ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

EFFICIENT POST-POLYMERIZATION MODIFICATION OF PENDANT ALDEHYDE FUNCTIONAL POLYMER VIA REDUCTIVE ETHERIFICATION REACTION

M.Sc. THESIS

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Department of Chemistry

Chemistry Programme

OCTOBER 2022

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ISTANBUL TEKNİK ÜNİVERSİTESİ ★ LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

YAN GRUBUNDA ALDEHİT BULUNAN POLİMERİN İNDİRGEYİCİ ETERLEŞME REAKSİYONU İLE POLİMERLEŞME SONRASI MODİFİKASYONU

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To my mother,

FOREWORD

Switching to a new university and a new research area for grad school was not easy but I must say that it was one of the best decisions I made in my 24-year long life so far. I feel lucky to be a part of Istanbul Technical University as both a student and an employee.

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October 2022 Emre AKAR
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ABBREVIATIONS

^{1}H NMR	: Hydrogen Nuclear Magnetic Resonance Spectroscopy
^{13}C NMR	: Carbon Nuclear Magnetic Resonance Spectroscopy
GPC	: Gel Permeation Chromatography
THF	: Tetrahydrofuran
DMSO	: Dimethylsulfoxide
FT-IR	: Fouirer-Transform Infrared Spectrometry
MHz	: Megahertz
RER	: Reductive Etherification Reaction
FRP	: Free Radical Polymerization
FPT	: Freeze-Pump-Thaw

SYMBOLS

°C : Celcius
Đ : Dispersity
δ : Chemical Shift
M_n : Number-Average Molecular Weight
M_w : Weight-Average Molecular Weight

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EFFICIENT POST-POLYMERIZATION MODIFICATION OF PENDANT ALDEHYDE FUNCTIONAL POLYMER VIA REDUCTIVE ETHERIFICATION REACTION

SUMMARY

Providing novel synthesis methods for functional polymers designed for specific applications is crucial in polymer chemistry research. While the most straightforward method for preparing functional polymers is the polymerization of specifically designed functional monomers, post-polymerization modification (PPM) of polymers is also an essential tool to obtain desired polymers. PPM is particularly useful when direct polymerization of functional monomers is not suitable due to the possibility of side reactions in the polymerization conditions that can lead to the loss of desired functionality. A good PPM technique should fulfill some requirements such as quantitative yields, easy to conduct under mild conditions and easy to purify. The reactions classified under the term “click” chemistry are commonly used for PPM of polymers.

Aldehydes have always been a privilege in polymer science since the aldehyde carbonyl readily undergoes several reactions efficiently under mild conditions, ranging from non-aldol reactions to multicomponent reactions, mostly without any additive. Aldehyde-functional polymers can be synthesized via polymerization of monomers with aldehyde functionality. Polymers with pendant aldehyde groups are known as good platforms for PPM given the reactivity of the aldehyde group.

Reductive etherification reaction (RER) is a method to synthesize ethers from ketone or aldehyde groups in the presence of an organosilane reductant, generally along with a Lewis or Bronsted-Lowry acid catalyst. Both symmetrical and unsymmetrical ethers can be obtained via the RER. While self-reduction of carbonyl compounds yields to symmetrical ethers, alcohols are used as nucleophiles to prepare unsymmetrical ethers. The RER is known to have high efficiency and good functional group tolerance under optimum conditions. It was shown that chlorodimethylsilane (CDMS)-mediated RER is a robust method for both synthesis and PPM of polymers.

In the current study, the versatility of the aldehyde group has been exploited using the RER. For this purpose, a polymer platform containing pendant aldehyde units was synthesized via free radical polymerization (FRP) and modified with a variety of alcohols using CDMS as the reducing agent. The resulting polymers were characterized by using ^{1}H NMR, ^{13}C NMR, GPC and FT-IR.

YAN GRUBUNDA ALDEHİT BULUNAN POLİMERİN İNDİRGEYİCİ ETERLEŞME REAKSİYONU İLE POLİMERLEŞME SONRASI MODİFİKASYONU

ÖZET

Spesifik uygulamalar için tasarlanmış fonksiyonel polimerler için yeni sentez yolları sağlamak polimer kimyası araştırmalarında çok önemlidir. Fonksiyonel polimerleri hazırlamak için en direkt metot spesifik olarak tasarlanmış fonksiyonel monomerlerin senteziyken polimerlerin polimerleşme sonrası modifikasyonu (PPM) da istenen polimerlerin eldesi için temel bir yoldur. PPM, özellikle, fonksiyonel monomerlerin direkt polimerizasyonunun polimerizasyon koşullarında istenen fonksiyonelliğin kaybına yol açabilecek yan reaksiyonlardan dolayı uygun olmadığı durumlarda faydalıdır. İyi bir PPM tekniği kantitatif verim, ılıman koşullarda kolay gerçekleştirme ve kolay saflaştırma gibi bazı gereklilikleri sağlamalıdır. "Click" kimyası terimi altında sınıflandırılan reaksiyonlar PPM için yaygın olarak kullanılmaktadır.

Aldehit karbonili, non-aldol reaksiyonlarından çok komponentli reaksiyonlara kadar, çoğu zaman bir katkı maddesi olmadan, kolayca reaksiyon verdiğinden aldehitler polimer kimyasında her zaman bir ayrıcalık olmuştur. Aldehit-fonksiyonel polimerler, aldehit fonksiyonelitesine sahip monomerlerin polimerizasyonundan elde edilebilir. Aldehit grubunun reaktvitesinden dolayı yan zincirinde aldehit grubuna sahip polimerlerin PPM için iyi platformlar olduğu bilinmektedir.

İndirgeyici eterleşme reaksiyonu (RER), genellikle bir Bronsted-Lowry ya da Lewis asidiyle beraber bir organosilan indirgeni varlığında keton ya da aldehit gruplarından eter sentezlemek için kullanılan bir metottur. RER yoluyla hem simetrik hem de asimetrik eterler sentezlenebilir. Karbonil bileşiklerinin kendi kendine indirgenmesi simetrik eterleri üretirken asimetrik eterleri hazırlamak için alkoller nükleofil olarak kullanılır. RER'in optimum koşullar altında yüksek verimliliğe ve iyi fonksiyonel grup toleransına sahip olduğu bilinmektedir. Klorodimetilsilan (CDMS)-aracılı RER'in polimerlerin hem sentezi hem de PPM'si için güçlü bir metot olduğu gösterilmiştir.

Bu çalışmada aldehit grubunun çok yönlülüğünden RER kullanılarak faydalanılmıştır. Bu amaçla yan zincirinde aldehit birimleri taşıyan bir polimer platformu serbest radikal polimerizasyonu (FRP) ile sentezlenmiş ve birçok farklı alkolle indirgeyici ajan olarak kullanılan CDMS kullanılarak modifiye edilmiştir. Elde edilen polimerler ^{1}H NMR, ^{13}C NMR, GPC ve FT-IR kullanılarak karakterize edilmiştir.

1. INTRODUCTION

Preparing polymers with functional or functionalizable groups at the end or side chain for certain applications is always desired in polymer chemistry [1,2]. Preparing these polymers via direct polymerization of functional monomers is the most employed method but sometimes it is complicated to polymerize functional monomers via general polymerization methods and thus designing a functional monomer for a particular polymerization method is needed. This strategy limits both the functionality and available polymerization methods. Post polymerization modification (PPM) of polymers is a crucial method to introduce functionality into a polymer chain and it has gained significant interest over the past two decades. A good PPM technique should be with high yield, easy to conduct under mild conditions and easy to purify [2-7].

Click chemistry term defines certain chemical reactions that follow some criteria such as being modular, with high yield, and easy to purify by simple methods like crystallization or distillation [8]. Cu(I) catalyzed azide-alkyne cycloaddition reaction (CuAAC), Diels-Alder (DA) reaction, and thiol-ene reaction are examples of “click” reactions and they are commonly used in polymer chemistry as a tool for PPM [9].

Polymers with pendant aldehyde groups can also be a good platform for PPM given the reactivity of the aldehyde group. Those polymers are generally synthesized by the polymerization of aldehyde-functional monomers such as 4-vinylbenzaldehyde and 4-formylphenyl methacrylate (4FPM) [10]. Aldehyde-functional polymers have received substantial interest in the literature, especially in the field of polymer-biomolecule conjugations as it is possible to functionalize aldehyde carbonyl efficiently in many ways [10-25]. In addition, the aldehyde group is a very precursor for the synthesis of different polymers. Aldehyde group can easily undergo oxime/imine/hydrazone ligations with amines, non-aldol reactions, and multicomponent reactions such as Passerini and Ugi 4-component reactions, as well as A3 coupling and organometallic reactions. These reactions generally proceed with high yield under mild and mostly additive-free conditions [10, 26-46].

Reductive etherification reaction (RER) is a chemical reaction where ethers are prepared from aldehydes or ketones via alcohols in the presence of an organosilane-based reducing agent, generally along with an acid catalyst. The RER was introduced to literature in 1970s by Doyle group [47-49]. After that many other groups have used the RER to prepare symmetrical or unsymmetrical ethers [50-55].

Application of the RER in polymer chemistry was very limited until recently. Yokozawa group successfully extended the RER to the macromolecular level in 1990s [56-60], and Luleburgaz *et al*. rejuvenated this chemistry in polymer science with two successive studies published in 2021 and 2022. First, they showed that the RER can be used to modify polymers [61]. In that study, they synthesized a polyketone platform and then subjected it to the RER via alcohols at room temperature to prepare several alkoxy-functional polymers in high yield. Chlorodimethylsilane (CDMS) was selected as the reducing agent since it has both reducing and Lewis acid properties. The RER efficiencies were between 39-90% and diverse alcohols with different structural properties were successfully attached to the polymer backbone. In a more recent study [62], they employed CDMS-mediated RER in the synthesis of linear polyethers using terephthalaldehyde (TPA) and structurally different diols. It was found that by adjusting the optimum conditions, a series of polyethers with different chemical backbones could be prepared rapidly at room temperature with high molecular weights up to 110.4 kDa. These studies have demonstrated that CDMS-mediated RER is a robust and versatile strategy for polymer chemistry.

In the current work, as depicted in Figure 1.1, a polymer with a pendant aldehyde group was synthesized via free radical polymerization (FRP) of 4FPM in the presence of 1,1'-azobis(cyclohexanecarbonitrile) (ABCN) as a radical initiator. The synthesized polymer platform was then subjected to the RER in the presence of CDMS and different alcohols with various functional groups in a nitromethane/dichloromethane (CH_3NO_2/CH_2Cl_2) solvent system. The reactions were performed at room temperature overnight to afford different alkoxy-functional polymers. Effects of different alcohols and mole equivalents of reactants on PPM were investigated. The resulting polymers were characterized by several spectroscopic methods such as ^1H and ^{13}C nuclear magnetic resonance (NMR) spectroscopies, Fourier transform infrared (FT-IR) spectroscopy, and gel permeation chromatography (GPC). It was found that modifications proceeded in high yields (95-100%).

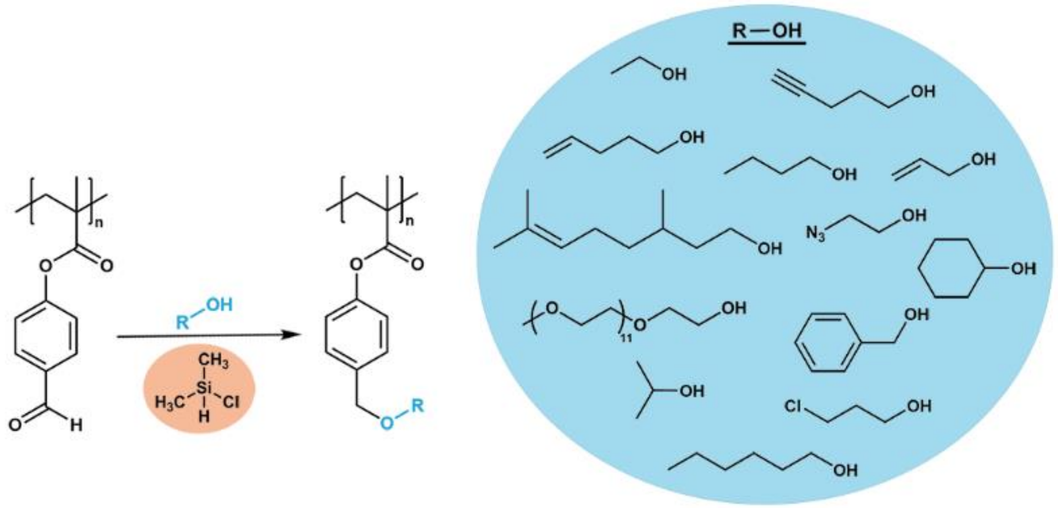

Figure 1.1: PPM of aldehyde-functional polymer.

2. THEORETICAL PART

2.1 Post-Polymerization Modification (PPM)

Functional polymers needed for useful applications can be obtained by either direct polymerization of functional monomers or functionalization of parent polymers. Both polymerization and postpolymerization modification (PPM) techniques advanced greatly in recent decades. While both techniques have their own advantages and disadvantages PPM allows polymer chemists to synthesize functional polymers which otherwise would have partially or fully lost the needed functional groups because of side reactions under polymerization conditions. Also, PPM enables the synthesis of series of functional polymers with the same degrees of polymerization and molecular weight distributions of the parent polymer [2].

A highly efficient, easy-to-perform and purify PPM technique is always desired. In 2001 Sharpless group introduced the concept of “click” chemistry which represents the chemical reactions that follow some stringent criteria such as being modular, wide in scope, having very high yields, generating only inoffensive byproducts, being easy to purify by nonchromatographic methods like distillation or crystallization and being stereospecific (but not necessarily enantioselective) [8]**.** This groundbreaking concept has received very great attention from chemists and material scientists over the last two decades. Some selected “click” chemistry reactions and their applications in polymer chemistry will be briefly given here.

2.1.1 Cu (I) catalyzed azide-alkyne cycloaddition reaction (CuAAC)

The Huisgen reaction of 1,3-dipolar cycloaddition of an organic azide and alkyne has been known since 1960s [63]. In this concerted reaction, azide and alkyne compounds react with each other to give a mixture of 1,4-triazole and 1,5-triazole. After several decades of its introduction to literature, the reaction started to receive tremendous attention as in 2001 Meldal group [64,65] and Sharpless group [66] independently discovered the effect of Cu(I) catalysis on the reaction. When Cu(I) is used the reaction becomes regioselective and only 1,4-isomer is formed as depicted in Figure 2.1.

CuAAC is used in from bioconjugation [67-71] to linear or hyperbranched polymer synthesis to polymer modification and coupling [72-77].

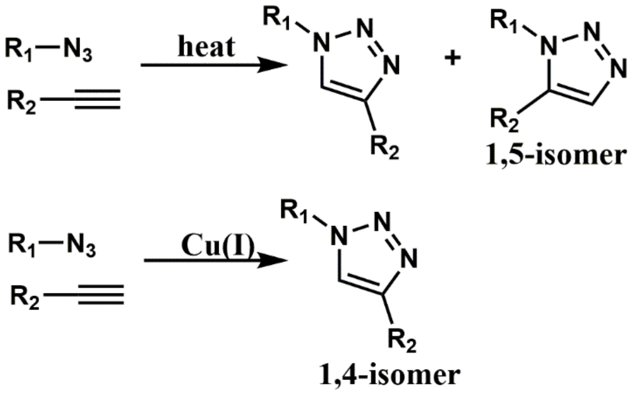

Figure 2.1: 1,3-dipolar cycloaddition of azide and alkyne.

In 2005, Lutz *et al*. [78] combined atom transfer radical polymerization (ATRP) and CuAAC reaction to synthesize various end-functional polymers. Briefly, they first polymerized styrene via ATRP, then, converted the bromine end group to azide using a substitution reaction and finally reacted the resulting polystyrene-N_3 with propargyl alcohol, propiolic acid and 2-methyl-1-buten-3-yne to obtain hydroxyl-, carboxylic acid-, and vinyl-functionalized polymers, respectively, as shown in Figure 2.2.

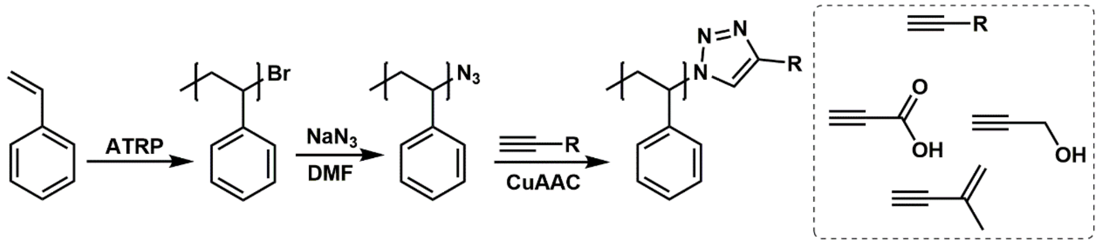

Figure 2.2: Modification of polystyrene-N_3 with functional terminal alkynes via CuAAC reaction.

2.1.2 Diels-Alder (DA) reaction

Diels-Alder (DA) reaction is first reported by Diels and Alder in 1928 [79] and they received the Nobel prize in 1950 for the discovery of this reaction. In DA reaction, a conjugated diene and dienophile react in a pericyclic fashion to give a cyclohexene derivative as depicted in Figure 2.3. The reaction works best when diene bears electron donating groups (alkoxy, amino etc) or dienophile bears electron-withdrawing groups (cyano, nitro, etc**)** [80].

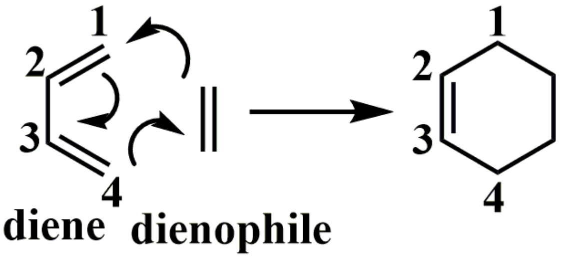

Figure 2.3: The DA reaction.

Due to its atom economic nature, lack of use of a catalyst and high-efficiency, DA reaction is frequently used in both molecular [81-83] and macromolecular [84-86] levels for useful carbon-carbon bond formation reactions.

In 2006 [87] Durmaz *et al*. showed that the DA reaction can be used to synthesize many block copolymers with similar characteristics. They first synthesized maleimide and anthracene functionalized polymers via ATRP and then successfully coupled different homopolymer blocks to give block copolymers as shown in Figure 2.4.

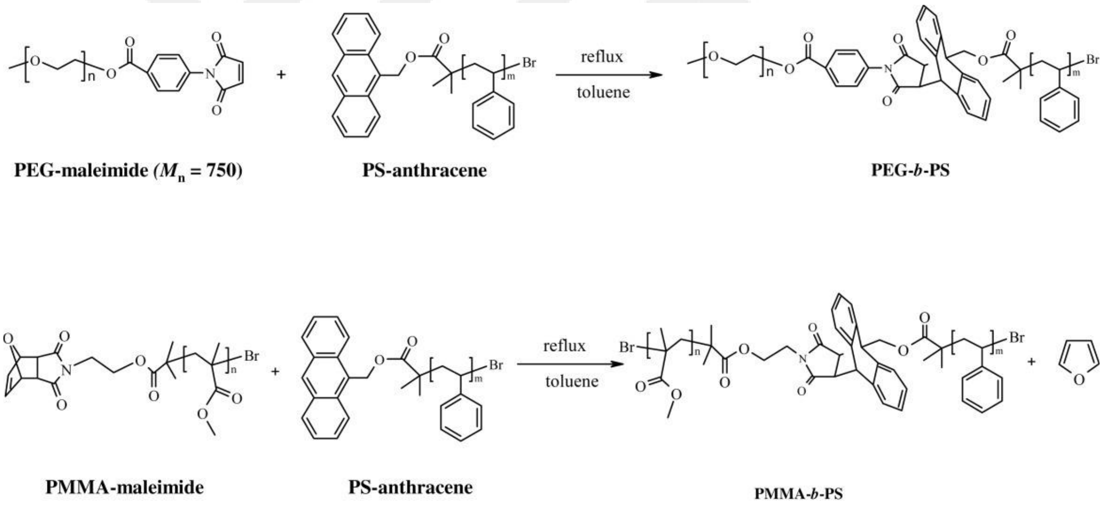

Figure 2.4: Synthesis of block copolymers via DA reaction.

