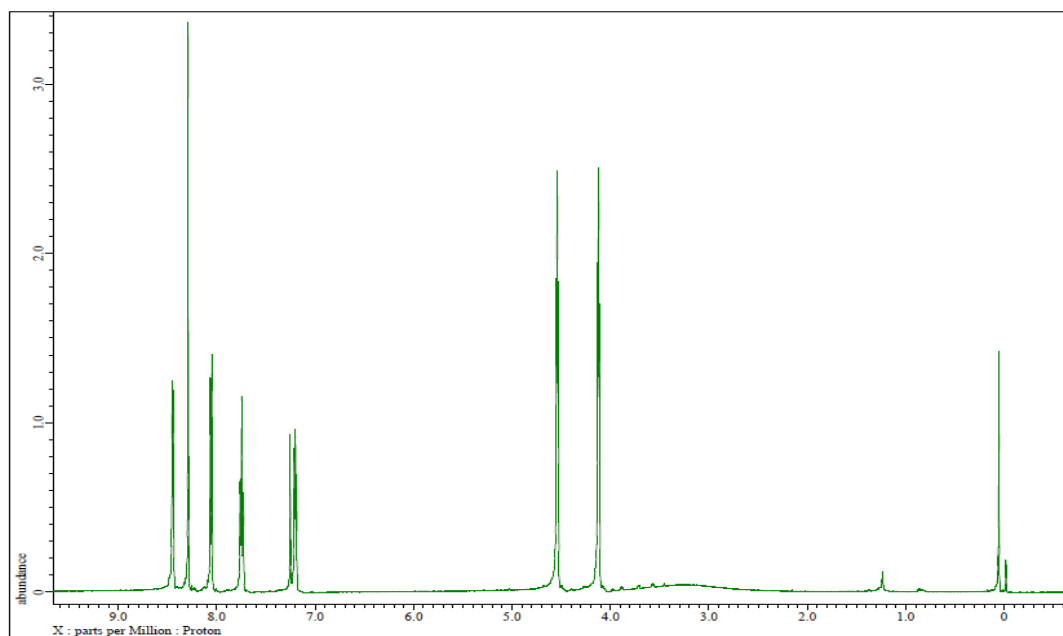
Nagaraju Pentela,^{a,b} P. Murugan,^a S. N. Jaisankar,^a Debasis Samanta,^{a*} and Asit Baran Mandal^{b,c*}

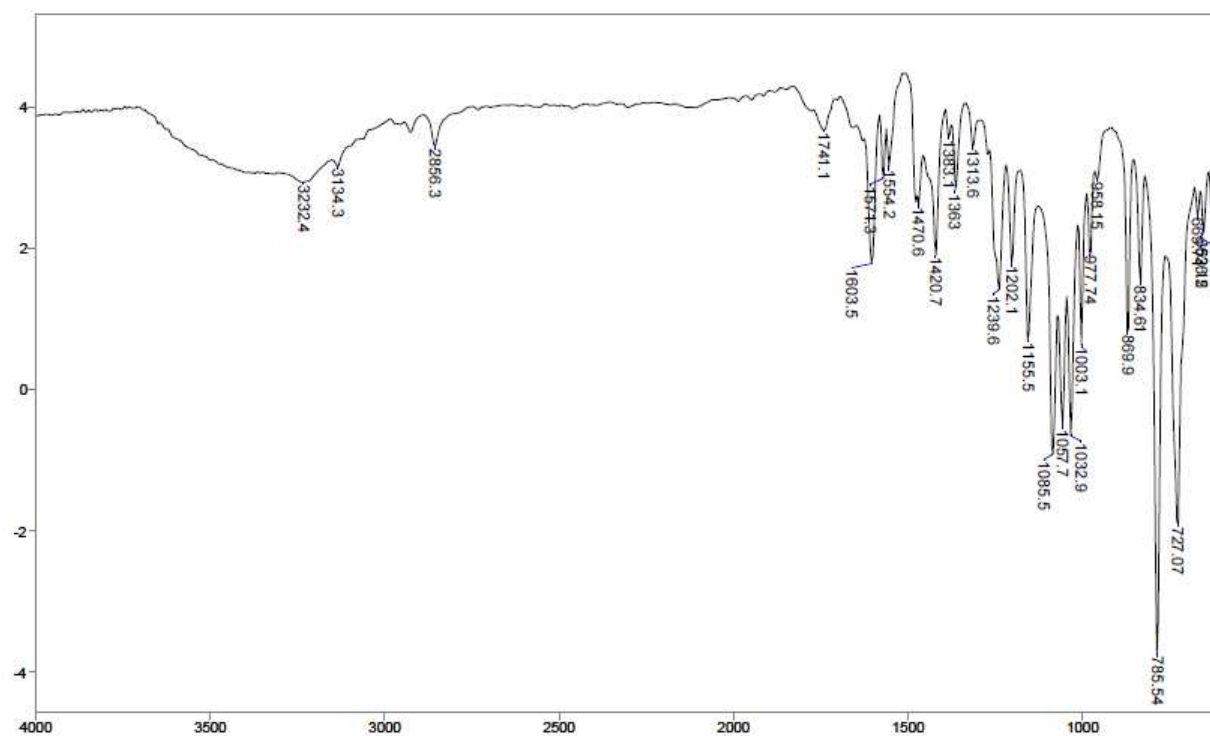
^a Polymer Division, Council of Scientific and Industrial Research (CSIR)- Central Leather Research Institute (CLRI), Adyar, Chennai-600020, India. Fax: 91-44-24911589, Tel: 91 -44 24422059; E-mail: debasis@clri.res.in.