2.1.3 Thiol-ene reaction

Thiol-ene reaction which is essentially the hydrothiolation of a double bond to give a thioether is in the literature for over 100 years [88]. The reaction, generally, proceeds under radical conditions and follows a typical process of initiation, propagation and termination. Apart from the radical mechanism, hydrothiolation can also work in the presence of a mild base such as triethyl amine and an electron deficient alkene (*e.g.* bearing electron-withdrawing groups such as nitro, ester, cyano, etc) via a nucleophilic process. Both nucleophilic and radical conditions result in an anti-Markovnikov oriented thioeter [89] as shown in Figure 2.5. Thiol-ene reaction is a useful tool for the synthesis of highly uniform polymer networks, polymerization, polymer modification and more [90]. Marvel and Chambers, in 1948, synthesized various low-to-moderate molecular weight poly(alkylene sulfides) via chain-growth polymerization of dithiols and unconjugated dienes under ultraviolet light [91].

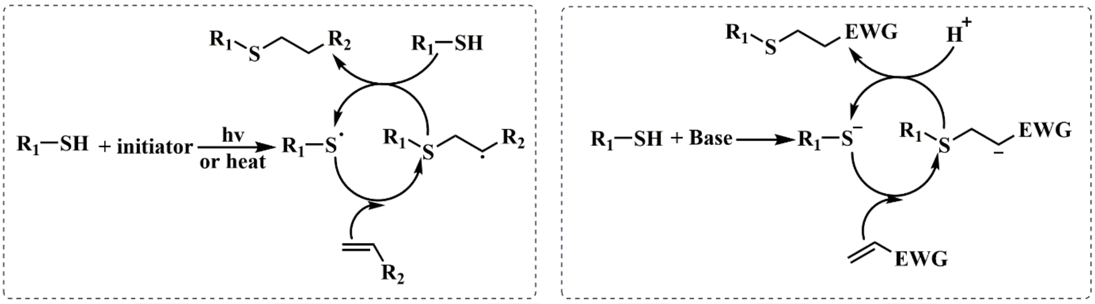

Figure 2.5: Radical and nucleophilic thiol-ene mechanisms.

Despite its long history, the reaction started to gain significant interest only in 2000s and now it is seen as a tool of great importance for both polymer synthesis and modification [9].

In 2007, Gress *et al.* [92] employed thiol-ene reaction for postpolymerization modification as depicted in Figure 2.6. Briefly, they first polymerized the 2-oxazoline derivative monomer, namely 2-(3-butenyl)-2-oxazoline, and then modified the polymer platform bearing a double bond with various thiol compounds using radical thiol-ene reaction under UV light at room temperature within 1 day.

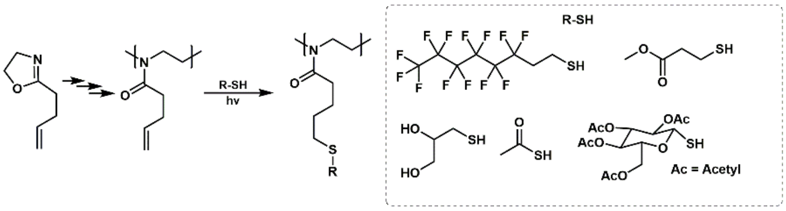

Figure 2.6: PPM via thiol-ene reaction.

2.2 Aldehyde Functional Polymers

Aldehyde functional polymers may be good platforms for polymer modification due to the inherent reactivity of aldehyde group. As shown in Figure 2.7, an aldehyde group can be obtained from controlled oxidation of primary alcohols, controlled reduction of carboxylic acids, nitriles or esters, ozonolysis of alkenes, and anti-Markovnikov oriented hydration of alkynes [93].

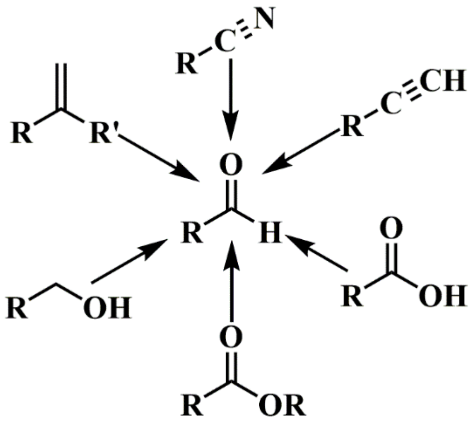

Figure 2.7: Syntheses of aldehydes.

Polymers with pendant aldehyde groups can be synthesized from the polymerization of aldehyde functional monomers and then can be further modified using the aldehyde group present [10].

4-vinylbenzaldehyde is an aldehyde functional styrene monomer that can be polymerized in the presence of a radical initiator when heated. Various methods are known for the preparation of the monomer. In 2008 Gao and Lam [94] synthesized 4-vinylbenzaldehyde from 4-vinylbenzyl chloride. They first converted 4-vinylbenzyl chloride to 4-vinylbenzyl alcohol according to previous literature [95]. Then, 4-vinylbenzyl alcohol was oxidized to 4-vinylbenzaldehyde with activated MnO_2 in hexane at room temperature as depicted in Figure 2.8.

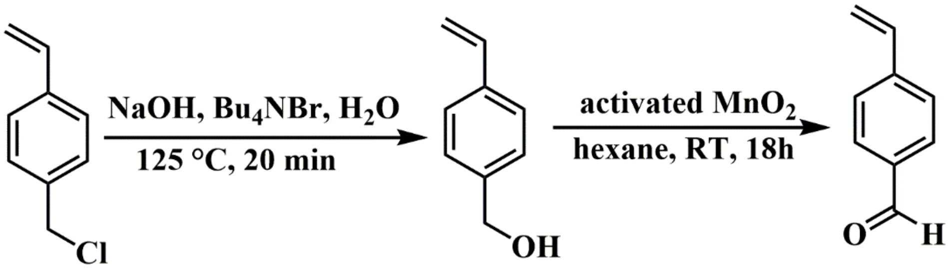

Figure 2.8: Synthesis of 4-vinylbenzaldehyde.

Gao and Lam [94] copolymerized 4-vinylbenzaldehyde with styrene in the presence of azobisisobutyronitrile (AIBN) at 70 °C in toluene to obtain an aldehyde functional polymer. That polymer was used to prepare the first polymer-supported N-benzenesulfonyl-3-phenyloxaziridine which they shown is a strong and selective oxidant for sulfides, selenides, amines, phosphines and enolates with high yields and simple work-up as shown in Figure 2.9.

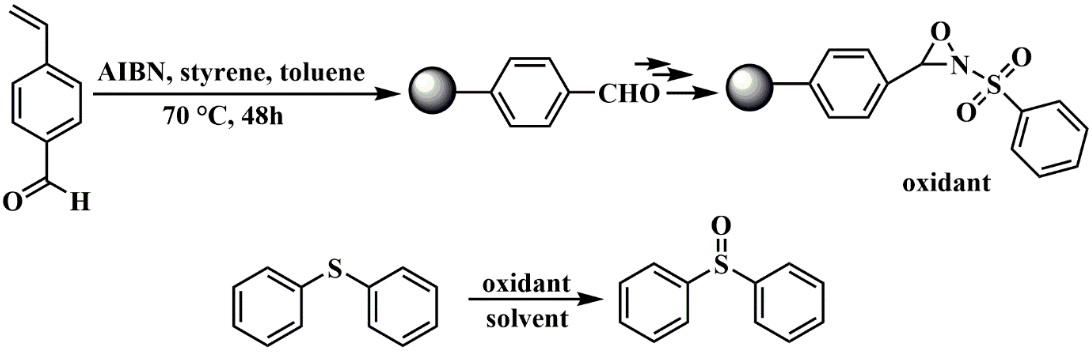

Figure 2.9: Synthesis of aldehyde functional copolymer and usage of it as oxidant.

Another synthesis route [96] of 4-vinylbenzaldehyde includes an extra step: 4-vinylbenzyl alcohol is first converted to 4-vinylbenzyl acetate which is later hydrolyzed to 4-vinylbenzyl alcohol. Then, 4-vinylbenzyl alcohol is oxidized to 4-vinylbenzaldehyde via Swern oxidation with oxalyl chloride at -78 °C. In that work, which is depicted in Figure 2.10, aldehyde- and amine-functionalized copolymers were synthesized and it was shown that these copolymers can cross-link through imine bonds to create star polymers and spherical cross-linked nanogels.

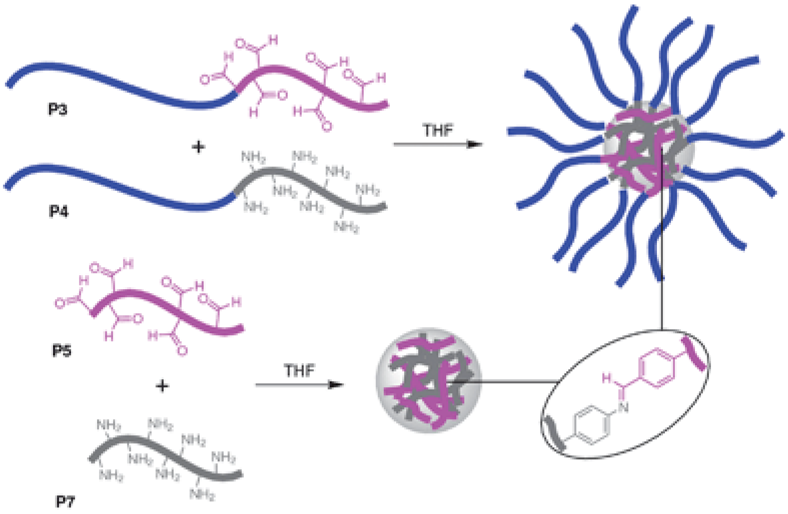

Figure 2.10: Synthesis of star copolymers and nanogels from an aldehyde functional polymer.

Other synthesis methods of 4-vinylbenzaldehyde include Heck reaction between bromobenzaldehyde and ethylene [97], Wittig olefination of 4-(diethoxymethyl)-benzaldehyde followed by deprotection [98], and direct synthesis from 4-vinylbenzyl chloride [99] via Sommelet reaction [100].

Poly(vinylbenzaldehyde) can also be synthesized from the oxidation of poly(vinylbenzyl chloride) via DMSO as shown in Figure 2.11 [101].

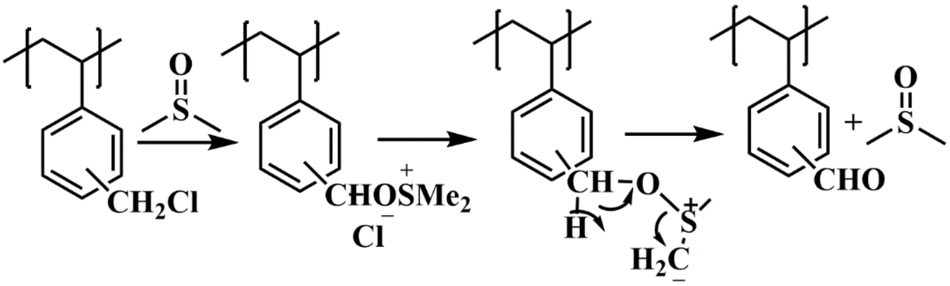

Figure 2.11: Oxidation of poly(vinylbenzyl chloride) to poly(vinylbenzaldehyde).

4-formylphenyl methacrylate is an aldehyde functional methacrylic monomer which is generally synthesized from the esterification of 4-hydroxybenzaldehyde with methacryloyl chloride in the presence of a base like triethylamine in an organic solvent such as dichloromethane, diethyl ether or tetrahydrofuran [102-104]. 4FPM can also be synthesized from 4-hydroxybenzaldehyde and methacrylic anhydride in the presence of dimethylaminopyridine (DMAP) in dichloromethane [105], Figure 2.12 shows both methods.

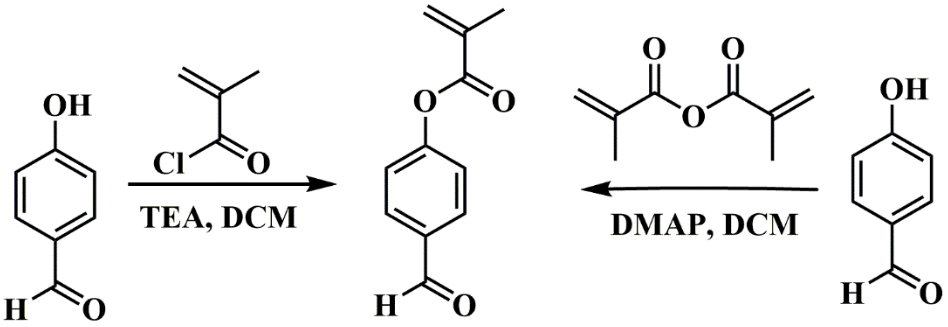

Figure 2.12: Syntheses of 4FPM.

In 2008 Ravi Sankar *et al.* [106] used 4FPM to synthesize polymer beads for preparing polymer-metal complexes. As shown in Figure 2.13, they polymerized 4FPM in the presence of benzoyl peroxide as radical initiator, poly(vinyl alcohol) (PVA) as stabilizer and divinylbenzene (DVB) as a cross-linking agent at 80 °C for 12 h. Then, the cross-linked polymer beads were functionalized with benzoyl hydrazone (BH) in DMF/water (1/1) mixture for 12 h. After that, they treated the polymer beads with $NiCl_2.6H_2O$ and $CuCl_2.2H_2O$ metal salts in DMF/water (1/1) mixture under reflux for 10 h at a pH of 6.9.

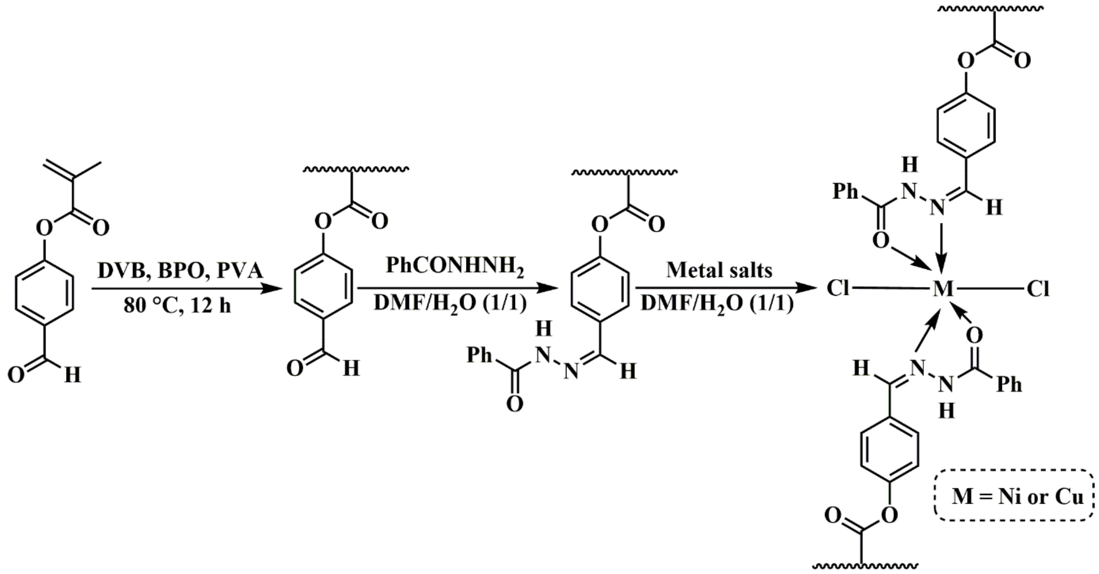

Figure 2.13: Synthesis of polymer-metal complexes from 4FPM.

In 2012 Kim *et al.* [107] synthesized random copolymers of poly(ethylene glycol) methyl ether methacrylate (PEGMA), 4FPM, and methyl methacrylate (MMA) for oligonucleotide immobilization as shown in Figure 2.14. For a proper immobilization, glass substrates should be bifunctional, *i.e.* bearing a bio-inert part and a bio-reactive part.

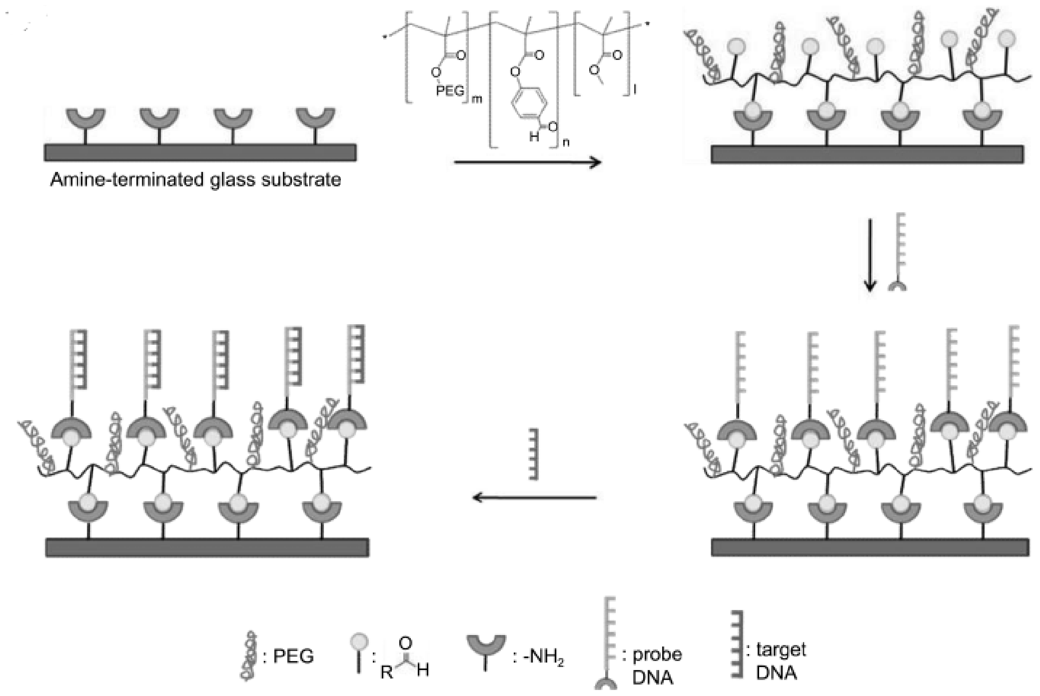

Figure 2.14: Immobilization of target oligonucleotides via 4FPM copolymers.

In this work 4FPM was used to generate bio-reactivity, PEGMA for bio-inertness and MMA for spacing. Briefly, they solubilized different molar concentrations of monomers in DMF, and copolymerized the monomers in the presence of AIBN (3% mol ratio to monomers) at 70 °C for 24 h.

Evaporation of the solvent yielded copolymers as a yellowish viscous liquid. They then treated the amine-modified glass substrates with copolymer solutions (20 wt % in THF) for 24 h at 60 °C which resulted in covalent bonding between the glass surface and copolymer layer through imine formation reaction between aldehyde and imine groups.