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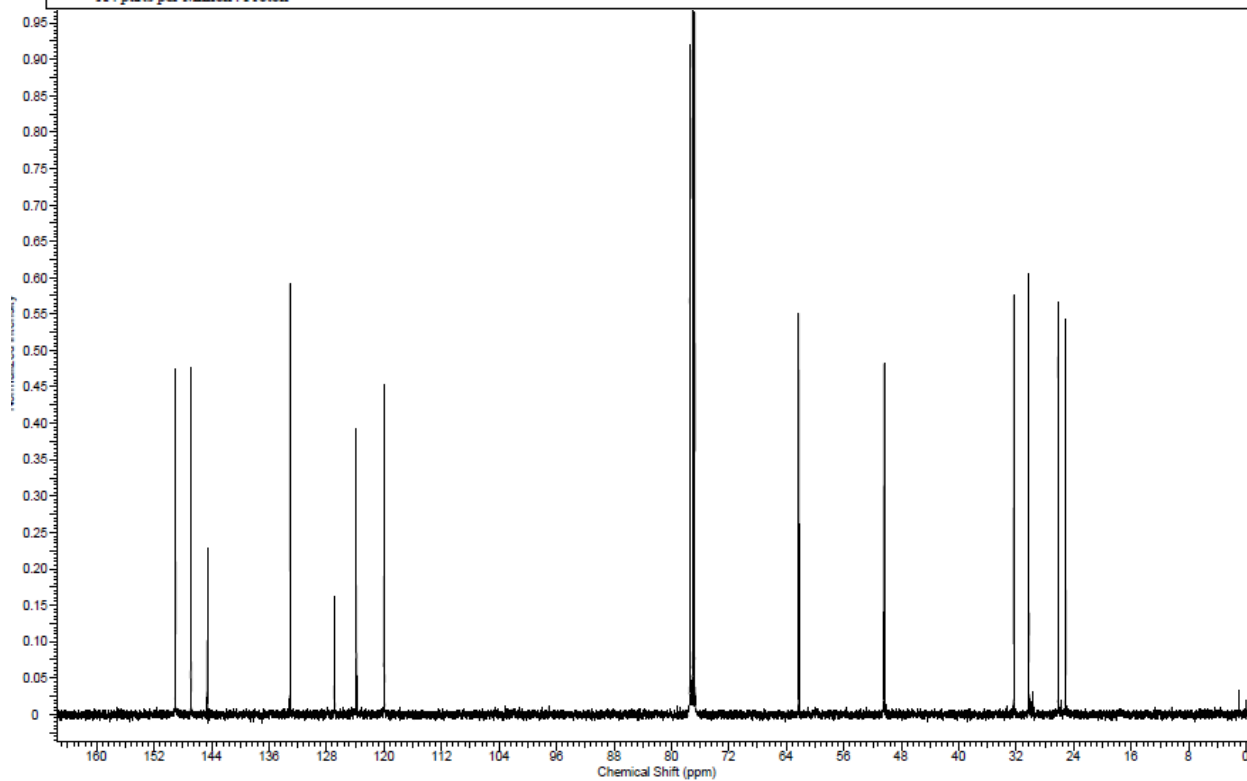
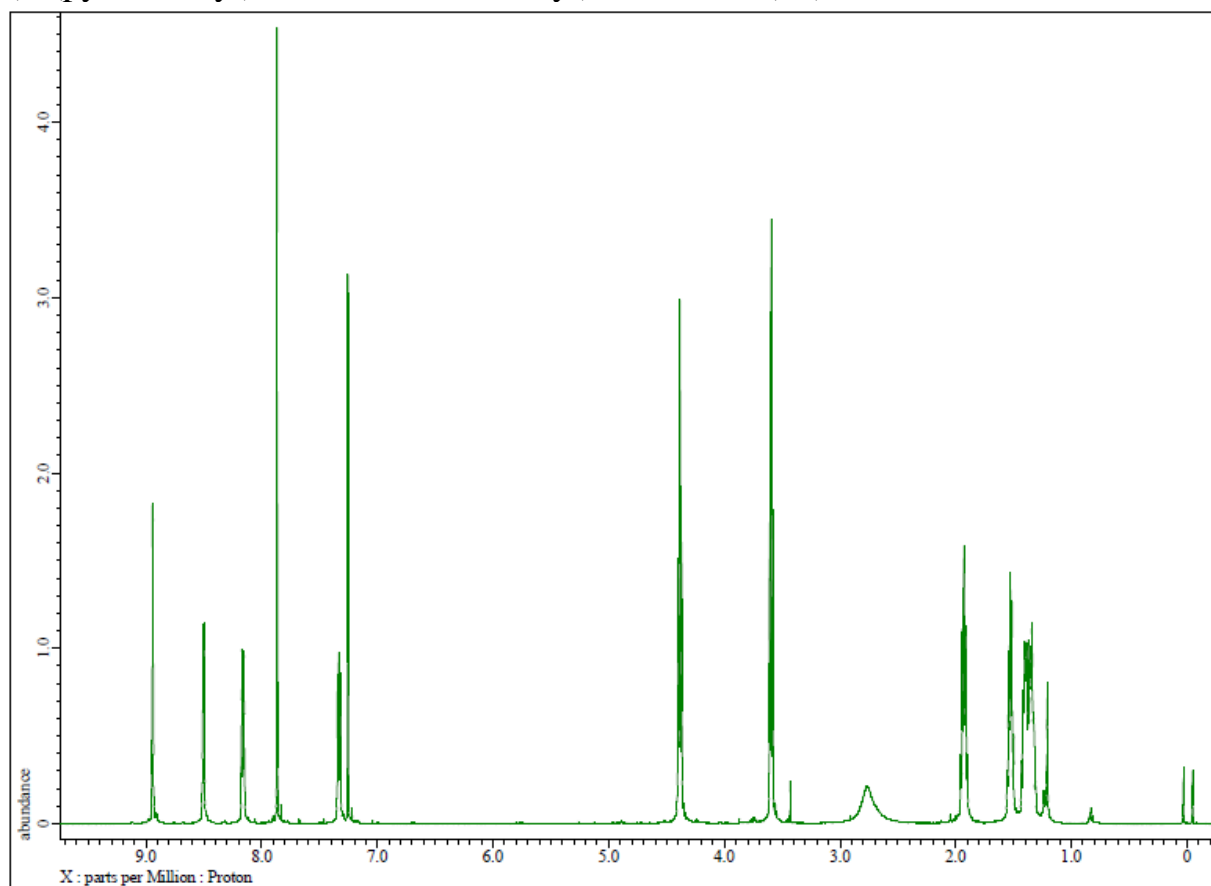
^c Chemical Lab, CSIR-CLRI, Chennai-600020. Fax: 91-44-24912150, Tel: 91 -44 24910846, Email: abmandal@hotmail.com.

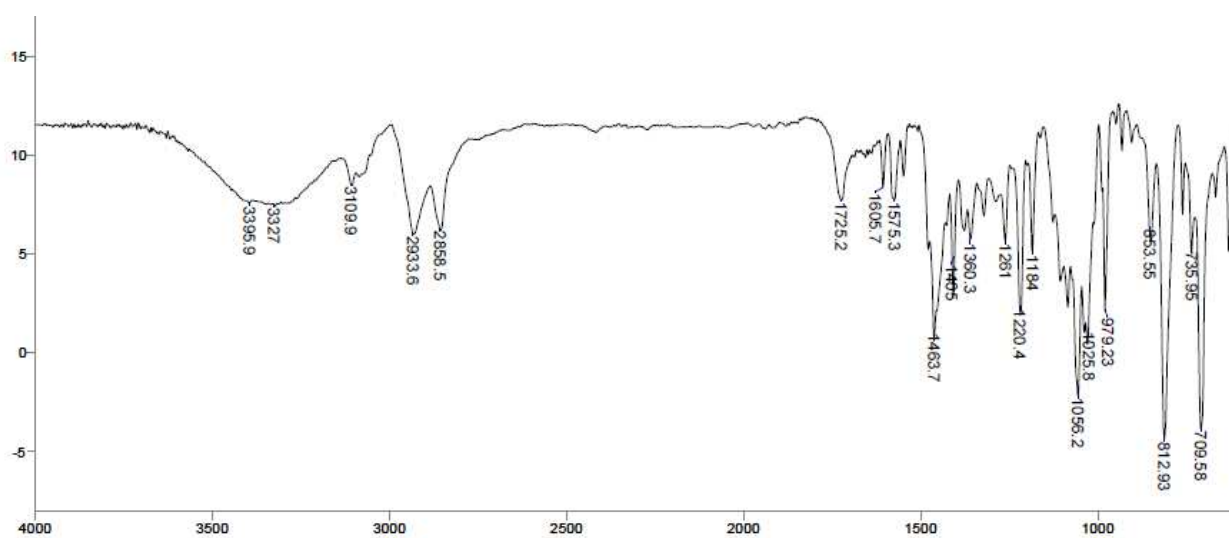
A. Copies of NMR spectra
2-(4-(pyridin-2-yl)-1H-1,2,3-triazol-1-yl)ethanol (3a)



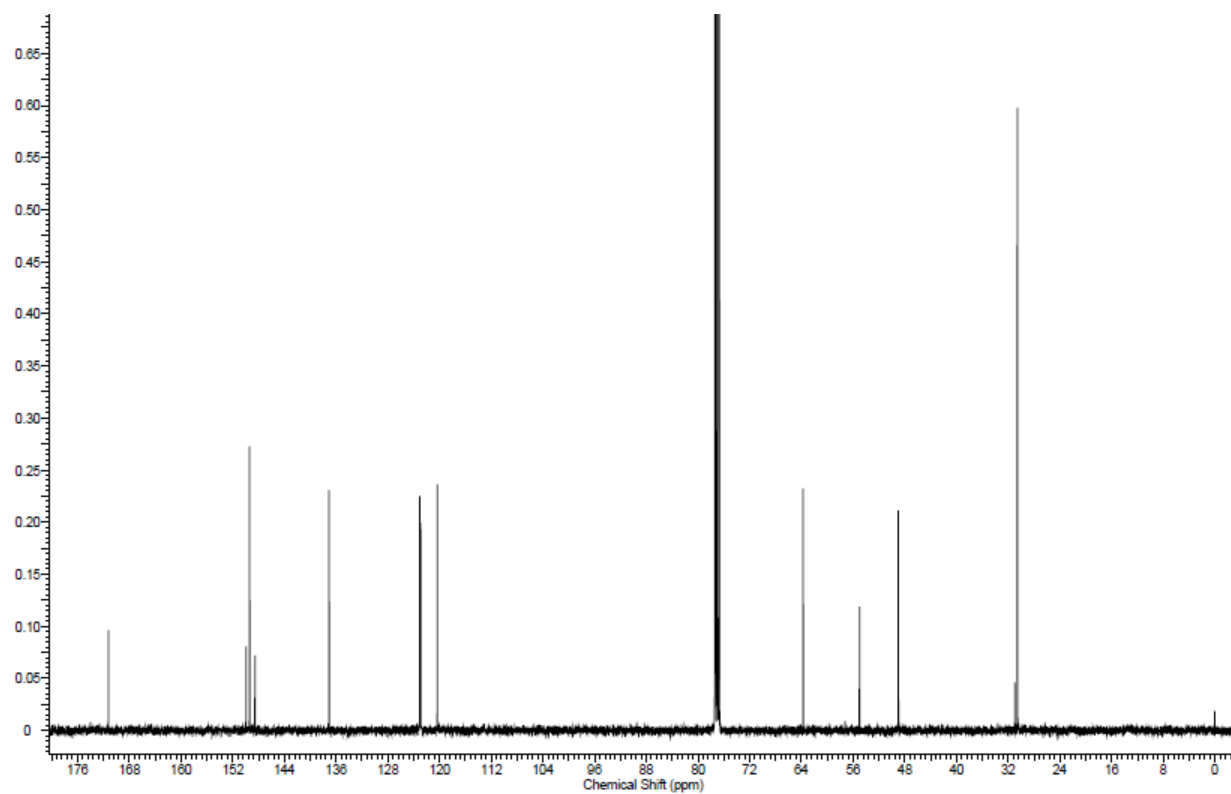
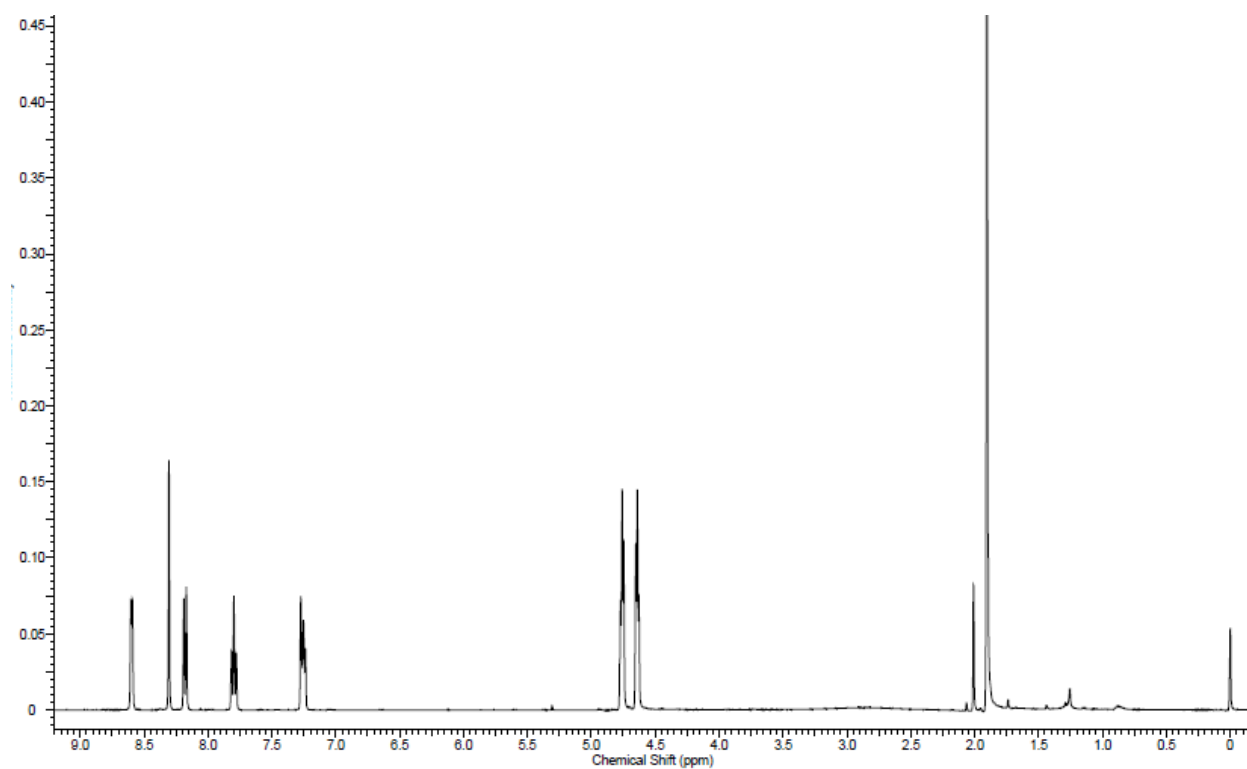


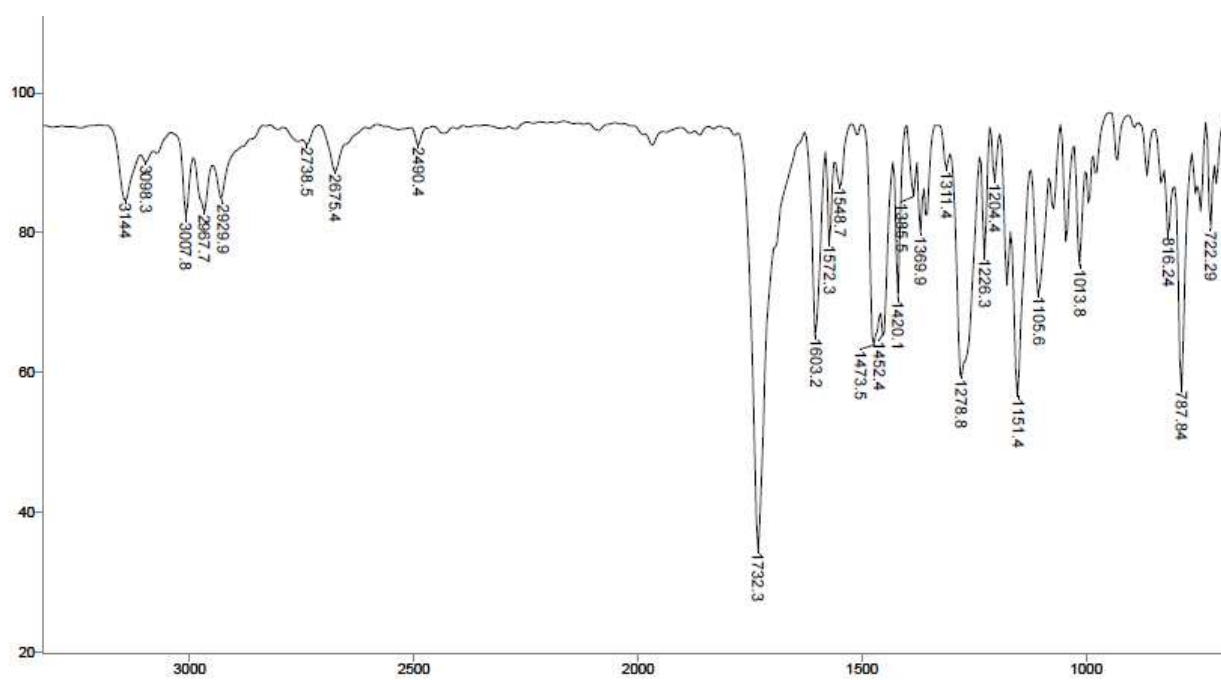
6-(4-(pyridin-3-yl)-1H-1,2,3-triazol-1-yl)hexan-1-ol (3b)