After functionalization of the glass substrate, they immobilized amine-modified probe oligonucleotide onto the copolymer layer, again through imine formation. They then immobilized target oligonucleotides which are complementary to the probe sequence.

2.3 Reductive Etherification Reaction (RER)

Ethers are chemical compounds that contain two alkyl or aryl groups bonded to an oxygen atom. Two identical alkyl or aryl groups form symmetrical ethers (R-O-R) while different alkyl or aryl groups form unsymmetrical ethers (R-O-R’) [108]. Traditionally ethers are synthesized from Williamson ether synthesis [109] which proceeds through the nucleophilic attack of an alkoxide to a sterically unhindered (primary) alkyl halide or tosylate as depicted in Figure 2.15. This method has inherited limitations such as harsh reaction conditions, and the necessity to convert hydroxyl groups into better leaving groups (*i.e.* tosylate or halide) before the etherification.

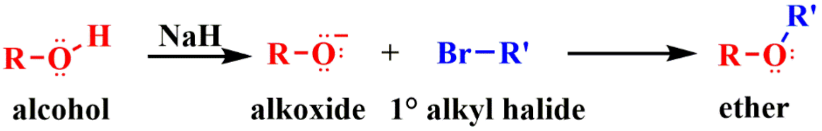

Figure 2.15: Williamson ether synthesis.

Being introduced to literature in 1970s, RER is a chemical process that yields ethers from ketones or aldehydes [47-49] as shown in Figure 2.16. Organosilanes are commonly used as reductant for RER together with an acid catalyst. Both symmetrical and unsymmetrical ether syntheses are possible. Symmetrical ethers are achieved when carbonyl compounds are used alone in the presence of an organosilane compound and unsymmetrical ethers are achieved when an alcohol is used as a nucleophile. In the first work of Doyle group [47], unsymmetrical ethers from both aldehydes and ketones utilizing triethylsilane (Et_3SiH) as a reducing agent and sulfuric acid or trifluoroacetic acid as catalysts were obtained in high yields.

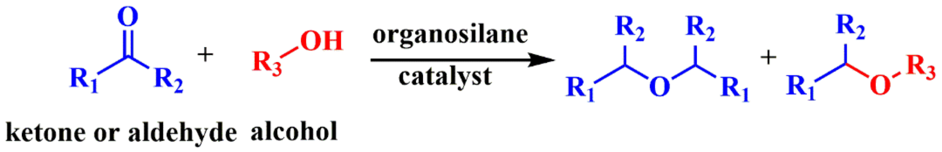

Figure 2.16: Schematic representation of a reductive etherification reaction.

After these pioneering works, many other studies on RER have been published over the years [50-54]. In 2017 Lee and Morandi [55] reported the use of CDMS, which is a reducing agent with Lewis acidic properties, as a tool to overcome the drawbacks of both traditional Williamson ether synthesis and RER. In this method, no additional catalyst is needed unlike other RER methods and reactions occur under mild conditions at room temperature. The authors showed that CDMS-mediated RER of both ketones and aldehydes with various alcohols from primary to sterically congested secondary ones proceeded smoothly under optimized conditions of 1.1 equivalents of alcohols and CDMS (respect to carbonyl compounds) in acetonitrile (MeCN) at room temperature for 12 hours. The procedure has a good functional group tolerance including alkenes, alkynes, carbamates, imides, esters and halogens.

2.3.1 RER in polymer chemistry

Studies concerning the application of RER in polymer chemistry started in the mid-1990s by Yokozawa and coworkers. As depicted in Figure 2.17, in their first study [56] they investigated the polymerization of isophthalaldehyde in the presence of Et_3SiH and trityl perchlorate ($TrClO_4$) in CH_2Cl_2 at depressed temperatures (0 °C to -50 °C) to avoid side reactions such as trityl perchlorate assisted Friedel-Crafts reaction that yields to cross-linking of aromatic rings. It was found that obtained polymers were of low to moderate molecular weights with moderate yields in 24 hours.

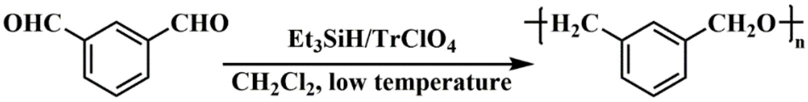

Figure 2.17: Polycondensation of isophthalaldehyde via RER.

In the following work [57], which is shown in Figure 2.18, the authors both broadened the dialdehyde scope for self-polycondensation of dialdehydes and showed that alternating type polyethers can also be synthesized via polycondensation between dialdehydes and bis(trimethyl silyl) ethers under the same conditions of their previous work. Bulky silanes such as triphenyl silane (Ph_3SiH) were required to obtain alternating type polyethers for relatively high molecular weights in good yield.

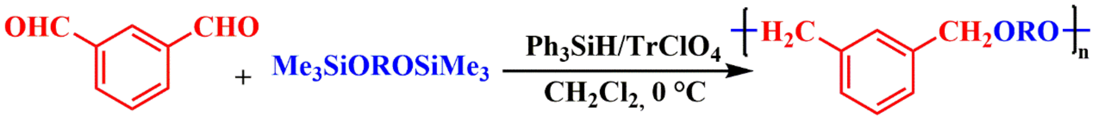

Figure 2.18: Polycondensation between a dialdehyde and bis(trimethyl silyl) ethers via RER.

The Yokozawa group also used a similar strategy to obtain polyethers in an alternating fashion with several pendant groups such as allyl [58], cyano [59], and propargyl [60] utilizing the three-component polycondensation of dialdehydes, bis(trimethyl silyl) ethers, and silyl nucleophiles. All these polymerizations had prominent disadvantages such as the resulting polymers were of low to moderate molecular weight, the alcohols were protected as silyl ethers prior to polymerization, reactions proceeded at low temperatures, and a catalyst (TrClO4) was required.

Inspired by Lee and Morandi’s work [55], Luleburgaz *et al*. [61] recently showed that CDMS-mediated RER can be used as a feasible method for PPM as shown in Figure 2.19. They first synthesized a polyketone platform via acyclic diene metathesis (ADMET) and subjected it to RER in the presence of CDMS and various alcohols at room temperature for 16 hours.

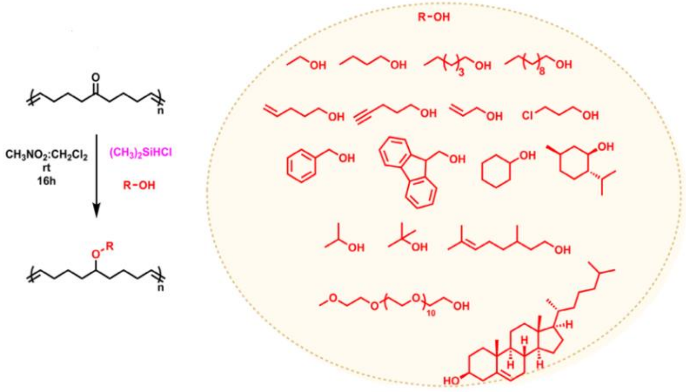

Figure 2.19: Modification of polyketone via CDMS-mediated RER.

The resulting polymers were characterized by ^1H and ^{13}C NMR, FT-IR and GPC. It was found that the most suitable solvent system was CH_2Cl_2/CH_3NO_2 (1 mL each) with 90% conversion of ketone backbone to various alkoxy-functional structures. It was also found that polyalcohol formation caused by direct reduction of ketone by CDMS was inevitable to some extent (up to 10% under optimum conditions).

The scope of this procedure was quite wide from simple primary alcohols like ethanol and butanol to sterically congested secondary alcohols like isopropyl alcohol, cyclohexanol and even cholesterol. Various functional groups such as alkene, alkyne, and halogen were well tolerated under mild reaction conditions. Primary alcohols showed high conversions up to 90%, attributable to their good nucleophilicity, while secondary alcohols showed lower yields up to 80%. Attempt to attach *tert*-butanol to polyketone backbone was unsuccsessful and yielded to the formation of polyalcohol along with unreacted polyketone. Another interesting case was PEG_{550} which resulted in 57% alkoxy formation mimicking a polymer-polymer conjugation. Inevitable polyalcohol formation was used as a way of further modification as well. Polymer obtained from the reaction of polyketone with ethanol which contains 90% alkoxy structure and 10% polyalcohol was successfully esterified with benzoyl chloride.

The authors also proposed a plausible mechanism for the alkoxy-functional polymer and polyalcohol formations as shown in Figure 2.20. In the RER case, the reaction starts with the nucleophilic attack of carbonyl oxygen to CDMS with chloride ion acting as leaving group. Then, the alcohol attacks the activated carbonyl carbon forming a hemiacetal and a HCl molecule. After protonation-deprotonation steps, silanol leaves the structure while another CDMS molecule reduces the intermediate product to the corresponding alkoxy-functional polymer. Protonated polyketone can also be directly reduced to polyalcohol by excess CDMS.

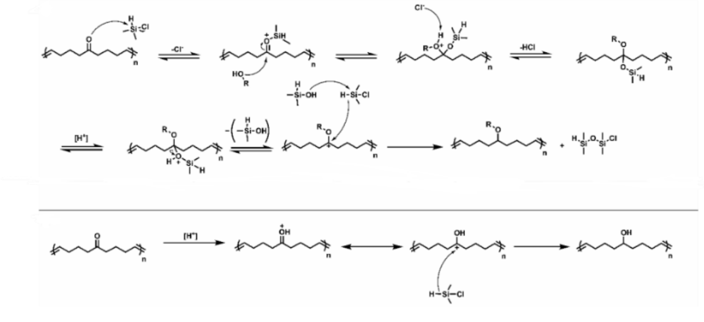

Figure 2.20: Mechanisms of CDMS-mediated RER of polyketone and polyalcohol formation.

In a more recent study [62], which is depicted in Figure 2.21, Lüleburgaz *et al*. employed the CDMS-mediated RER to prepare linear polyethers from dialdehydes and unprotected diols. They investigated the step-growth polymerizations of terephthalaldehyde (TPA) and its isomers in the presence of CDMS and various diols in CH_3NO_2 for 1 h at room temperature. The optimized mole ratio of dialdehyde/diol/CDMS was found to be 1.1/1/6 with a slight excess of dialdehyde to compensate for the aldehyde loss due to direct reduction of aldehyde to alcohol by CDMS. High molecular weight polymers (up to 110.4 kDa) were obtained under the optimum conditions mentioned above.

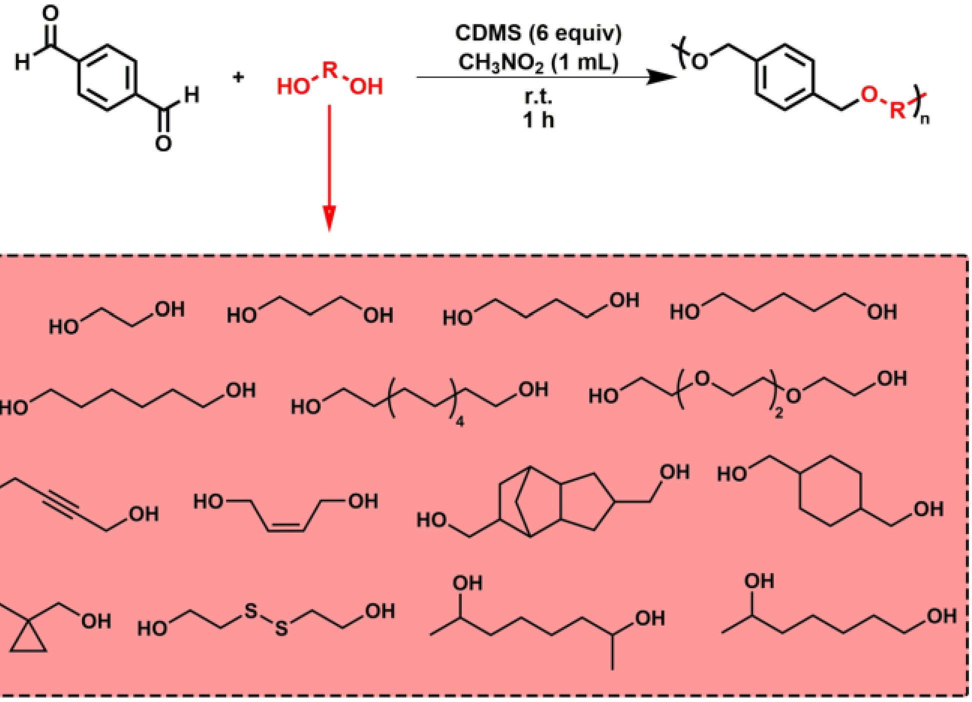

Figure 2.21: Synthesis of linear polyethers via RER.

3. EXPERIMENTAL PART

3.1 Materials

Chlorodimethylsilane (CDMS, 99.5%, ABCR), ethanol (absolute, Sigma-Aldrich), 1-butanol (99.8% anhydrous, Sigma-Aldrich), 1-hexanol (99% anhydrous, Sigma-Aldrich), 4-pentene-1-ol (99%, ACROS Organics™), 4-pentyn-1-ol (97%, Sigma-Aldrich), allyl alcohol (99%, Sigma-Aldrich), benzyl alcohol (99.8%, Sigma-Aldrich) , β-citronellol (95%, Sigma-Aldrich), 3-chloro-1-propanol (98%, Aldrich), isopropyl alcohol (99.7%, Sigma-Aldrich), cyclohexanol (98%, Merck), 2-bromoethanol (95%, Sigma-Aldrich), sodium azide (≥99.5%, Sigma-Aldrich), poly(ethylene glycol) monomethyl ether (PEG$_{550}$, M_n = 550, Sigma-Aldrich), 1,1’-azobis(cyclohexanecarbonitrile) (ABCN, 98%, Sigma-Aldrich) were used as received. Tetrahydrofuran (THF, HPLC Grade, 99%, Aldrich), nitromethane (CH_3NO_2, 96%, Merck), dichloromethane (CH_2Cl_2, 99.8%, Aldrich), dimethylsulfoxide (DMSO, ≥99.9%, Sigma-Aldrich), chloroform ($CHCl_3$, 99%, Sigma-Aldrich), diethyl ether were anhydrous and were of HPLC quality, and used without further purification. Methanol was reagent grade and used as received.

3.2 Instrumentation

^{1}H NMR (500 MHz) and ^{13}C NMR (125 MHz) spectra were recorded using an Agilent VNMRS 500 instrument in $CDCl_3$. Gel permeation chromatography (GPC) measurements were carried out with Agilent Instrument (series 1100), using a refractive index detector, loaded with Waters Styragel columns (HR 5E, HR 4E, HR 3, HR 2, 4.6 mm internal diameter, 300 mm length, packed with 5 μm particles). The effective molecular weight ranges of the columns are 2000−4 000 000, 50−100 000, 500−30 000, and 500−20 000 g/mol, respectively. THF was used as eluent at a flow rate of 0.3 mL/min at 30 □C, and 2,6-di-*tert*-butyl-4-methylphenol (BHT) was used as an internal standard. The number-average molecular weight (M_n), weight-average molecular weight (M_w) and dispersity ($Đ$) of the polymers were calculated based on narrow linear polystyrene (PS) standards (Polymer Laboratories) ranging between 2300 and 3 050 000 g/mol. FT-IR spectra were recorded on an Agilent Technologies Cary 630 FTIR instrument over the range 4000–400 cm^{-1}.

^1H and ^{13}C NMR spectra of 4FPM are given in Figure 4.1 and Figure 4.2, respectively. ^1H, ^{13}C NMR and FT-IR spectra of P2 are given in Figure 4.6, Figure 4.7 and Figure 4.8, respectively. ^1H, ^{13}C NMR and FT-IR spectra of P3 are given in Figure 4.9, Figure 4.10 and Figure 4.11, respectively. ^1H, ^{13}C NMR and FT-IR spectra of P4 are given in Figure 4.12, Figure 4.13 and Figure 4.14, respectively. ^1H, ^{13}C NMR and FT-IR spectra of P5 are given in Figure 4.15, Figure 4.16 and Figure 4.17, respectively. ^1H, ^{13}C NMR and FT-IR spectra of P6 are given in Figure 4.18, Figure 4.19 and Figure 4.20, respectively. ^1H, ^{13}C NMR and FT-IR spectra of P7 are given in Figure 4.21, Figure 4.22 and Figure 4.23, respectively. ^1H, ^{13}C NMR and FT-IR spectra of P8 are given in Figure 4.24, Figure 4.25 and Figure 4.26, respectively. ^1H, ^{13}C NMR and FT-IR spectra of P9 are given in Figure 4.27, Figure 4.28 and Figure 4.29, respectively. ^1H, ^{13}C NMR and FT-IR spectra of P10 are given in Figure 4.30, Figure 4.31 and Figure 4.32, respectively. ^1H, ^{13}C NMR and FT-IR spectra of P11 are given in Figure 4.33, Figure 4.34 and Figure 4.35, respectively. ^1H, ^{13}C NMR and FT-IR spectra of P12 are given in Figure 4.36, Figure 4.37 and Figure 4.38, respectively. ^1H, ^{13}C NMR and FT-IR spectra of P13 are given in Figure 4.39, Figure 4.40 and Figure 4.41, respectively. ^1H, ^{13}C NMR and FT-IR spectra of P14 are given in Figure 4.42, Figure 4.43 and Figure 4.44, respectively.

3.3 Synthetic Procedures

3.3.1 Synthesis of 4FPM

4FPM was synthesized according to a literature procedure [102]. ^1H NMR ($CDCl_3$, δ) 9.97 (s, 1H, $CH{=}O$), 7.89 (d, 2H, ArH), 7.28 (d, 2H, ArH), 6.36 (s, 1H, $CH_2{=}C$), 5.79 (s, 1H, $CH_2{=}C$), 2.05 (s, 3H, CH_3). ^{13}C NMR ($CDCl_3$, δ) 190.90, 165.06, 155.66, 135.40, 133.93, 131.15, 128.07, 122.40, 18.26.

3.3.2 Synthesis of aldehyde functional polymer (P0)

To a 100 mL Schlenk flask, 8 g of 4-FPM (42.1 mmol) was added and dissolved in 40 mL of DMSO. 0.51 g of ABCN (2.10 mmol) was then added. After that, the reaction mixture was degassed by two freeze-pump-thaw (FPT) cycles, left in vacuum, and stirred at 80 °C for 16 h. After the specified time, the reaction mixture was cooled to room temperature and precipitated into 400 mL of diethyl ether, the residual solvent was decanted, and the dissolution-precipitation ($CHCl_3$-diethyl ether) process was repeated two times. Finally, the obtained polymer was dried in a vacuum oven at room temperature overnight to give P0 as a white powder. (Yield = 6.0 g, 75%). ^1H NMR ($CDCl_3$, δ) 9.96 (s, 1H, C*H*=O), 7.83 (m, 2H, Ar*H*), 7.24 (m, 2H, Ar*H*), 2.24- 1.42 (m, 5H, main backbone). ^{13}C NMR (CDCl3, δ) 190.72, 173.96, 154.80, 134.15, 131.24, 121.72, 45.82, 20.33, 18.75.

3.3.3 General procedure for modification of P0 via RER

To a 10 mL round-bottomed-flask, 50 mg of P0 (0.26 mmol based on repeating unit, 1 equiv) was dissolved in 2 mL of CH_2Cl_2/CH_3NO_2 mixture (1 mL each). Then, alcohol (2 equiv per repeating unit of P0) and CDMS (4 equiv per repeating unit of P0) were added to the flask in the given order, and the reaction mixture was stirred at room temperature for 16 h. After that, the mixture was directly precipitated into 20 mL of methanol and the solvent was decanted. The dissolution-precipitation ($CHCl_3$-methanol) process was repeated two times to yield the final products. Finally, the modified polymer was dried in a vacuum oven at room temperature overnight.

Synthesis of P1

General procedure was followed: P0 (50 mg, 0.26 mmol), ethanol (0.52 mmol, 30.4 μL) and CDMS (1.04 mmol, 116.9 μL) were used. P1 was obtained as a white sticky solid. (Yield = 54 mg, 93%). ^1H NMR ($CDCl_3$, δ) 7.30- 7.05 (m, 4H, Ar*H*), 4.48 (s, 2H, $ArCH_2O$), 3.52 (s, 2H, OCH_2CH_3), 2.35-1.42 (m, 5H, main backbone), 1.24 (s, 3H, OCH_2CH_3). ^{13}C NMR (CDCl3, δ) 175.86, 149.88, 136.27, 128.76, 120.92, 71.97, 65.72, 45.82, 19.98, 18.18, 15.23.

Synthesis of P2

P0 (50 mg, 0.26 mmol), 1-butanol (0.52 mmol, 47.6 μL) and CDMS (1.04 mmol, 116.9 μL) were used. P2 was obtained as a white sticky solid. (Yield = 60 mg, 91%). ^{1}H NMR ($\mathrm{CDCl_3}$, δ) 7.29-7.05 (m, 4H, $\mathrm{Ar}H$), 4.48 (s, 2H, $\mathrm{ArC}H_2\mathrm{O}$), 3.47 (s, 2H, $\mathrm{OC}H_2$), 2.36-1.40 (m, 9H, main backbone and $\mathrm{OCH_2(C}H_2\mathrm{)_2CH_3}$), 0.92 (s, 3H, $\mathrm{OCH_2(CH_2)_2C}H_3$). ^{13}C NMR (CDCl3, δ) 175.43, 149.89, 136.52, 128.69, 120.92, 72.14, 70.26, 45.71, 31.84, 19.94, 19.39, 18.23, 13.97.

Synthesis of P3

P0 (50 mg, 0.26 mmol), 1-hexanol (0.52 mmol, 64.8 μL) and CDMS (1.04 mmol, 116.9 μL) were used. P3 was obtained as a white sticky solid. (Yield = 64 mg, 88%). ^{1}H NMR ($\mathrm{CDCl_3}$, δ) 7.29-7.05 (m, 4H, $\mathrm{Ar}H$), 4.47 (s, 2H, $\mathrm{ArC}H_2\mathrm{O}$), 3.46 (s, 2H, $\mathrm{OC}H_2\mathrm{(CH_2)_4CH_3}$), 2.37-1.30 (m, 13H, main backbone and $\mathrm{OCH_2(C}H_2\mathrm{)_4CH_3}$), 0.88 (s, 3H, $\mathrm{OCH_2(CH_2)_4C}H_3$). ^{13}C NMR (CDCl3, δ) 175.76, 149.89, 136.38, 128.69, 120.92, 72.15, 70.59, 45.72, 31.72, 29.74, 25.88, 22.63, 19.89, 18.12 14.09.

Synthesis of P4

P0 (50 mg, 0.26 mmol), 4-pentene-1-ol (0.52 mmol, 53.7 μL) and CDMS (1.04 mmol, 116.9 μL) were used. P4 was obtained as a white sticky solid. (Yield = 61 mg, 89%). ^{1}H NMR ($\mathrm{CDCl_3}$, δ) 7.30-7.05 (m, 4H, $\mathrm{Ar}H$), 5.81 (s, 1H, $\mathrm{C}H\mathrm{{=}CH_2}$), 5.04-4.95 (m, 2H, $\mathrm{CH{=}C}H_2$), 4.47 (s, 2H, $\mathrm{ArC}H_2\mathrm{O}$), 3.48 (s, 2H, $\mathrm{OC}H_2\mathrm{(CH_2)_2CH{=}CH_2}$), 2.36-1.43 (m, 9H, main backbone and $\mathrm{OCH_2(C}H_2\mathrm{)_2CH{=}CH_2}$). ^{13}C NMR (CDCl3, δ) 175.42, 149.88, 138.20, 136.37, 128.72, 120.93, 114.86, 72.18, 69.77, 45.71, 30.34, 28.93, 19.90, 18.25.

Synthesis of P5

P0 (50 mg, 0.26 mmol, 4-pentyn-1-ol (0.52 mmol, 48.4 μL) and CDMS (1.04 mmol, 116.9 μL) were used. P5 was obtained as a brown sticky solid. (Yield = 60 mg, 88%). ^{1}H NMR ($\mathrm{CDCl_3}$, δ) 7.30-7.05 (m, 4H, $\mathrm{Ar}H$), 4.49 (s, 2H, $\mathrm{ArC}H_2\mathrm{O}$), 3.57 (s, 2H, $\mathrm{OC}H_2\mathrm{(CH_2)_2C{\equiv}CH}$), 2.31-1.42 (m, 10H, main backbone and $\mathrm{OCH_2(C}H_2\mathrm{)_2C{\equiv}C}H$).

^{13}C NMR (CDCl3, δ) 175.00, 149.94, 136.35, 128.74, 120.94, 83.86, 72.26, 68.71, 68.66, 45.72, 28.60, 19.86, 18.37 15.29.

Synthesis of P6

P0 (50 mg, 0.26 mmol), allyl alcohol (0.52 mmol, 35.4 μL) and CDMS (1.04 mmol, 116.9 μL) were used. P6 was obtained as a white sticky solid. (Yield = 54 mg, 88%). ^{1}H NMR ($CDCl_3$, δ) 7.28-7.05 (m, 4H, Ar*H*), 5.94 (s, 1H, $OCH_2C\mathit{H}{=}CH_2$), 5.30-5.21 (m, 2H, $OCH_2CH{=}C\mathit{H}_2$), 4.50 (s, 2H, $ArC\mathit{H}_2O$), 4.02 (s, 2H, $OC\mathit{H}_2CH{=}CH_2$), 2.36-1.43 (m, 5H, main backbone). ^{13}C NMR (CDCl3, δ) 175.84, 149.92, 136.10, 134.62, 128.83, 120.94, 117.24, 71.35, 71.12, 45.71, 19.88, 18.11.

Synthesis of P7

P0 (50 mg, 0.26 mmol), β-citronellol (0.52 mmol, 94.8 μL) and CDMS (1.04 mmol, 116.9 μL) were used. P7 was obtained as a white sticky solid. (Yield = 75 mg, 86%). ^{1}H NMR ($CDCl_3$, δ) 7.27-7.05 (m, 4H, Ar*H*), 5.09 (s, 1H, $(CH_3)_2C{=}C\mathit{H}$), 4.47 (s, 2H, $ArC\mathit{H}_2O$), 3.49 (s, 2H, $OC\mathit{H}_2$), 2.39-1.13 (m, 18H, main backbone and β-citronellyl), 0.90 (s, 3H, $CH_2CHC\mathit{H}_3$). ^{13}C NMR (CDCl3, δ) 175.75, 149.90, 136.35, 131.10, 128.70, 124.80, 120.95, 72.23, 68.75, 46.25, 36.76, 32.47, 29.81, 25.48, 22.49, 19.62, 17.69.

Synthesis of P8

P0 (50 mg, 0.26 mmol), 3-chloro-1-propanol (0.52 mmol, 43.5 μL) and CDMS (1.04 mmol, 116.9 μL) were used. P8 was obtained as a white sticky solid. (Yield = 63 mg, 89%). ^{1}H NMR ($CDCl_3$, δ) 7.30-7.06 (m, 4H, Ar*H*), 4.50 (s, 2H, $ArC\mathit{H}_2O$), 3.66-3.62 (d, 4H, $OC\mathit{H}_2CH_2C\mathit{H}_2Cl$), 2.37-1.43 (m, 7H, main backbone and $OCH_2C\mathit{H}_2CH_2Cl$). ^{13}C NMR (CDCl3, δ) 175.40, 149.99, 136.12, 128.75, 120.98, 72.39, 66.79, 45.71, 41.96, 32.73, 19.90, 18.22.

Synthesis of P9

P0 (50 mg, 0.26 mmol) benzyl alcohol (0.52 mmol, 53.8 μL) and CDMS (1.04 mmol, 116.9 μL) were used. P9 was obtained as a white sticky solid. (Yield = 67 mg, 90%). ^{1}H NMR ($CDCl_3$, δ) 7.32-7.06 (m, 9H, Ar*H*), 4.50-4.48 (d, 4H, $ArC\mathit{H}_2OC\mathit{H}_2C_6H_5$)

2.28-1.28 (m, 5H, main backbone). ^{13}C NMR (CDCl3, δ) 175.44, 150.00, 138.10, 136.04, 128.88, 128.78, 128.44, 127.75, 120.98, 72.13, 71.33, 45.75, 19.73, 18.34.

Synthesis of P10

2-azidoethanol was synthesized according to a literature procedure [110].

P0 (50 mg, 0.26 mmol), 2-azidoethanol (0.52 mmol, 45.3 mg), and CDMS (1.04 mmol, 116.9 μL) were used. P10 was obtained as a white solid. (Yield = 62 mg, 90%). ^{1}H NMR ($CDCl_3$, δ) 7.29-7.05 (m, 4H, Ar*H*), 4.56 (m, 2H, ArCH_2O), 3.65-3.39 (d, 4H, OCH_2CH_2N$_3$) 2.23-1.26 (m, 5H, main backbone). ^{13}C NMR (CDCl3, δ) 172.81, 150.13, 135.73, 128.76, 120.98, 72.54, 68.98, 50.80.

Synthesis of P11

P0 (50 mg, 0.26 mmol), monomethoxy PEG$_{550}$ (0.52 mmol, 286 mg) and CDMS (1.04 mmol, 116.9 μL) were used. P11 was obtained as a colorless sticky solid. (Yield = 174 mg, 90%). ^{1}H NMR ($CDCl_3$, δ) 7.32-7.02 (m, 4H, Ar*H*), 4.52 (m, 2H, ArCH_2O), 3.64 (s, 46H, CH_2 of PEG chain), 3.54 (s, 2H, ArCH$_2$OCH_2-PEG), 3.37 (s, 3H, PEG-OCH_3), 2.14-1.26 (m, 5H, main backbone). ^{13}C NMR (CDCl3, δ) 175.49, 149.98, 136.02, 128.75, 121.02, 71.93, 70.56, 70.51, 59.04.6

Synthesis of P12

P0 (50 mg, 0.26 mmol), isopropyl alcohol (0.52 mmol, 39.8 μL) and CDMS (1.04 mmol, 116.9 μL) were used. P12 was obtained as a white sticky solid. (Yield = 52 mg, 84%). ^{1}H NMR ($CDCl_3$, δ) 7.30-7.04 (m, 4H, Ar*H*), 4.48 (s, 2H, ArCH_2O), 3.66 (s, 1H, OC*H*(CH$_3$)$_2$), 2.36-1.42 (m, 5H, main backbone), 1.21 (s, 6H, OCH(CH_3)$_2$). ^{13}C NMR (CDCl3, δ) 175.46, 149.80, 136.75, 128.60, 120.90, 70.89, 69.30, 45.71, 22.12, 19.58, 18.12.

Synthesis of P13

P0 (50 mg, 0.26 mmol), cyclohexanol (0.52 mmol, 54.9 μL) and CDMS (1.04 mmol, 116.9 μL) were used. P13 was obtained as a white sticky solid. (Yield = 62 mg, 86%). ^{1}H NMR ($CDCl_3$, δ) 7.30-7.04 (m, 4H, Ar*H*), 4.52 (s, 2H, ArCH_2O), 3.34 (s, 1H, OC*H*), 2.34-1.24 (m, 15H, main backbone and cyclohexyl). ^{13}C NMR (CDCl3, δ)

175.03, 149.76, 137.00, 128.54, 120.89, 76.85, 68.95, 45.72, 32.22, 25.84, 24.10, 19.89, 18.17.

Synthesis of P14

P0 (50 mg, 0.26 mmol), ethanol (0.26 mmol, 15.2 μL), allyl alcohol (0.26 mmol, 17.7 μL) and CDMS (1.04 mmol, 116.9 μL) were used. P14 was obtained as a white sticky solid. (Yield = 50 mg, 85%). ^{1}H NMR ($CDCl_3$, δ) 7.30-7.05 (m, 4H, Ar*H*), 5.93 (s, 1H, $OCH_2CH{=}CH_2$), 5.33-5.21 (m, 2H, $OCH_2CH{=}CH_2$), 4.48 (s, 2H, $ArCH_2O$), 4.02 (s, 2H, $OCH_2CH{=}CH_2$), 3.52 (s, 2H, OCH_2CH_3), 2.36-1.42 (m, 5H, backbone), 1.24 (s, 3H, OCH_2CH_3). ^{13}C NMR (CDCl3, δ) 175.39, 149.89, 136.38, 134.62, 128.77, 120.92, 117.22, 71.98, 71.36, 65.73, 45.72, 20.02, 18.34, 15.23.

4. RESULTS AND DISCUSSION

Monomer 4FPM was synthesized from the esterification of 4-hydroxybenzaldehyde and methacryloyl chloride according to a literature procedure. ^{1}H and ^{13}C NMR spectrums of the monomer confirm the structure.

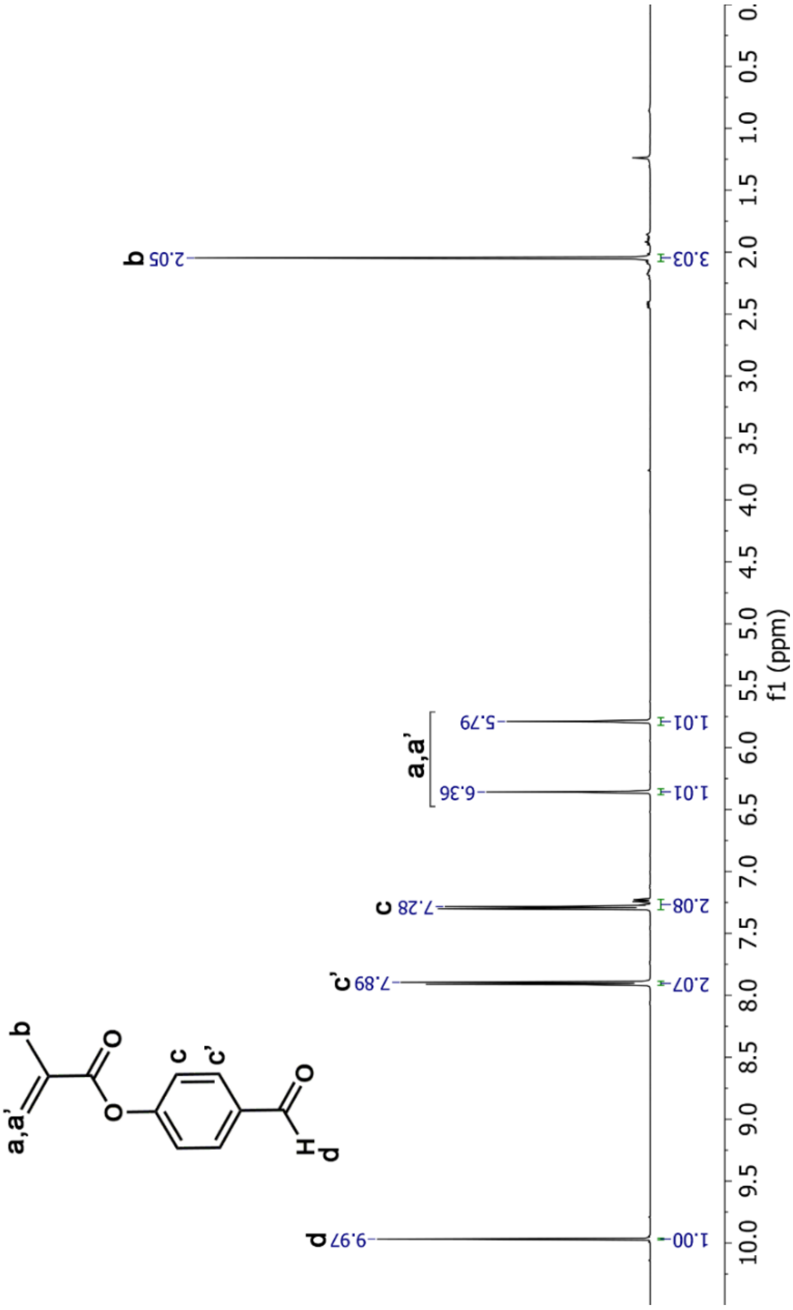

Figure 4.1: ^{1}H NMR spectrum of 4-FPM in $CDCl_3$ (500 MHz).

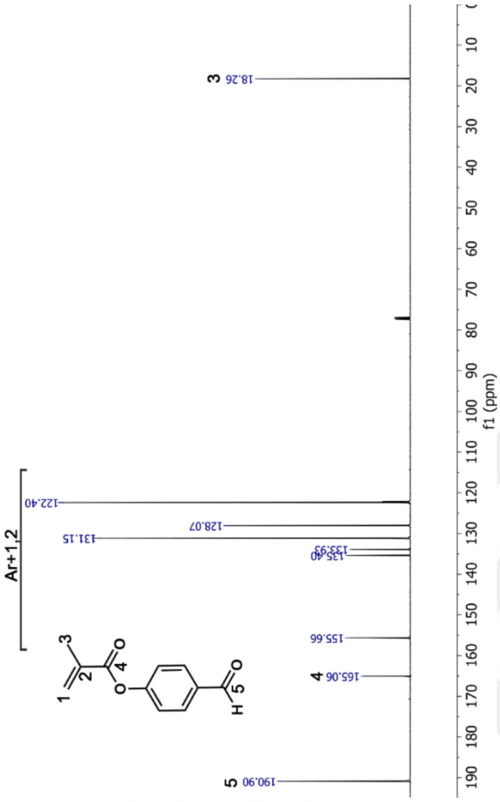

Figure 4.2: ^{13}C NMR spectrum of 4-FPM in $CDCl_3$ (125 MHz).

4FPM was polymerized by FRP technique using ABCN as a radical initiator, and the polymerization reaction proceeded at 80 °C for 16 h in DMSO. The obtained polymer (P0) displayed a high molecular weight (M_n = 80.1 kDa) and a broad polydispersity index (Đ = 2.79), emphasizing the character of FRP. The GPC chromatogram of P0 is given in Figure 4.4. The ^{1}H NMR spectrum of P0 is given in Figure 4.3A. As can be seen in this Figure, the characteristic aldehyde proton (HC=O) was detected at 9.96 ppm together with the aromatic protons between 7.83-7.24 ppm. Next, this polymer was reacted with a variety of alcohols via CDMS-mediated RER. In the first trial, ethanol was selected as the model alcohol, and the alcohol and CDMS molar equivalents were used to be 2:4 per aldehyde, similar to our previous study [61], the reaction was performed at room temperature for 16 h in a CH_2Cl_2/CH_3NO_2 solvent mixture (1 mL each). It is worth noting here that CH_3NO_2 is an essential solvent in the proposed strategy as it triggers RER [52, 55, 61, 62]. However, since the parent polymer itself is not soluble in CH_3NO_2, CH_2Cl_2 was used as a co-solvent to dissolve the polymer. After the reaction, the modified polymer (P1) was analyzed by ^{1}H NMR spectroscopy (Figure 4.3A). In the spectrum, the aldehyde signal completely disappeared and new signals associated with the benzylic ether ($ArCH_2O$) and ethyl ether (OCH_2CH_3) were detected at δ 4.48 and 3.52 ppm, respectively. Also, the integral ratio of these signals to each other as well as to the aromatic protons afforded the expected 1:1, indicating the complete conversion of aldehyde to ether. The ^{13}C NMR spectra of the polymers (Figure 4.3B) were also informative about the modification. Here, the aldehyde carbonyl carbon, which appeared at 190.72 ppm, disappeared after the RER, and new peaks associated with the etheric carbons appeared at 71.97 and 65.72 ppm. Moreover, the removal of the aldehyde carbonyl stretching peak at 1698 cm^{-1} could be readily detected in the FT-IR spectrum of P1 (Figure 4.3C). These results confirmed that aldehyde units of P0 turned into etheric units with quantitative RER efficiency. It is worth mentioning here that decreasing the equivalents of either of the reactants did not provide quantitative RER efficiency. For instance, when the ethanol equivalent was reduced to 1.1 while keeping the CDMS equivalent the same or decreasing the CDMS to 2 equivalents while keeping the ethanol equivalent the same, the RER efficiencies were found to be 80% and 90%, respectively.