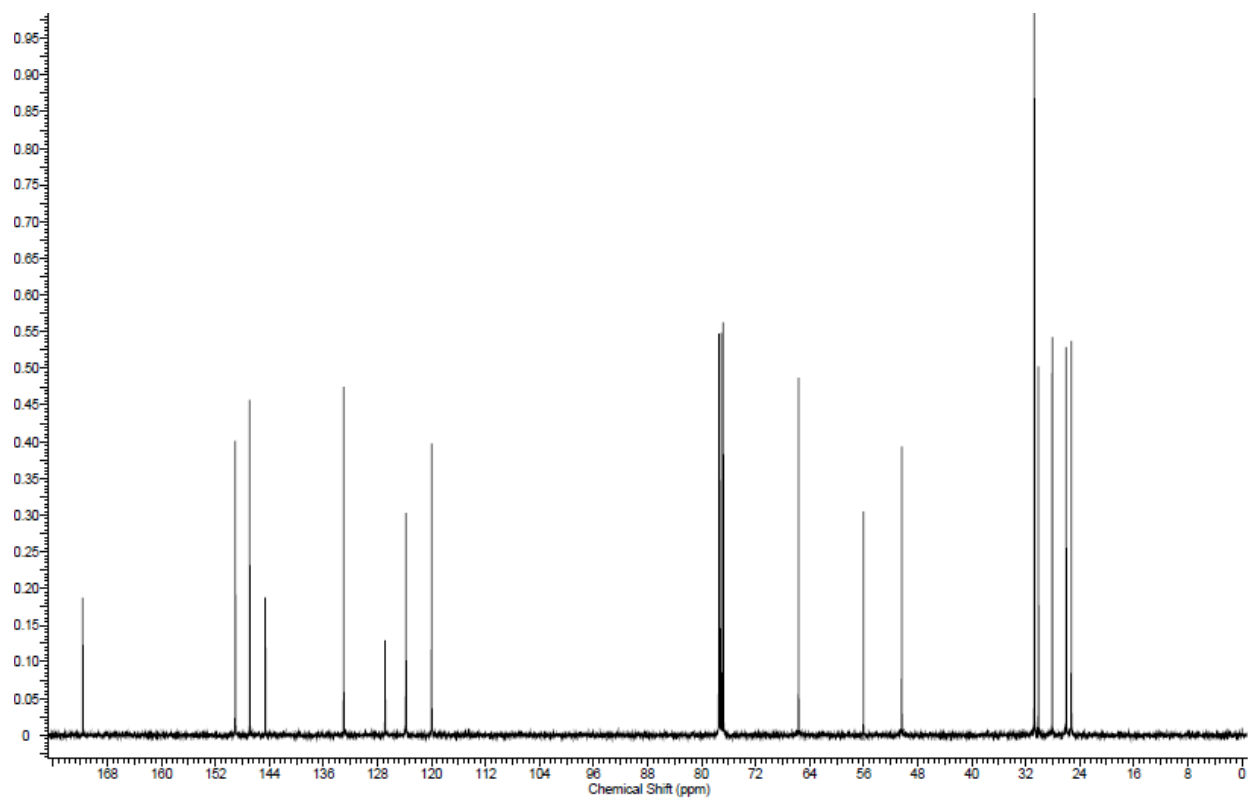
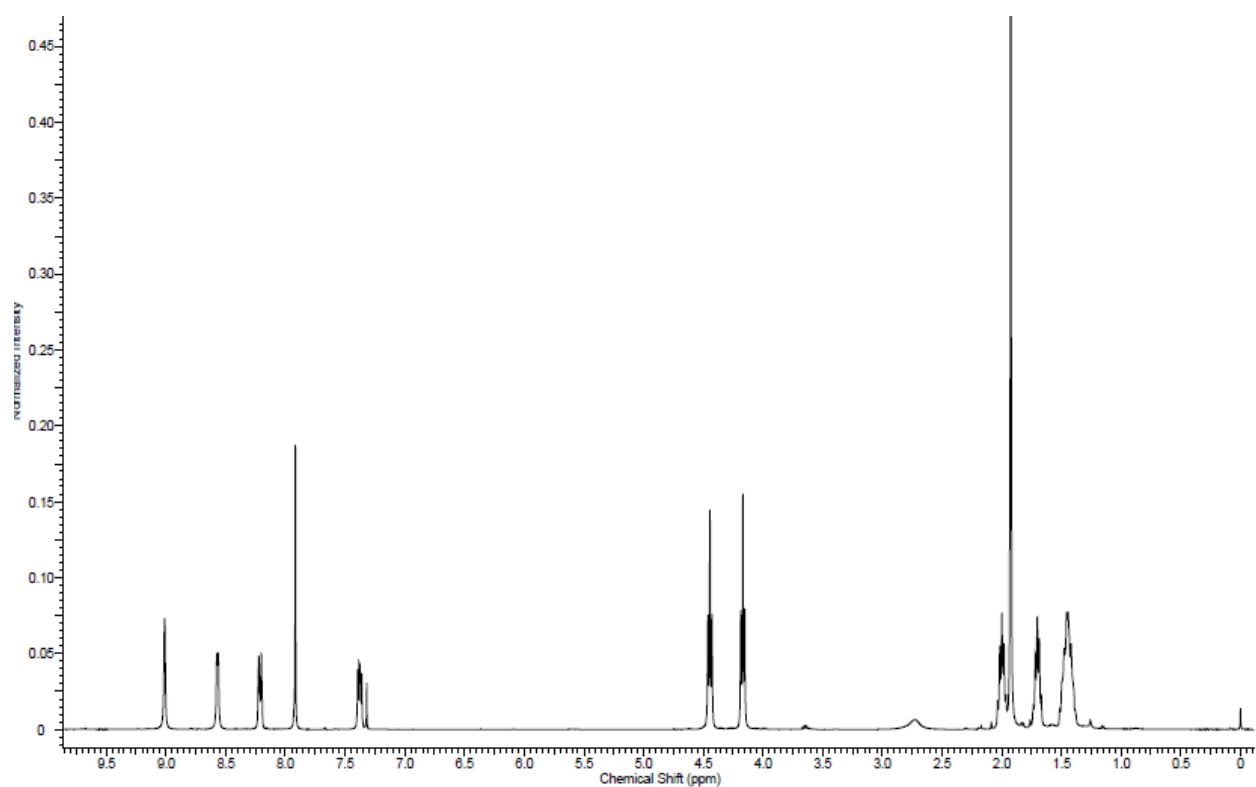


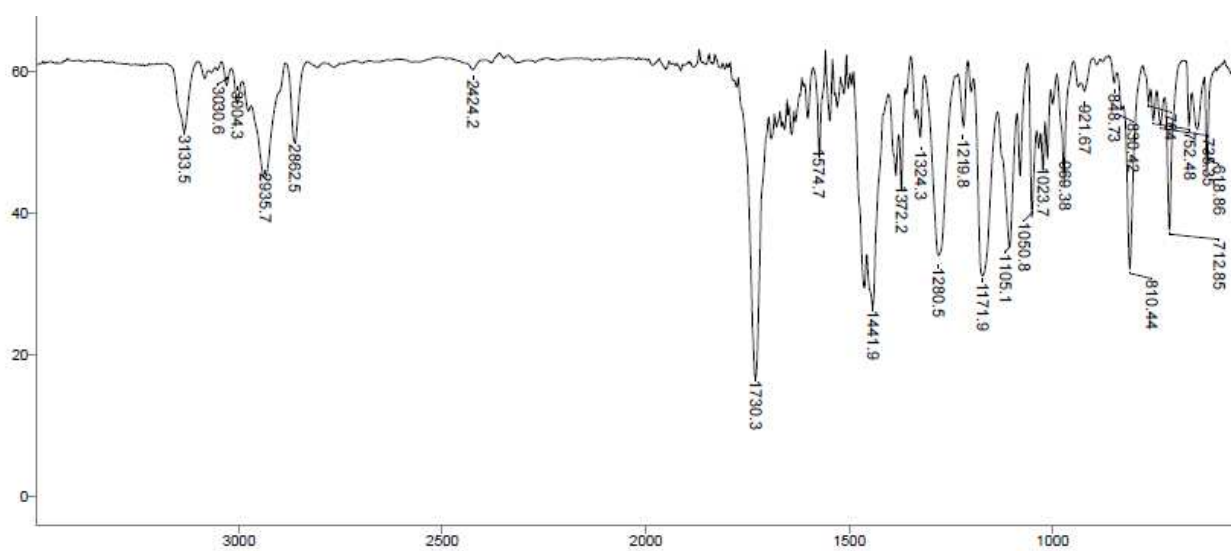
2-(4-(pyridin-2-yl)-1H-1,2,3-triazol-1-yl)ethyl 2-bromo-2-methylpropanoate (5a)