A variety of alcohols were then reacted with P0 using the same equivalents of alcohol (2 equivalents) and CDMS (4 equivalents) regarding the aldehyde. The characterization data and the final structures of the resultant polymers are given in Table 4.1 and Figure 4.5, respectively.

As shown in Table 1, quantitative or near quantitative RER efficiencies were found for all alcohols examined by comparing the integral areas of the aromatic protons to the integral areas of the newly formed etheric protons (^{1}H NMR, ^{13}C NMR, and FT-IR spectra of all studied polymers are given in the supporting information). Importantly, the proposed strategy was unaffected by the nature of alcohol (i.e., primary or secondary) and exhibited good functional group tolerance; alkene, alkyne, azide, and halogen were well tolerated. Moreover, the modified polymers displayed mostly high molecular weights compared to P0, as expected. Among them, the polymer modified with 2-azidoethanol (P10) exhibited low molecular weight (M_n =

28.7 kDa) than the parent polymer, which might be attributed to the lower hydrodynamic volume of this polymer due to pendant azide units. Also, a low molecular weight PEG was reacted with P0; however, the resulting polymer (P11) was found to be barely soluble in THF, though it was fully soluble in $CHCl_3$, and thus reliable results could not be obtained from the GPC analysis of this polymer.

To further demonstrate the versatility of the proposed strategy, a heterofunctionalization study was performed on P0 using two different alcohols (allyl alcohol and ethanol) in equal amounts (1 equiv of each per aldehyde). The resultant polymer (P14) showed a ratio of 20:80% (allyl:ethyl), indicating higher nucleophilic character and thus higher reactivity of ethanol than allyl alcohol.

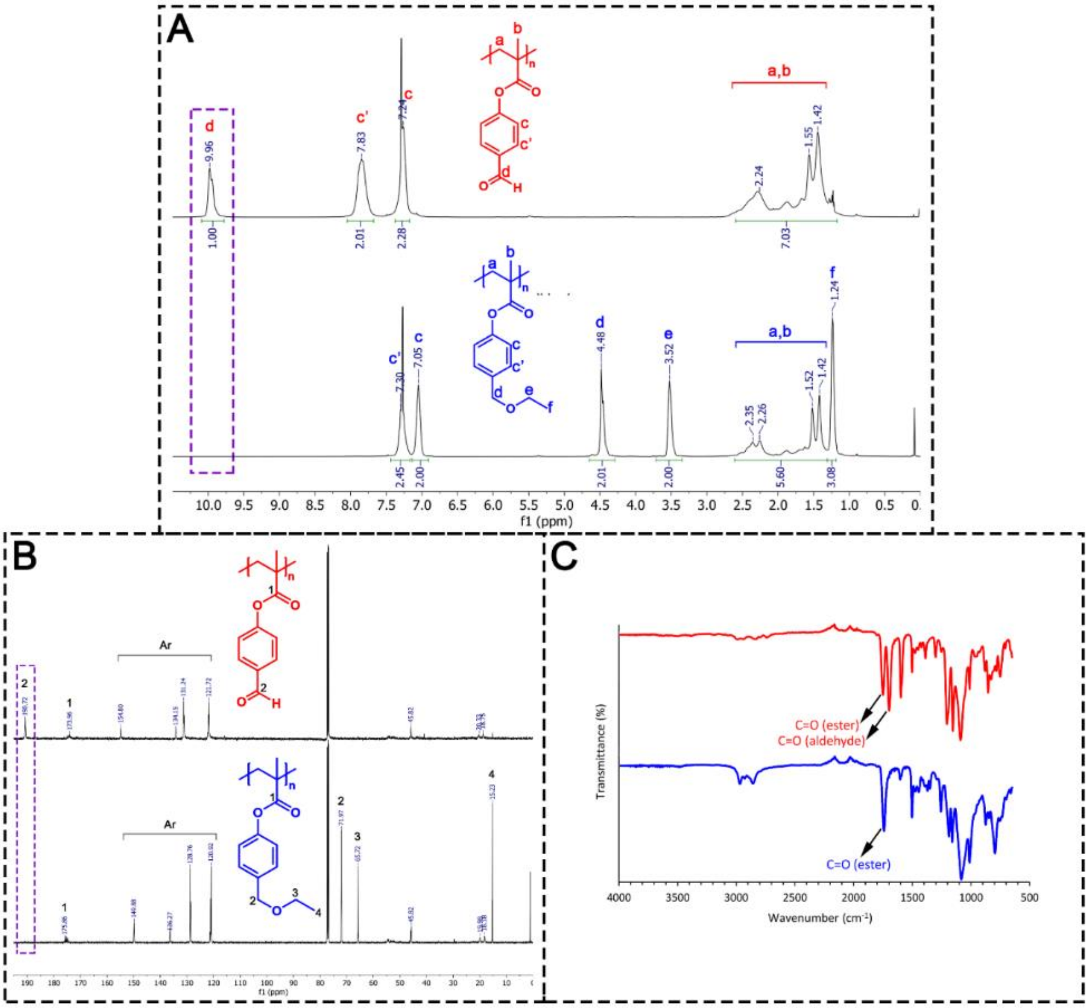

Figure 4.3: Overlay of ^1H NMR (A), ^{13}C NMR (B), and FT-IR spectra (C) of P0 and P1.

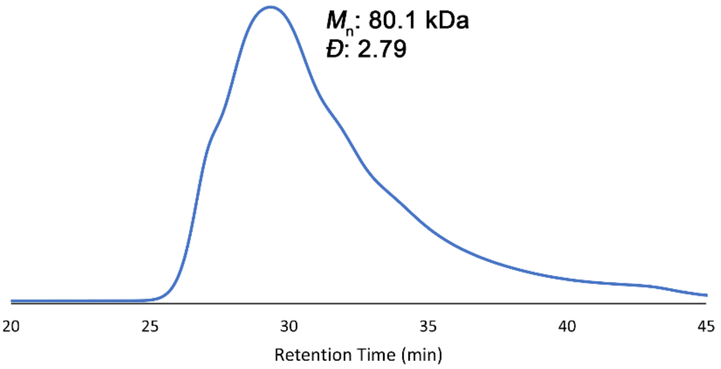

Figure 4.4: GPC chromatogram of P0.

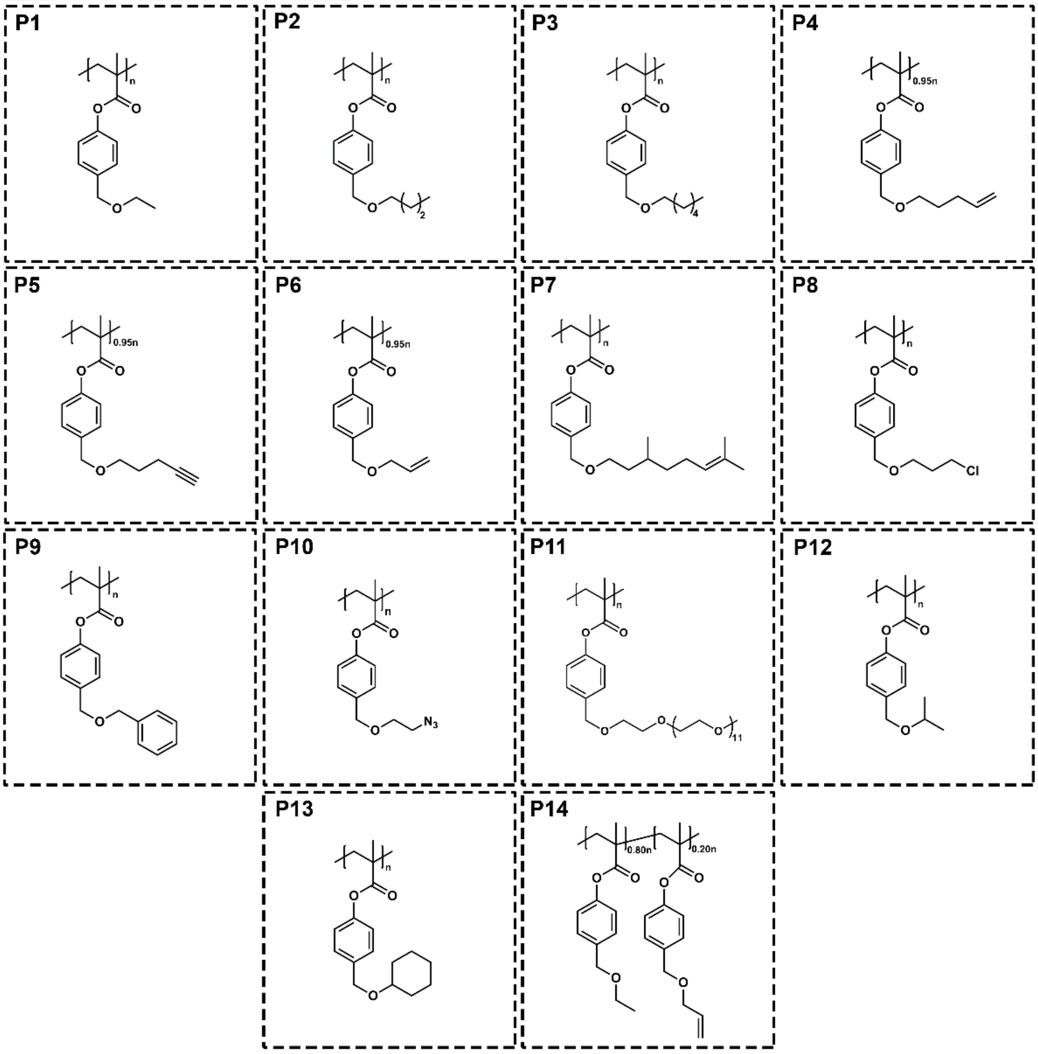

Figure 4.5: Final structures of the resulting polymers after RER in the presence of alcohols.

Table 4.1: Results of the PPM via RER using different alcohols[a].

polymer	alcohol	M_n(kDa)[b]	$Đ$[b]	*eff.* (%)[c]
P0	-	80.1	2.79	
P1	ethanol	117.4	2.82	≥99
P2	1-butanol	134.3	2.45	≥99
P3	1-hexanol	154.7	2.47	≥99
P4	4-pentene-1-ol	99.1	2.60	95
P5	4-pentyn-1-ol	103.5	2.45	95
P6	allyl alcohol	134.4	2.50	95
P7	β-citronellol	287.1	2.27	≥99
P8	3-chloro-1-propanol	165.3	2.44	≥99
P9	benzyl alcohol	254.4	2.78	≥99
P10	2-azidoethanol	28.7	2.84	≥99
P11[d]	PEG_{550}	5.8	1.74	≥99
P12	isopropyl alcohol	97.1	2.33	≥99
P13	cyclohexanol	178.9	2.94	≥99
P14[e]	allyl alcohol/ethanol	147.8	2.84	20/80 (allyl/ethyl)

[a]All reactions were carried out using: 2 equiv of alcohol/4 equiv of CDMS per repeating unit of P0 in a mixture of CH_2Cl_2/CH_3NO_2 (1 mL each) at room temperature for 16 h unless stated otherwise. [b]Determined by GPC calibrated based on linear PS standards in THF. [c]Determined by ^1H NMR. [d]Molecular weight of the soluble fraction. [e]Equal amounts (1 equiv each) of allyl alcohol and ethanol were used.

Full characterization data of other modified polymers are given below.

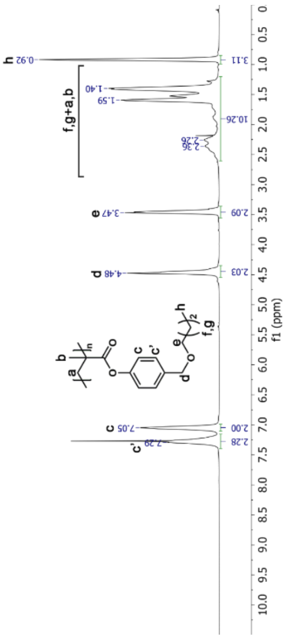

Figure 4.6: ^1H NMR spectrum of P2 in $CDCl_3$ (500 MHz).

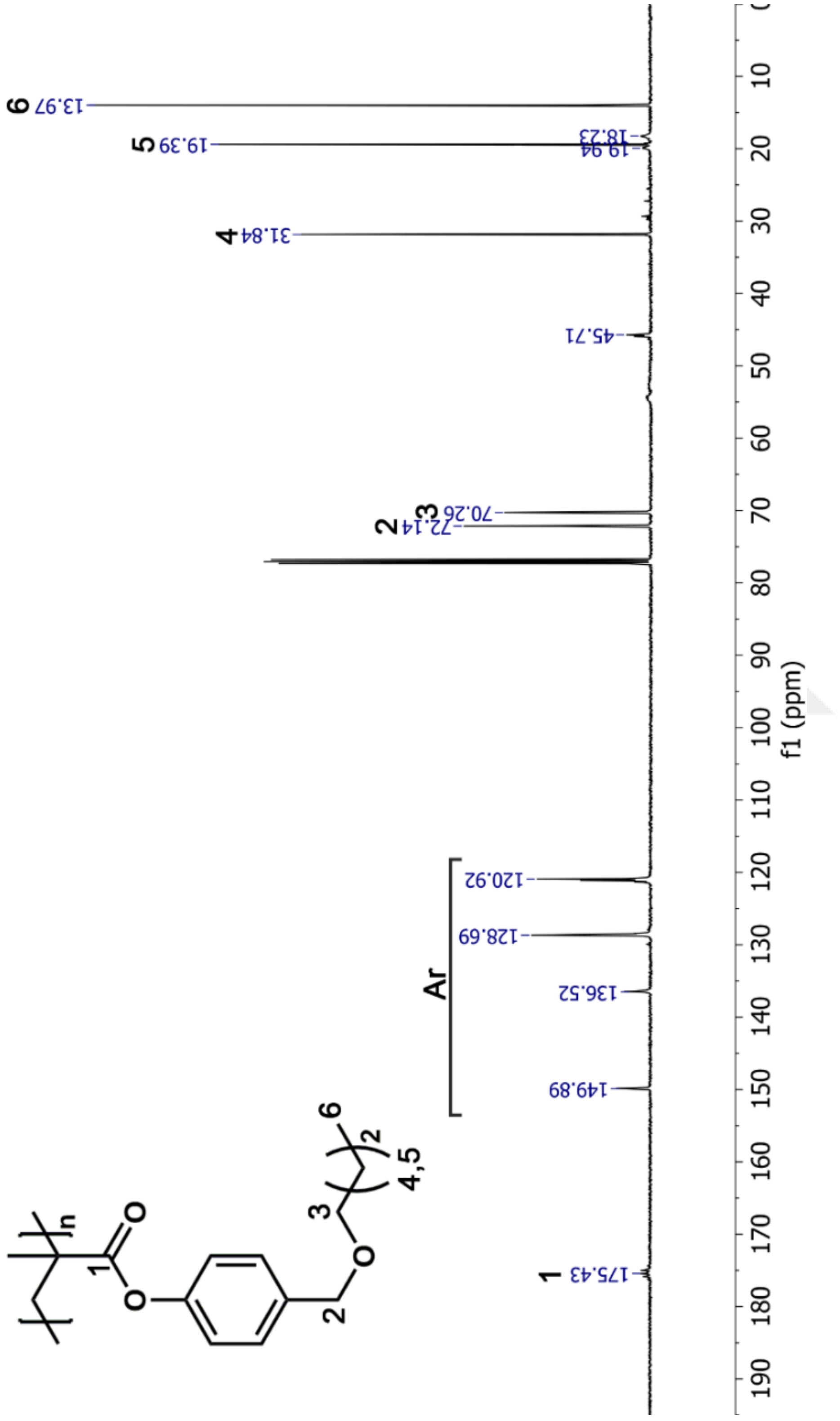

Figure 4.7: ^{13}C NMR spectrum of P2 in $CDCl_3$ (125 MHz).

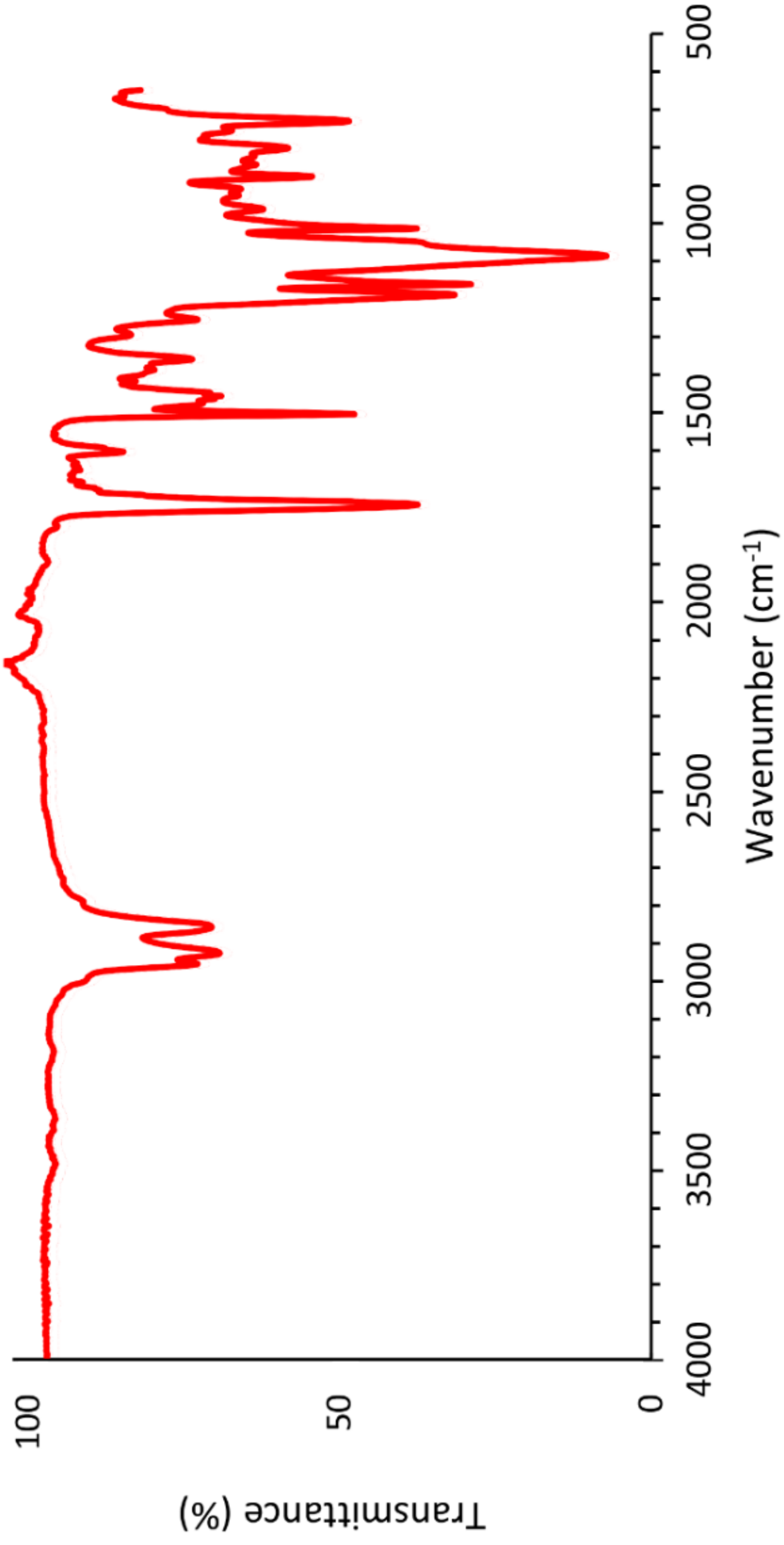

Figure 4.8: FT-IR spectrum of P2.