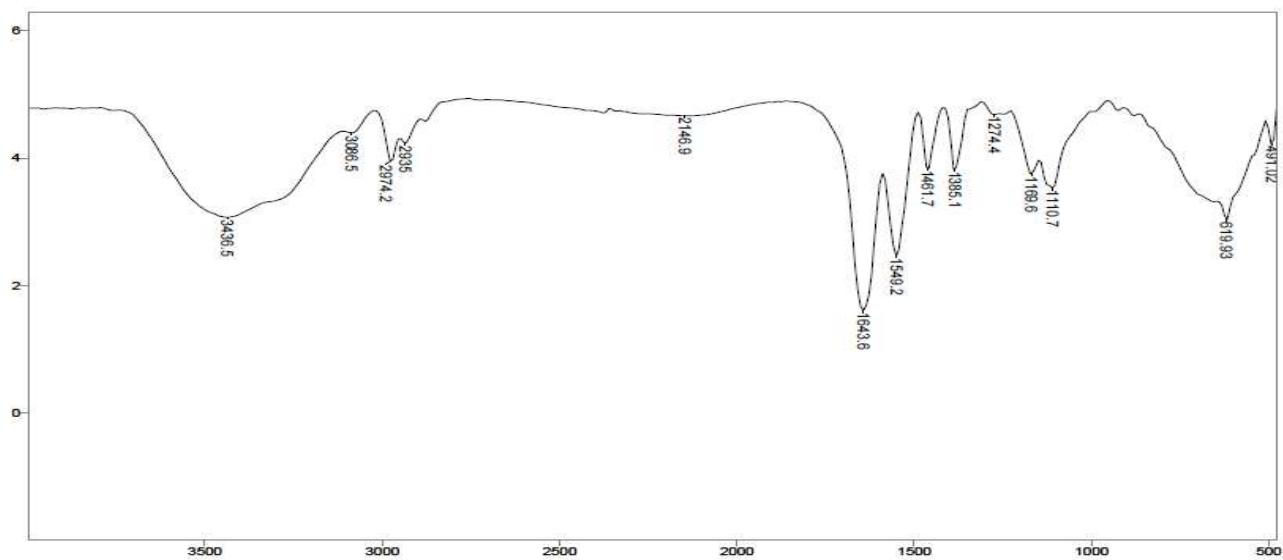
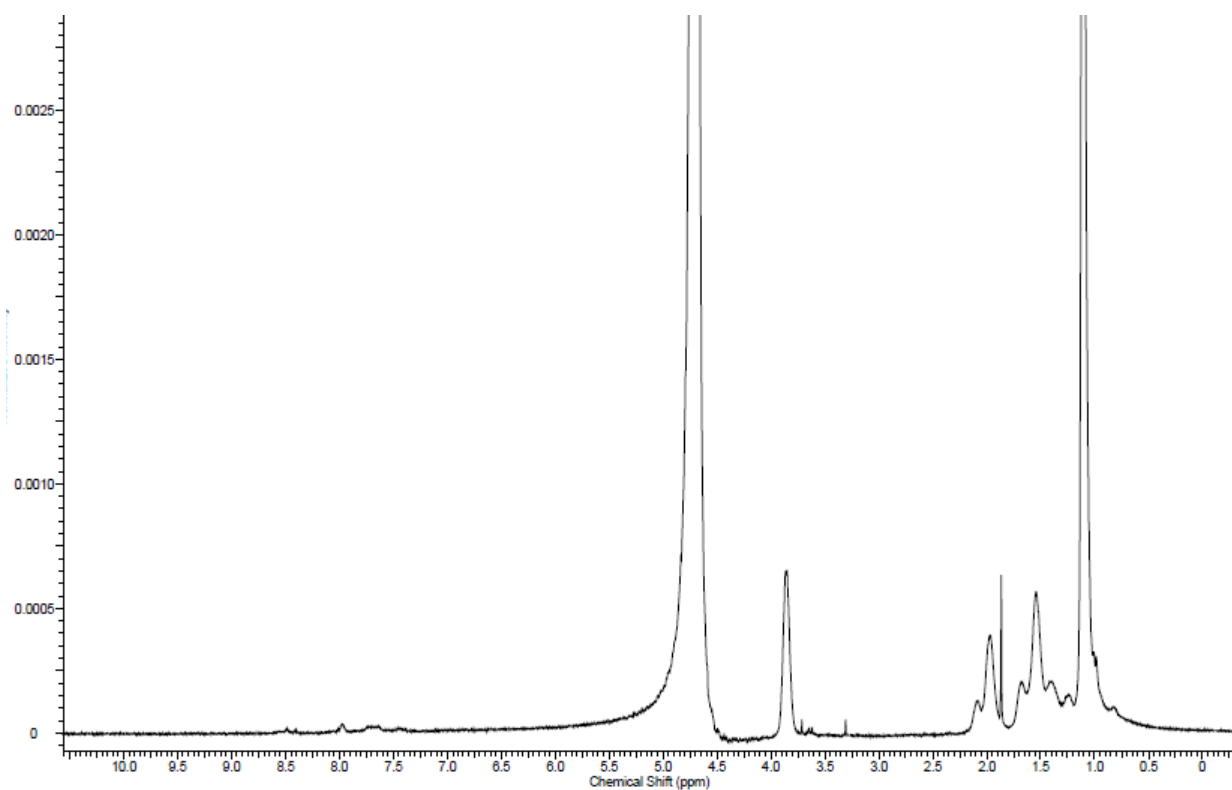


6-(4-(pyridin-3-yl)-1H-1,2,3-triazol-1-yl)hexyl 2-bromo-2-methylpropanoate (5b)

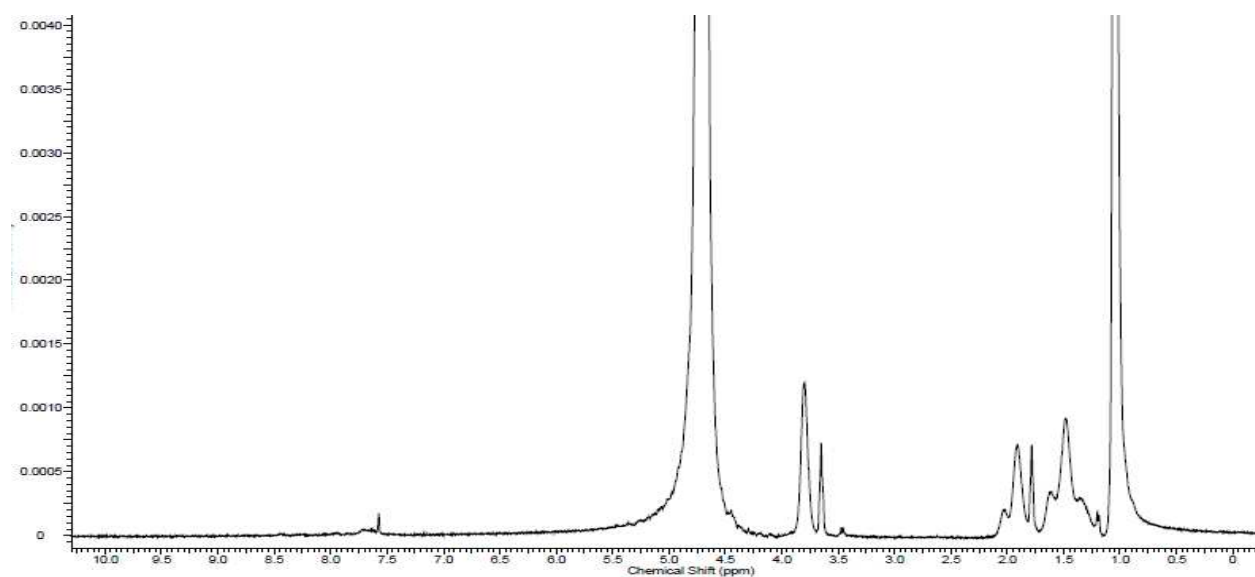
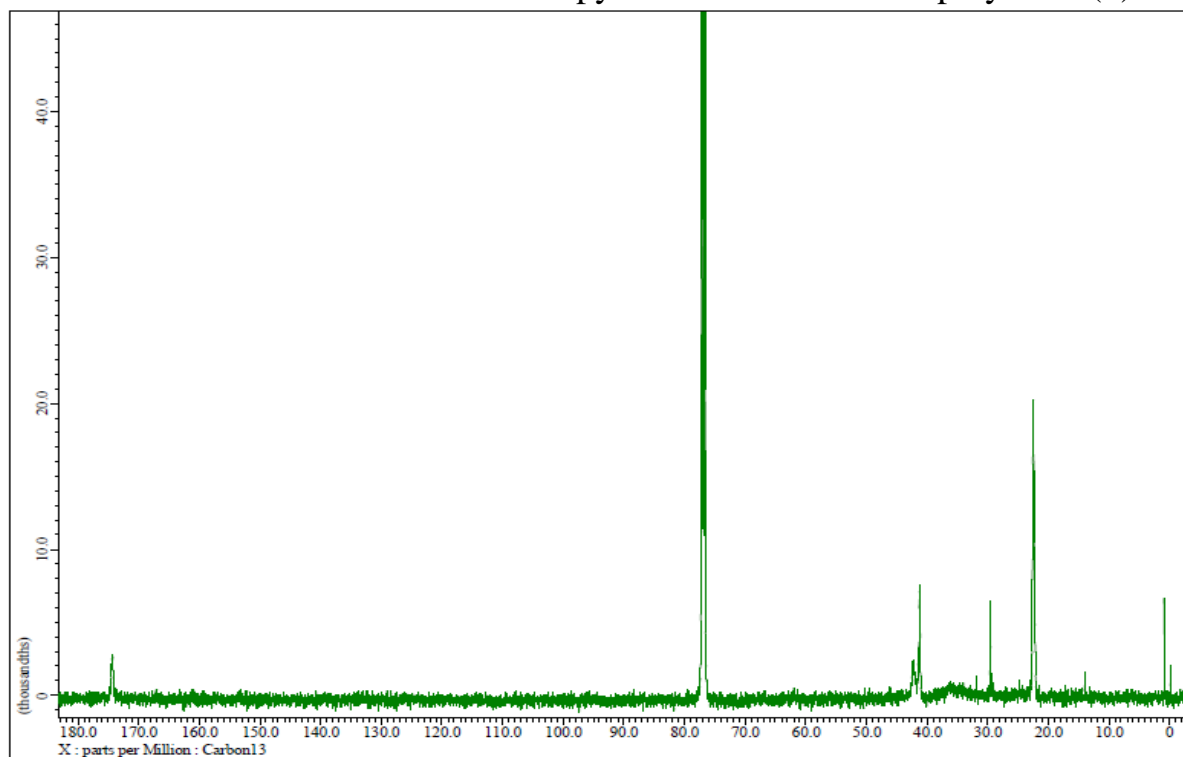


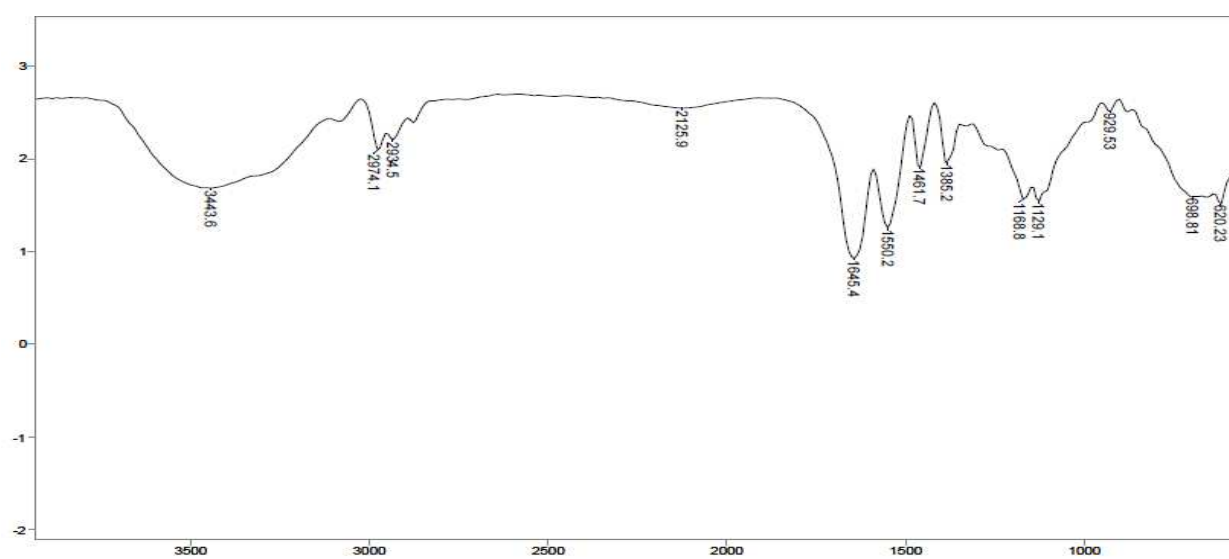
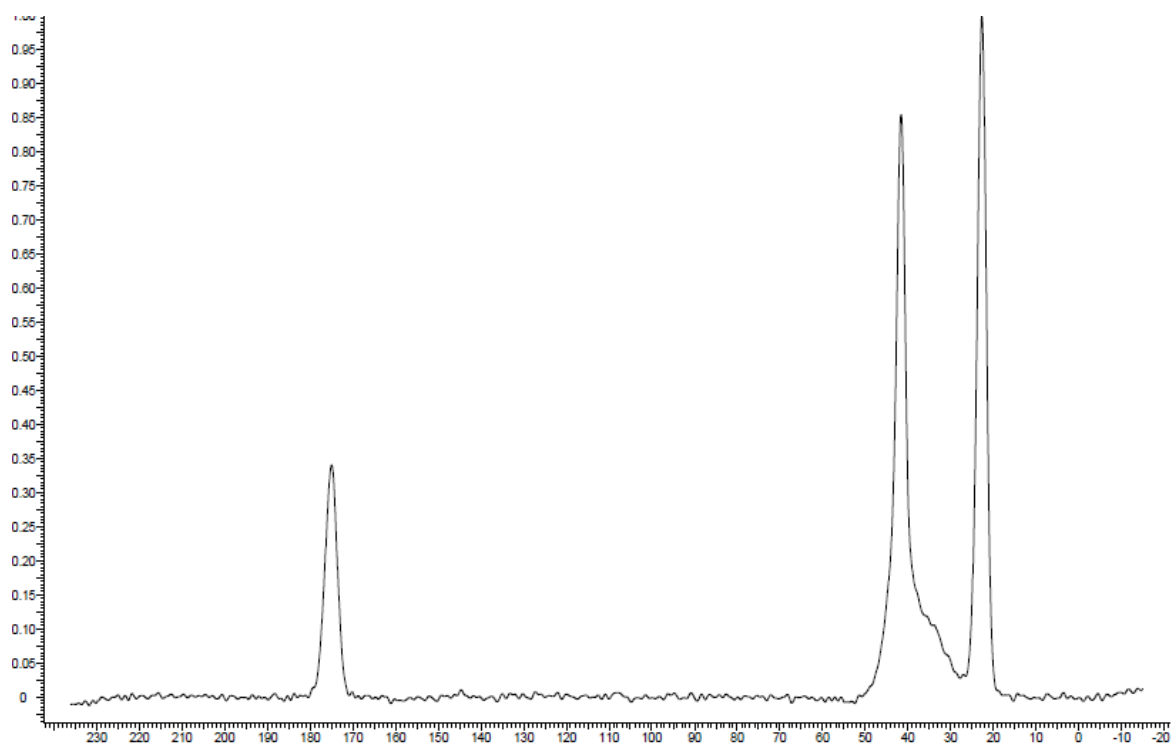