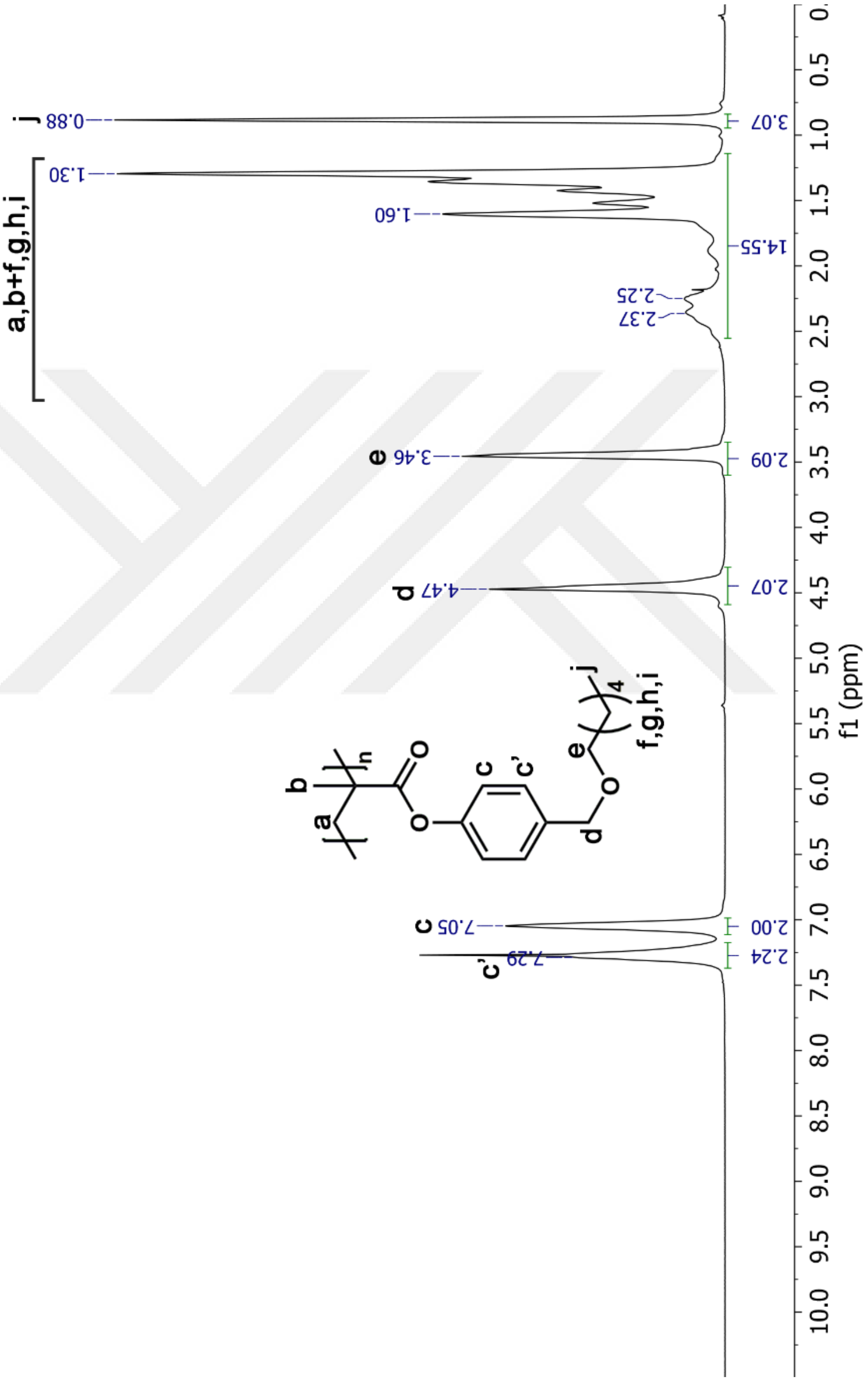

Figure 4.9: ^{1}H NMR spectrum of P3 in $CDCl_3$ (500 MHz).

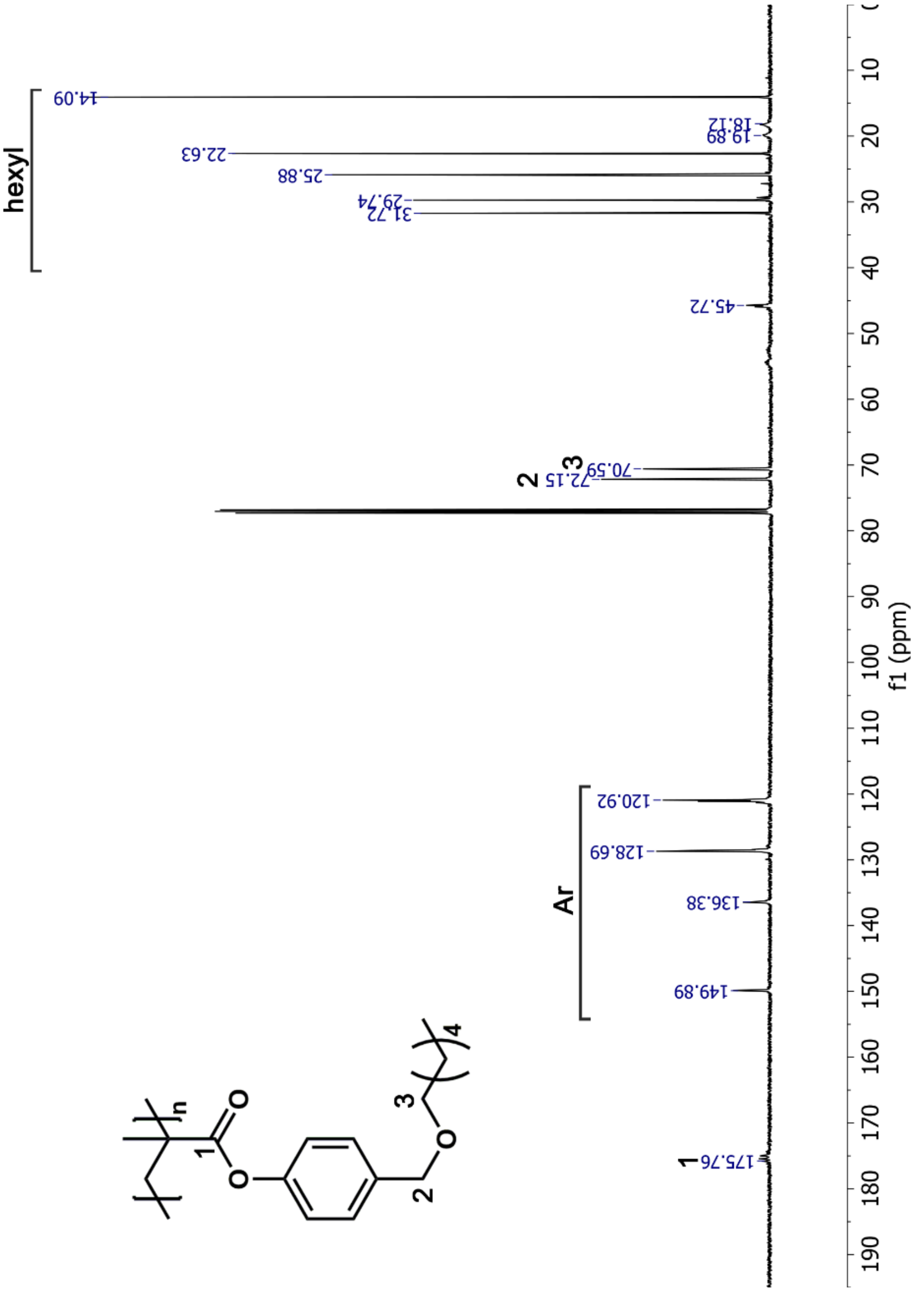

Figure 4.10: ^{13}C NMR spectrum of P3 in CDCl$_3$ (125 MHz).

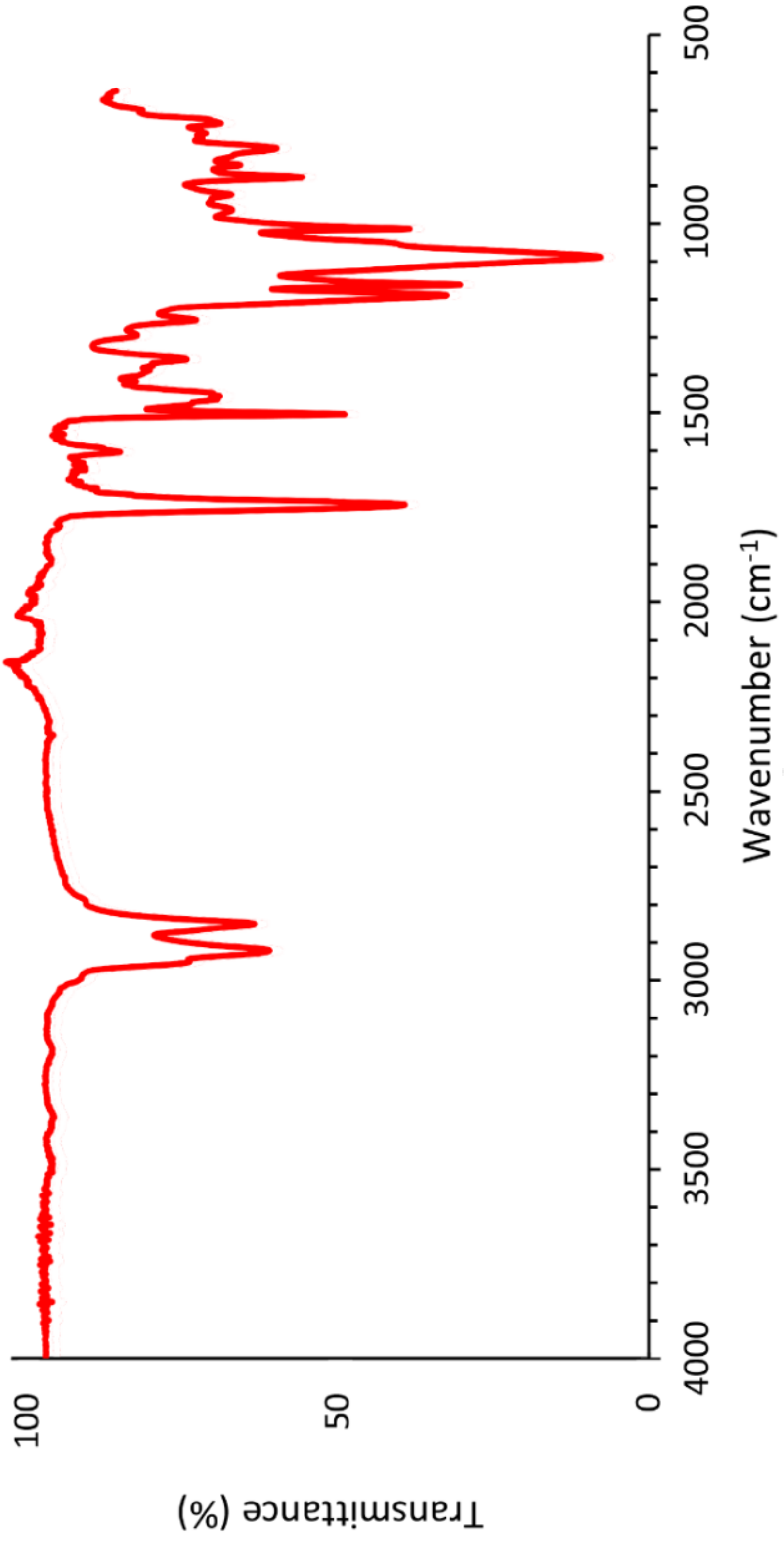

Figure 4.11: FT-IR spectrum of P3.

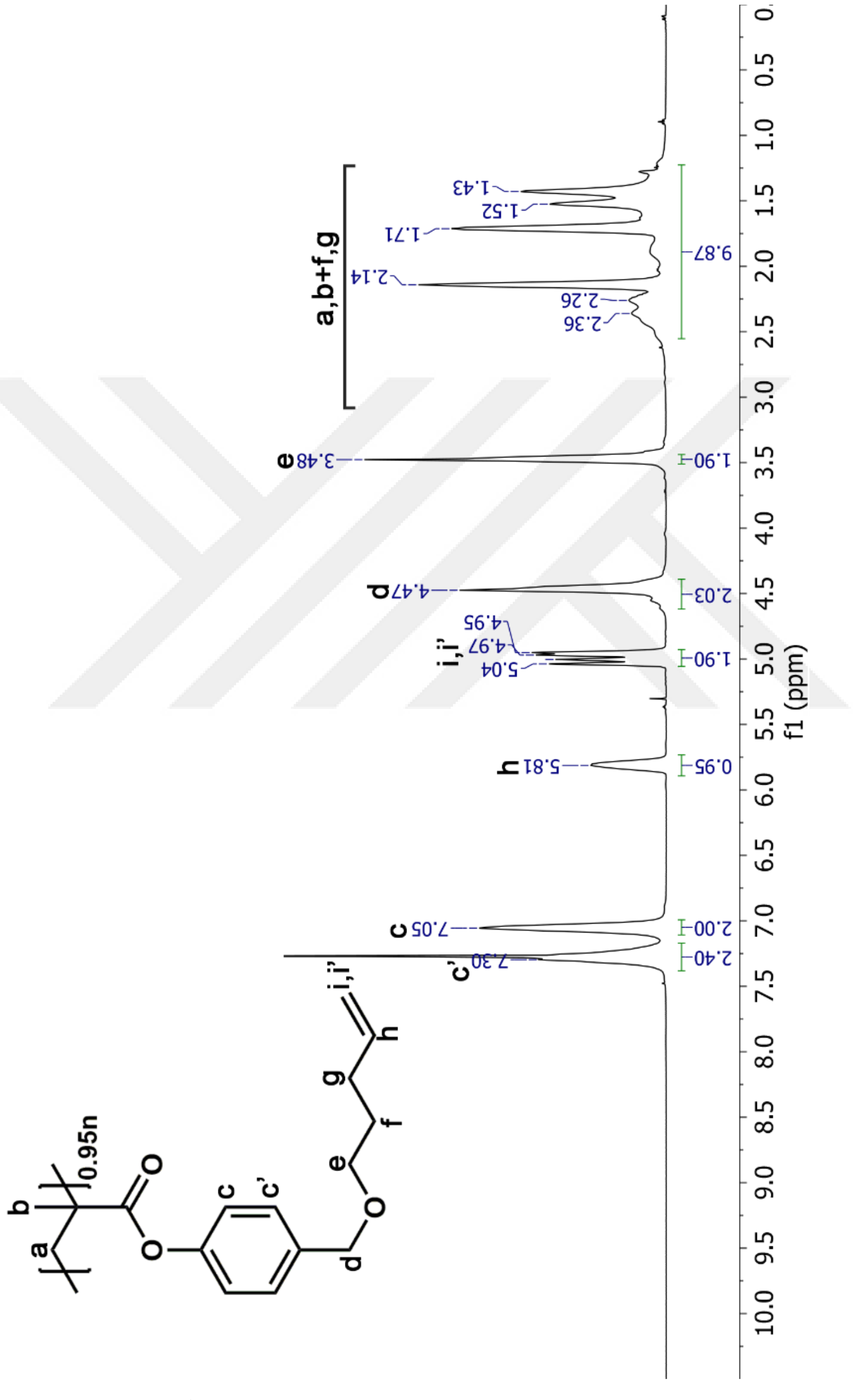

Figure 4.12: ^{1}H NMR spectrum of P4 in $CDCl_3$ (500 MHz).

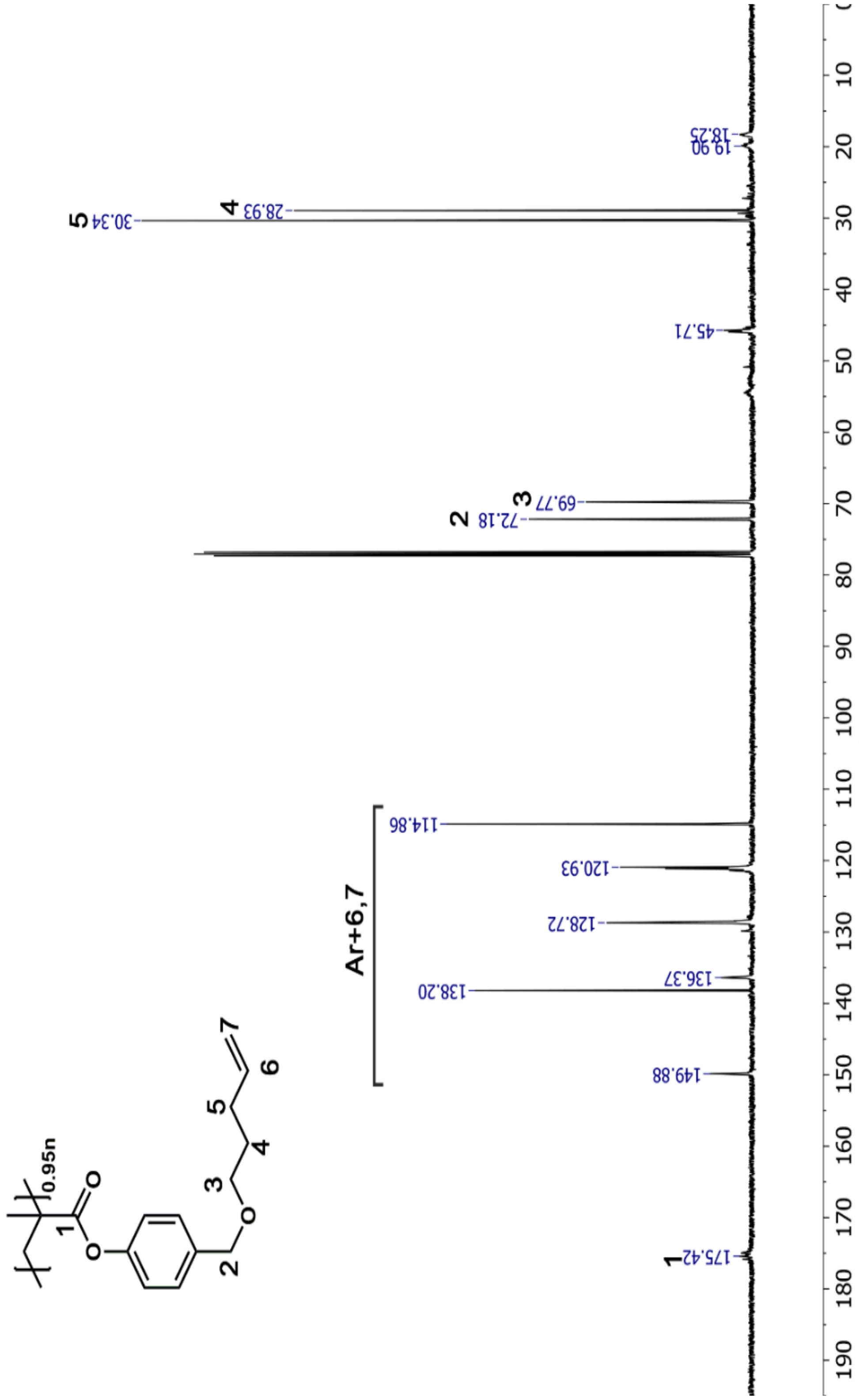

Figure 4.13: ^{13}C NMR spectrum of P4 in $CDCl_3$ (125 MHz).

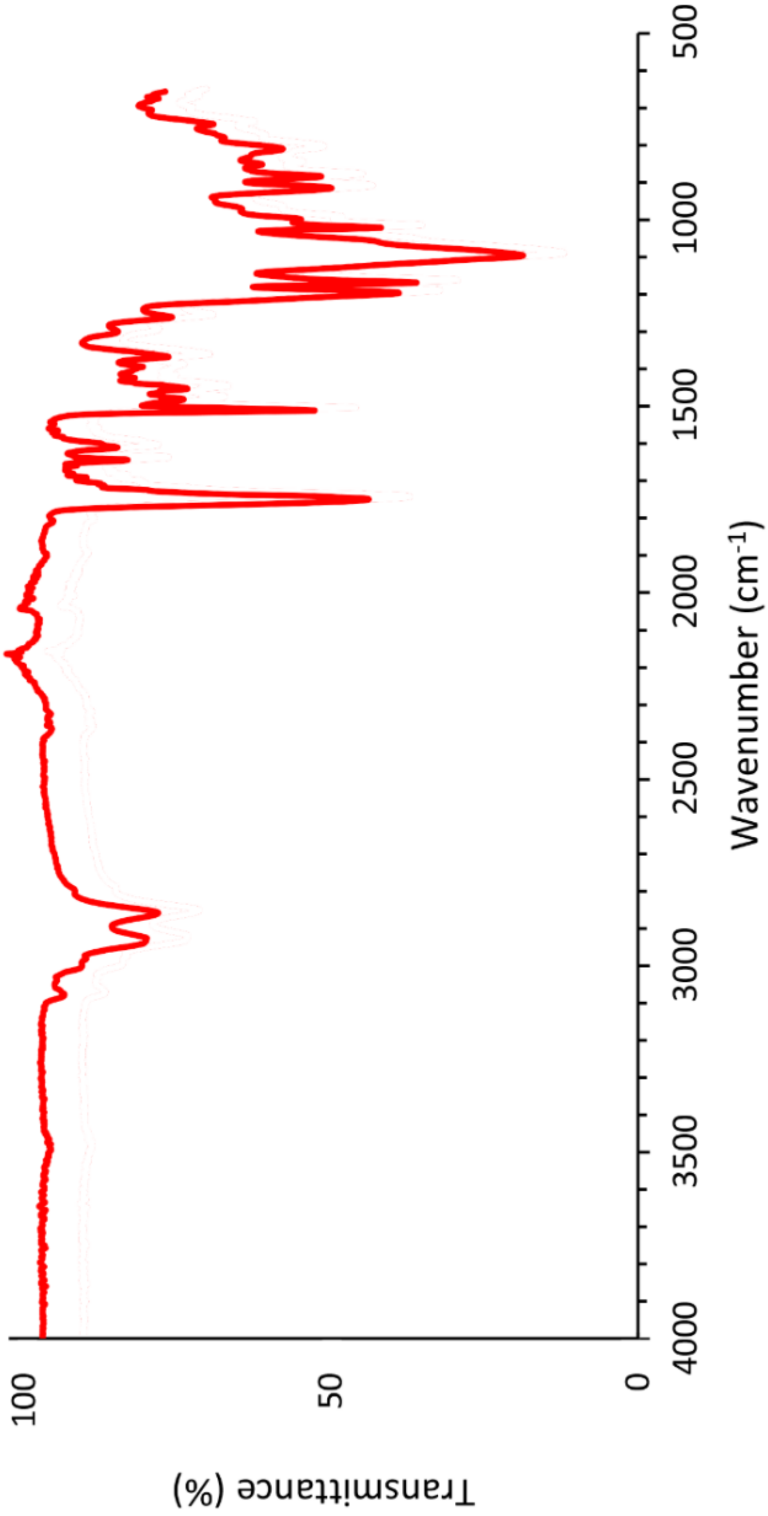

Figure 4.14: FT-IR spectrum of P4.

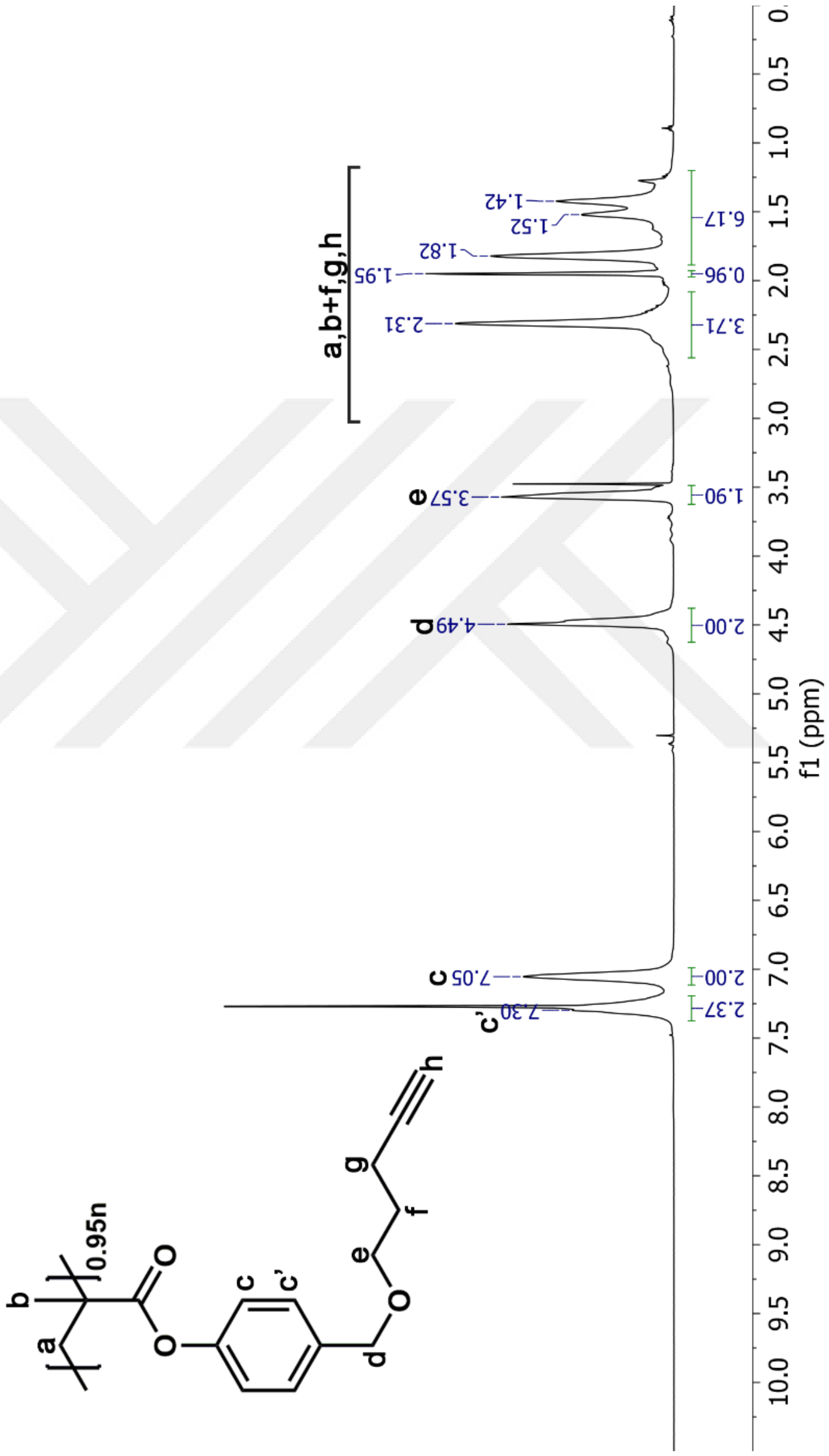

Figure 4.15: ^{1}H NMR spectrum of P5 in $CDCl_3$ (500 MHz).

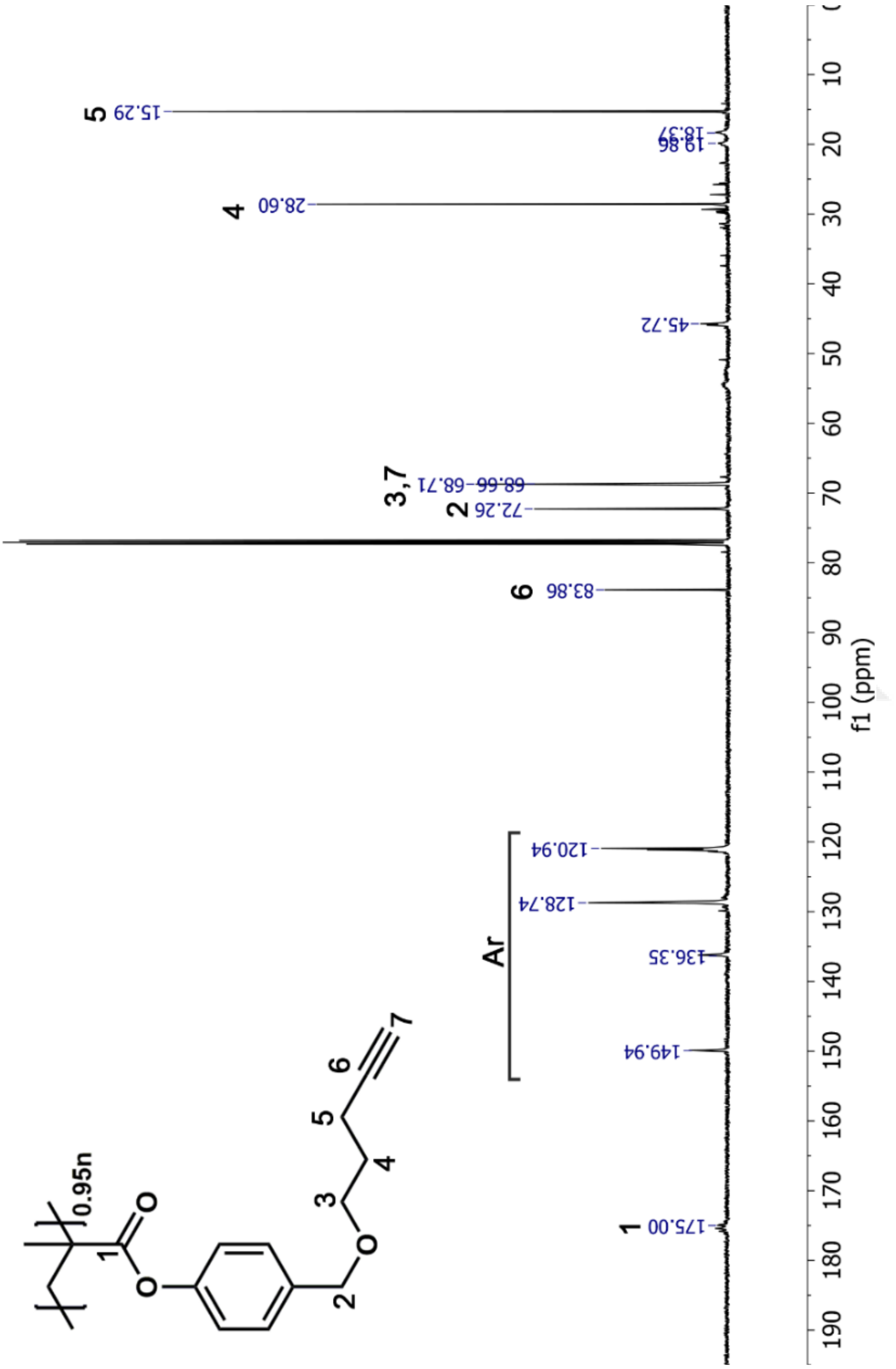

Figure 4.16: ^{13}C NMR spectrum of P5 in $CDCl_3$ (125 MHz).

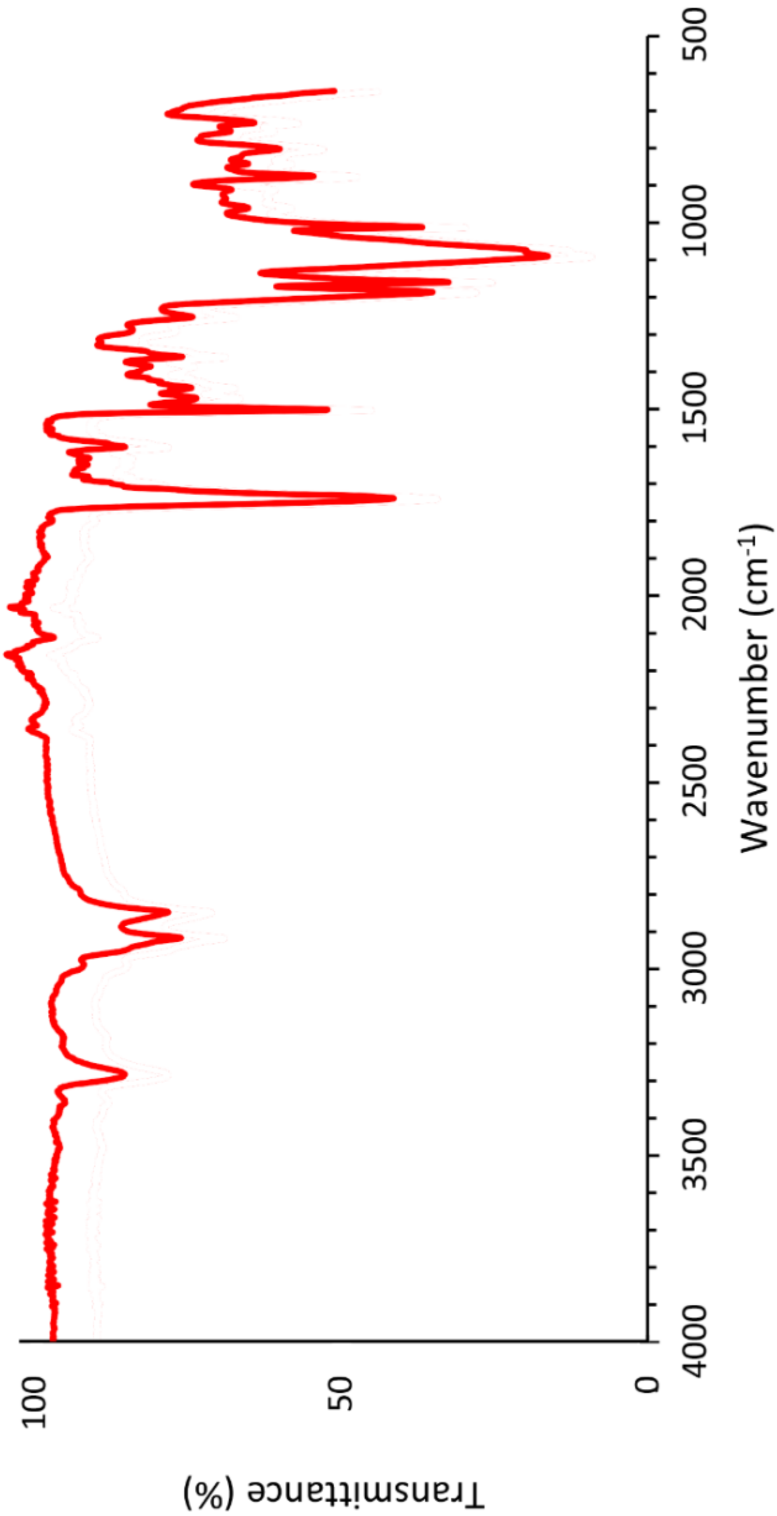

Figure 4.17: FT-IR spectrum of P5.

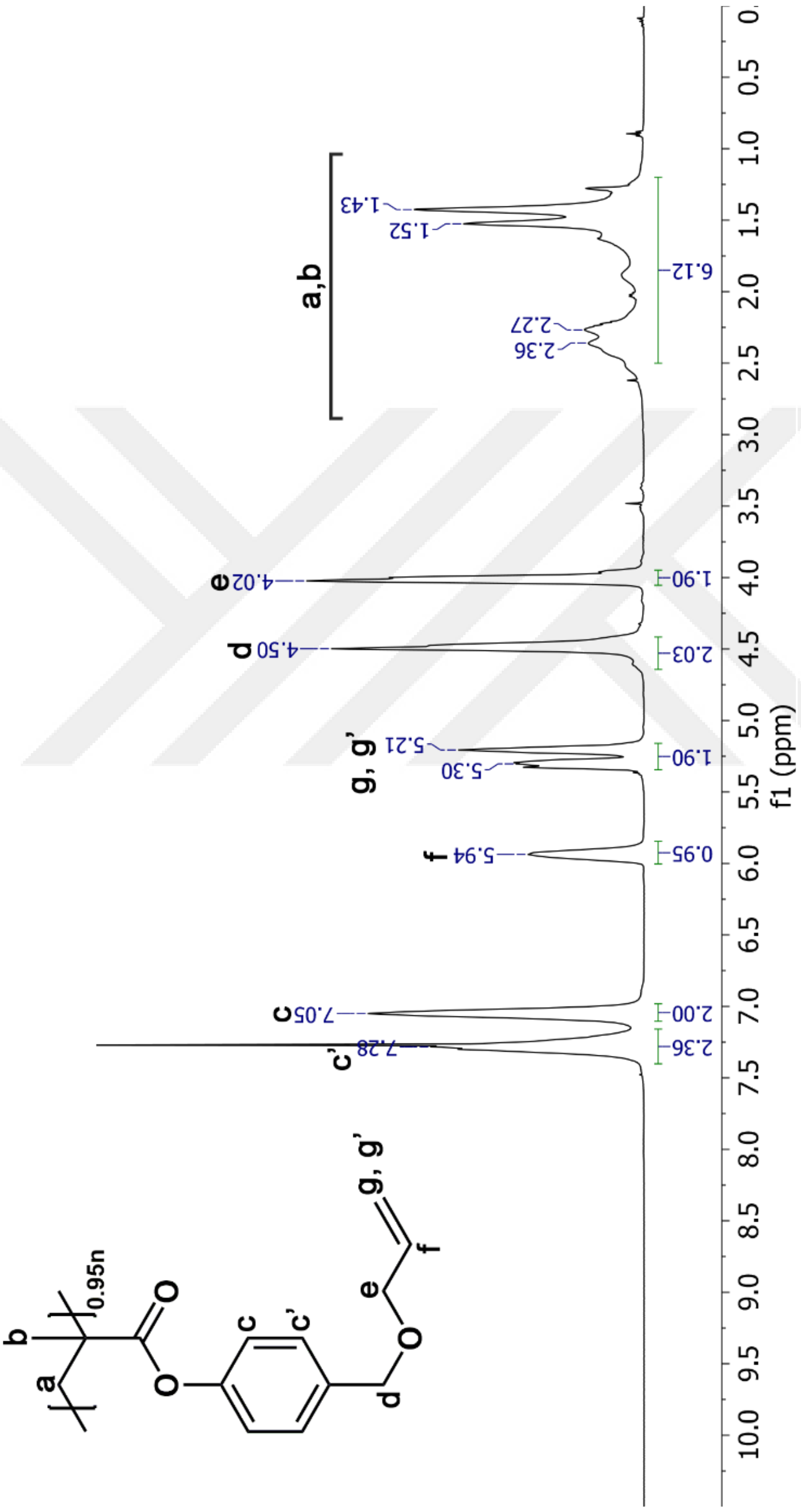

Figure 4.18: ^{1}H NMR spectrum of P6 in $CDCl_3$ (500 MHz).