2-substituted pyridine-based NIPAM polymer (7a)

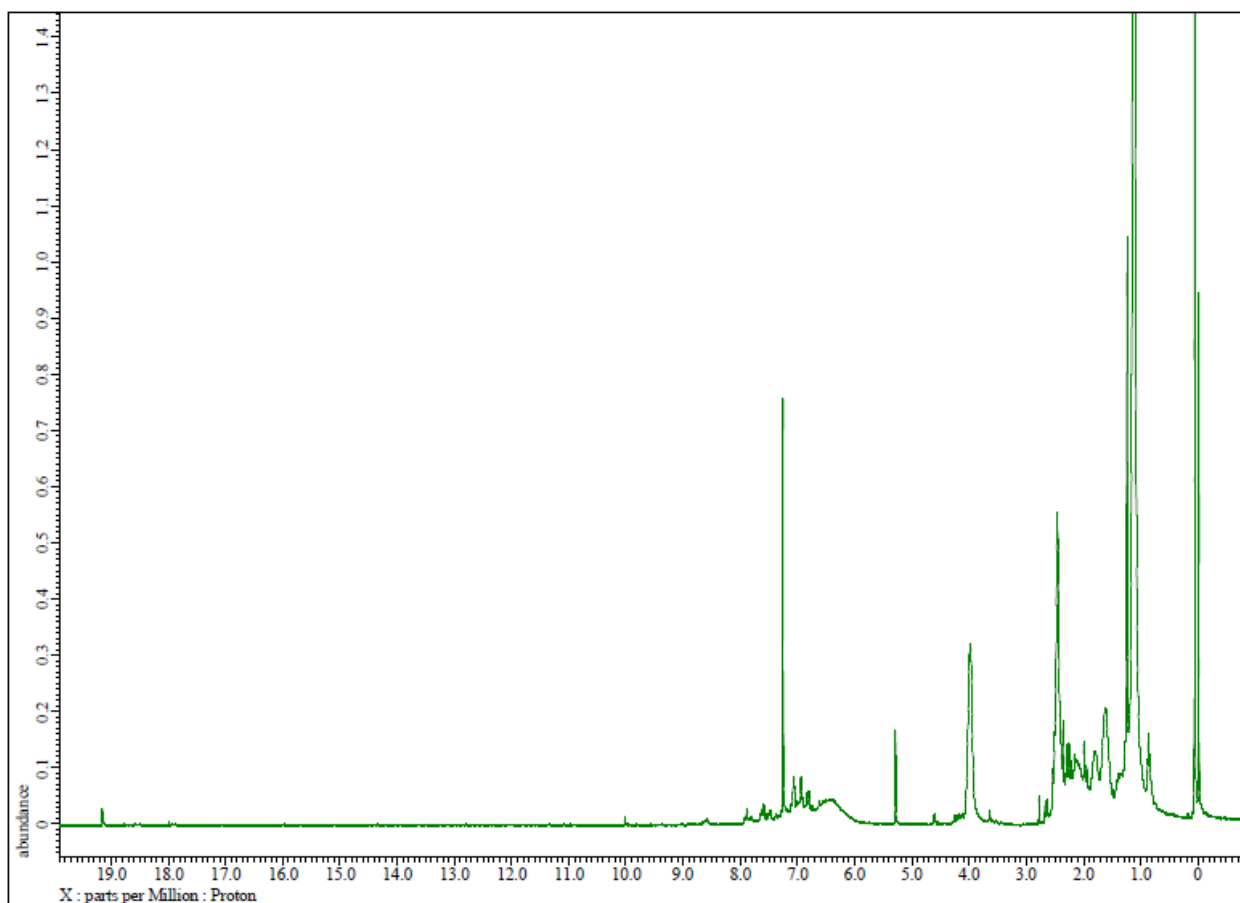


3-substituted pyridine-based NIPAM polymer (7b)

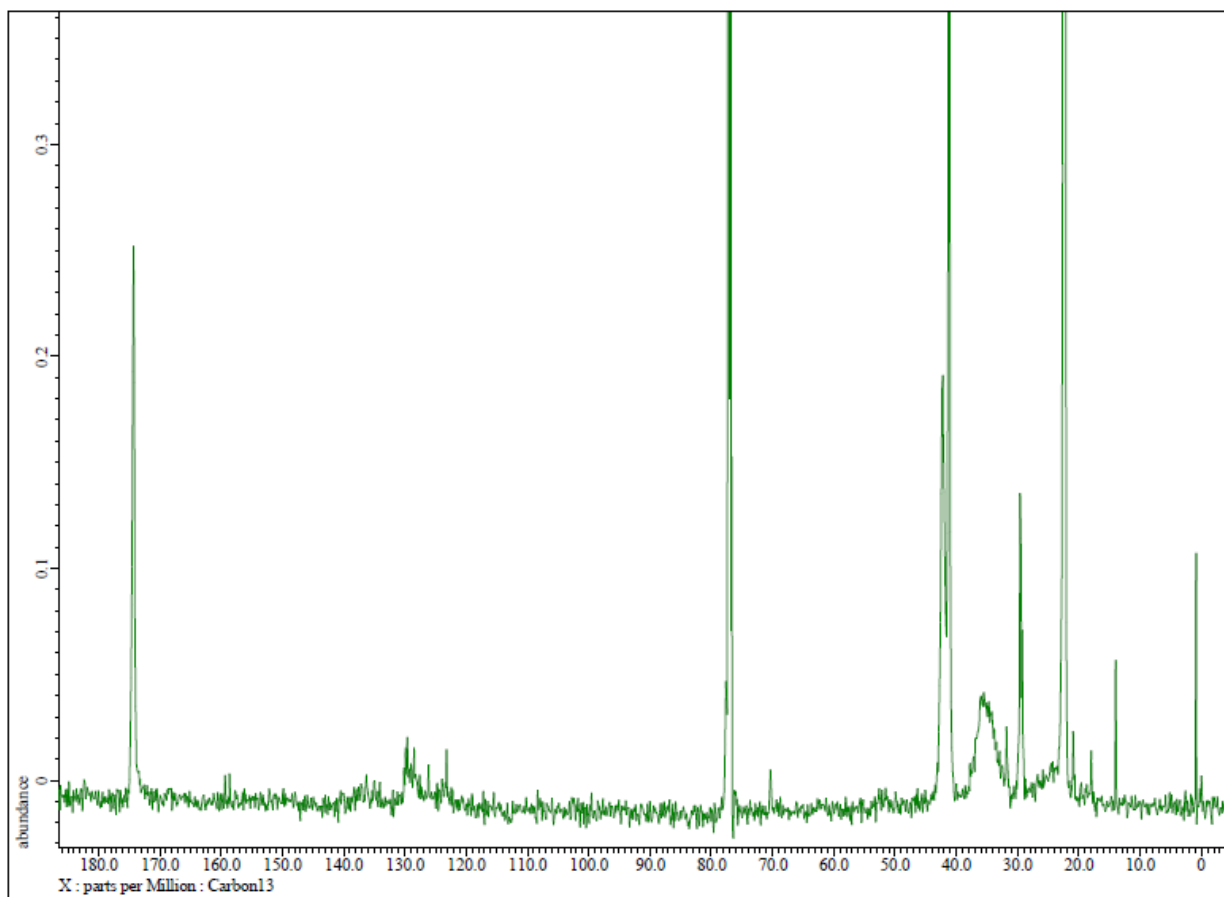
solution state ^{13}C nmr of 3-substituted pyridine-based NIPAM polymer 7(b)solid state ^{13}C nmr of 3-substituted pyridine-based NIPAM polymer 7(b)

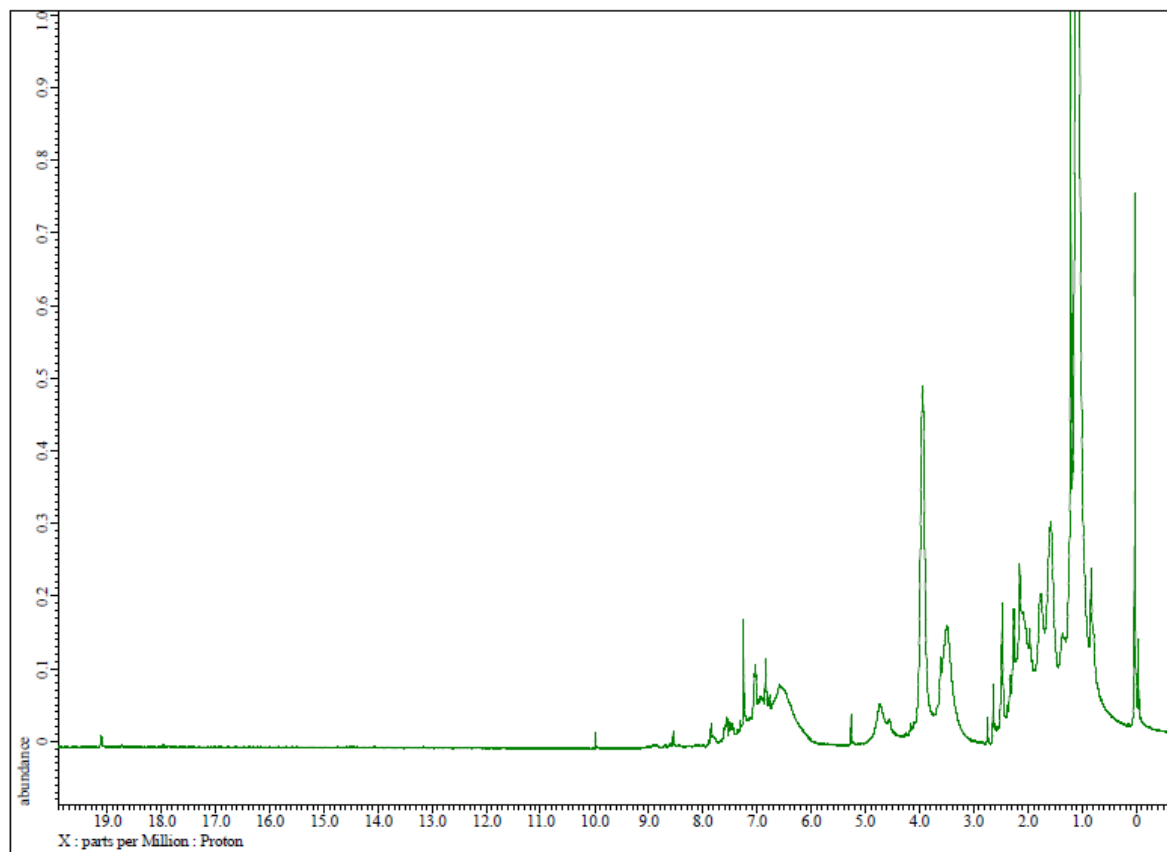


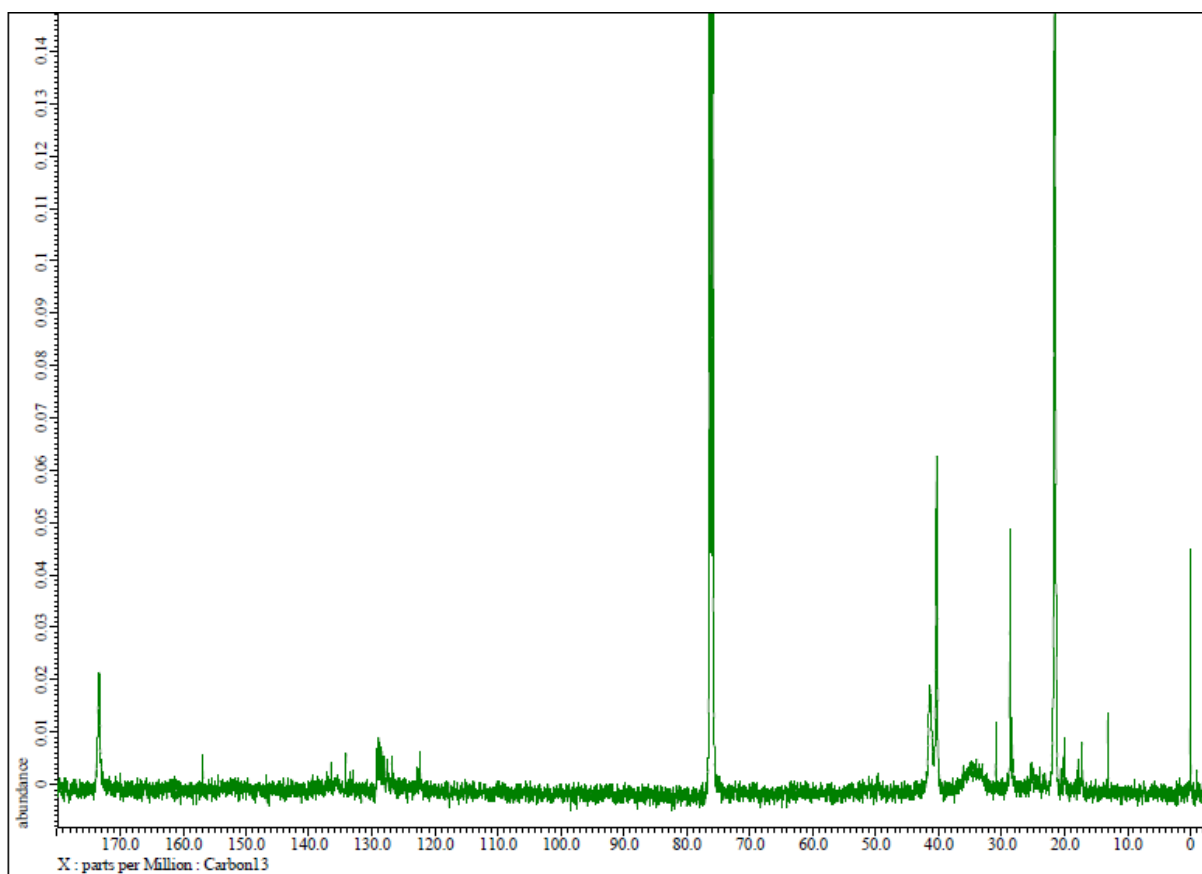
o-substituted ruthenium benzylidene compound, **9a**



^{13}C NMR of *m*-substituted ruthenium benzylidene compound (9a)



m-substituted ruthenium benzylidene compound (9b)

m-substituted ruthenium benzylidene compound (9b)

B. Calculation of the turn over number for the conversion of allyl alcohol using catalyst **9a**

TON = Mol of product / Mol catalyst

Hence the turn over number for the first cycle is $0.95 \times 0.15 \text{ (m. mol)} / 0.0038 \text{ (m. mol)} = 38$ (round off figure)

For the second cycle is: $0.66 \times 0.15 \text{ (m. mol)} / 0.0038 \text{ (m. mol)} = 26$ (round off figure)

C. ICP studies

Ruthenium metal concentration was determined by Inductively Coupled Plasma (ICP) experiments (using model prodigy XP, make: Leeman lab) before and after metathesis reaction for different cycles. For this, we took out 0.2 ml each from cold D₂O solution (soluble part) before or after reaction for different cycles and diluted in cold acidified 25 ml water. We presumed that leached out ruthenium complex is insoluble in small quantity of water while polymer bound complex is soluble in water. We observed that concentration of ruthenium complex in solution decreased for both the catalyst after reaction (manuscript text) indicating the leaching phenomenon. Further, we compared the content of ruthenium in solution for “after the first cycle” and “after the thirds cycle”. We found only a slight change of ruthenium content between “after the first cycle” and “after the 3rd cycle”, indicating that most of leaching phenomenon occurred during the first cycle of reaction.