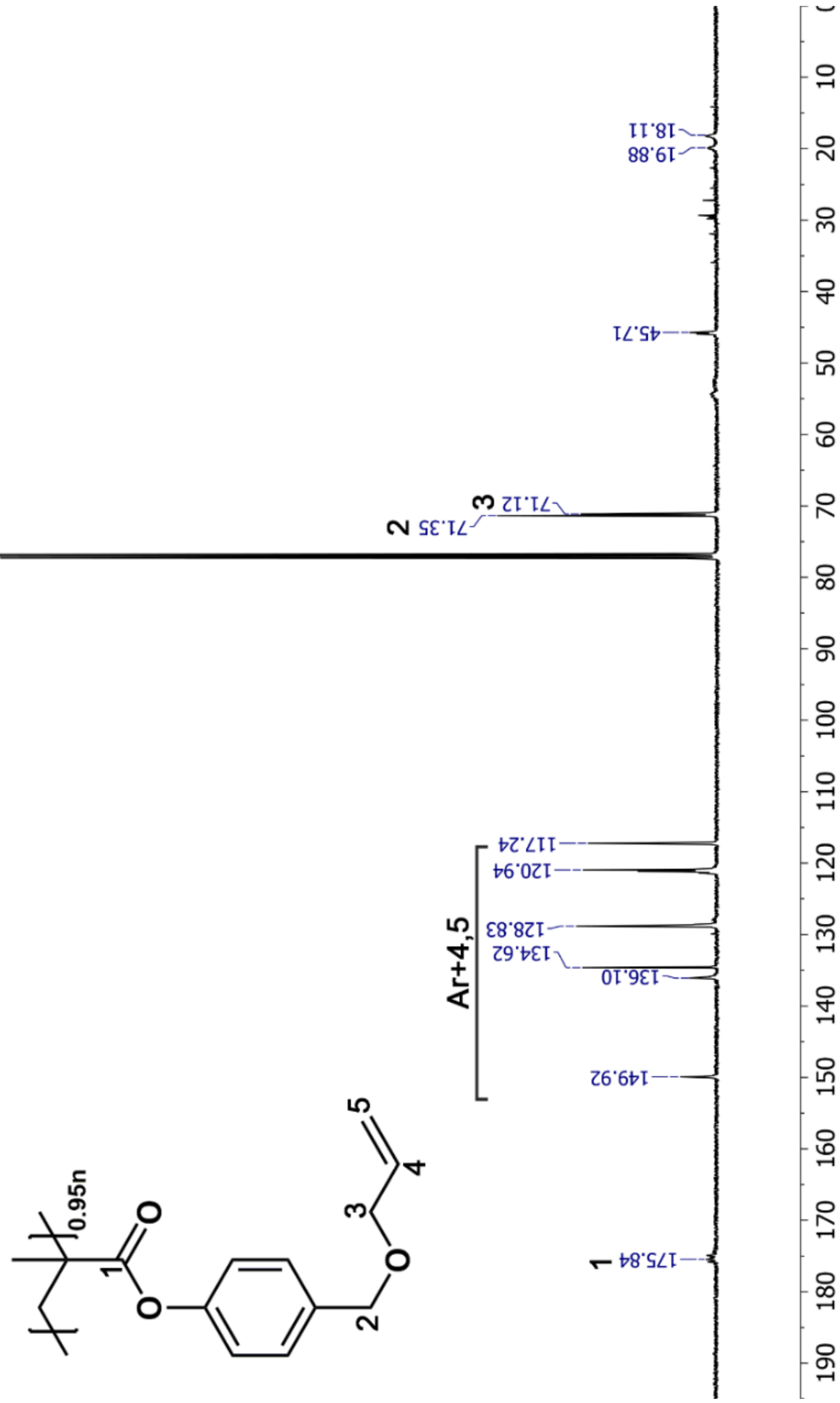

Figure 4.19: ^{13}C NMR spectrum of P6 in $CDCl_3$ (125 MHz).

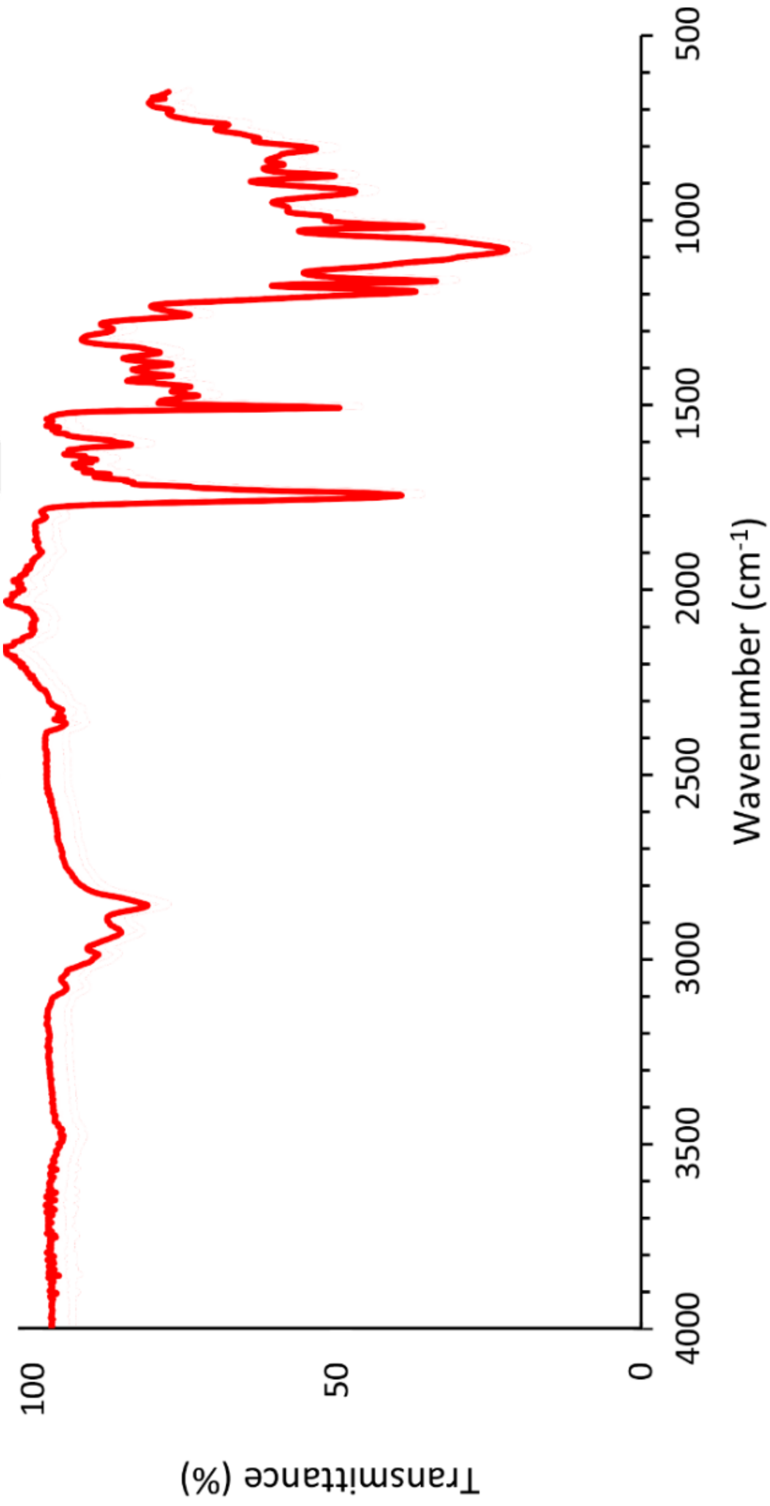

Figure 4.20: FT-IR spectrum of P6.

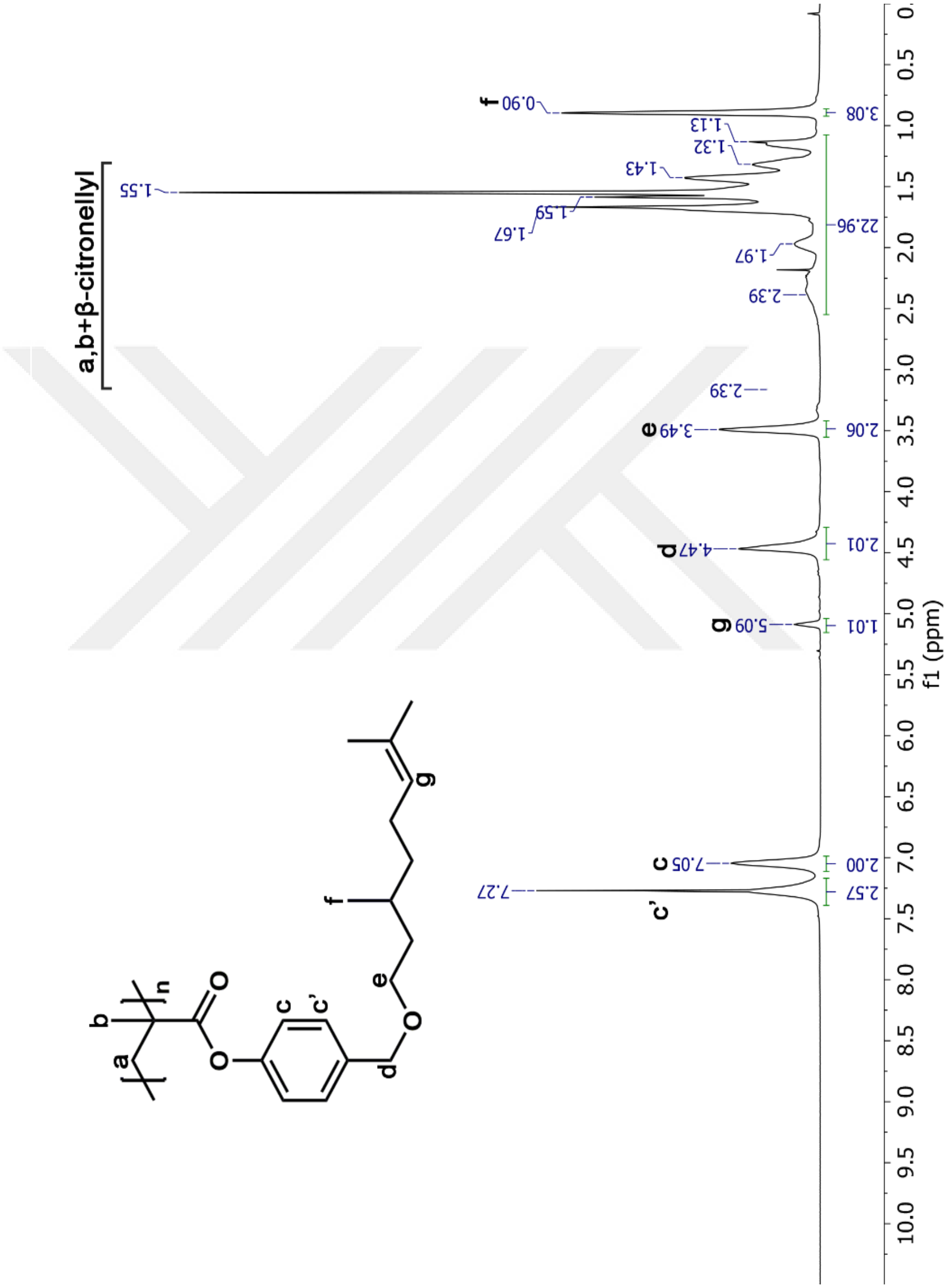

Figure 4.21: ^{1}H NMR spectrum of P7 in $CDCl_3$ (500 MHz).

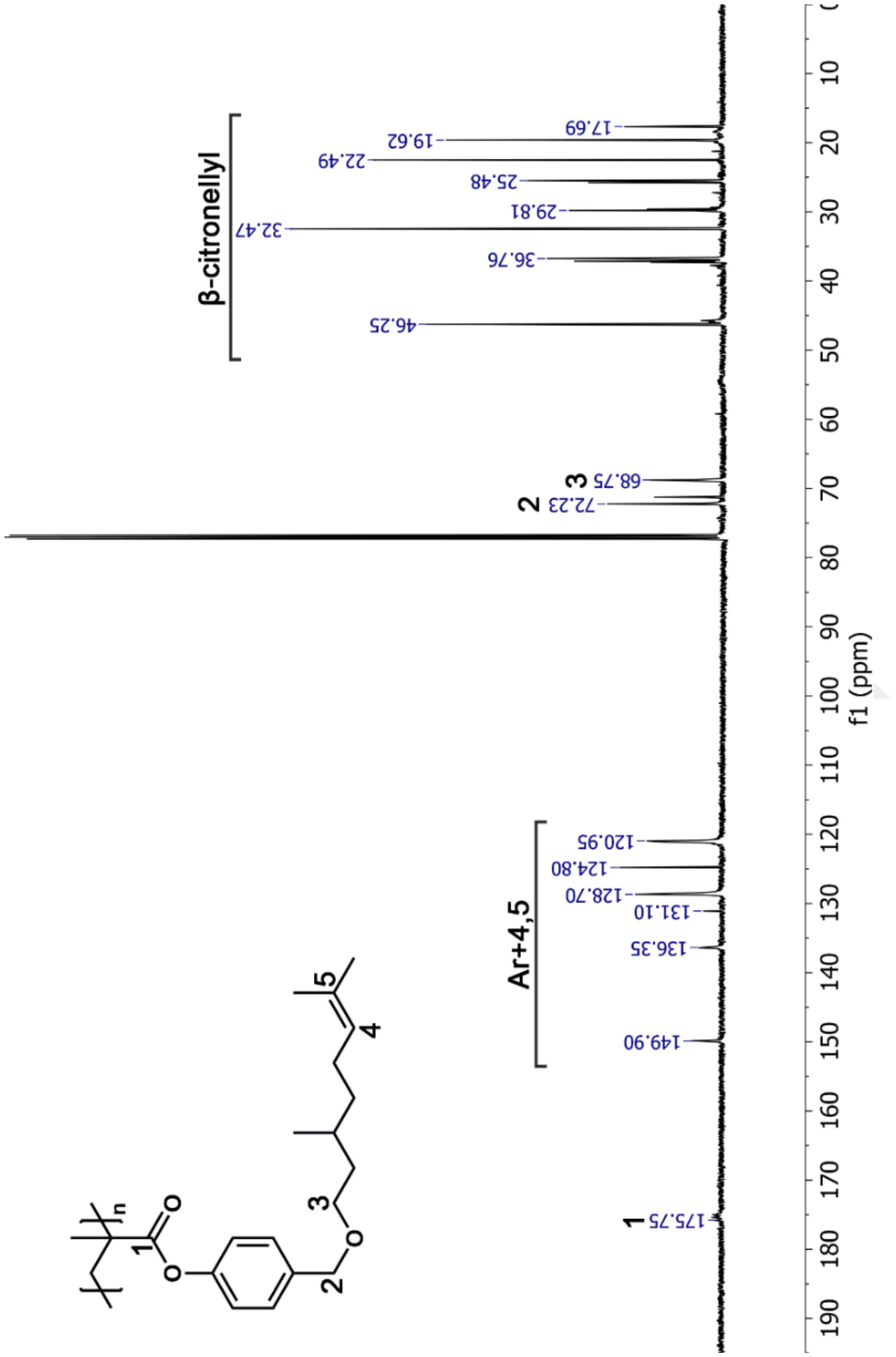

Figure 4.22: ^{13}C NMR spectrum of P7 in CDCl$_3$ (125 MHz).

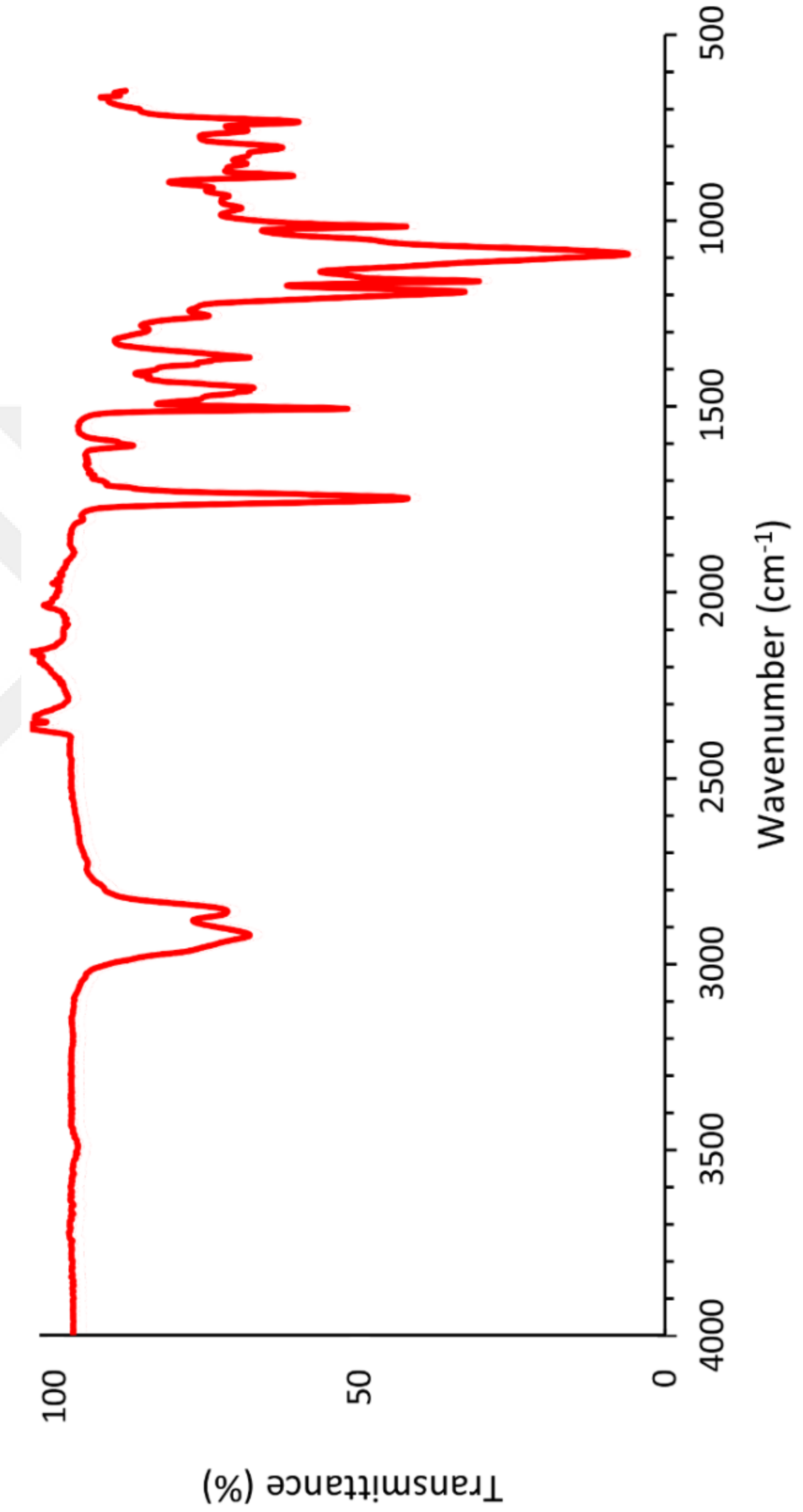

Figure 4.23: FT-IR spectrum of P7.

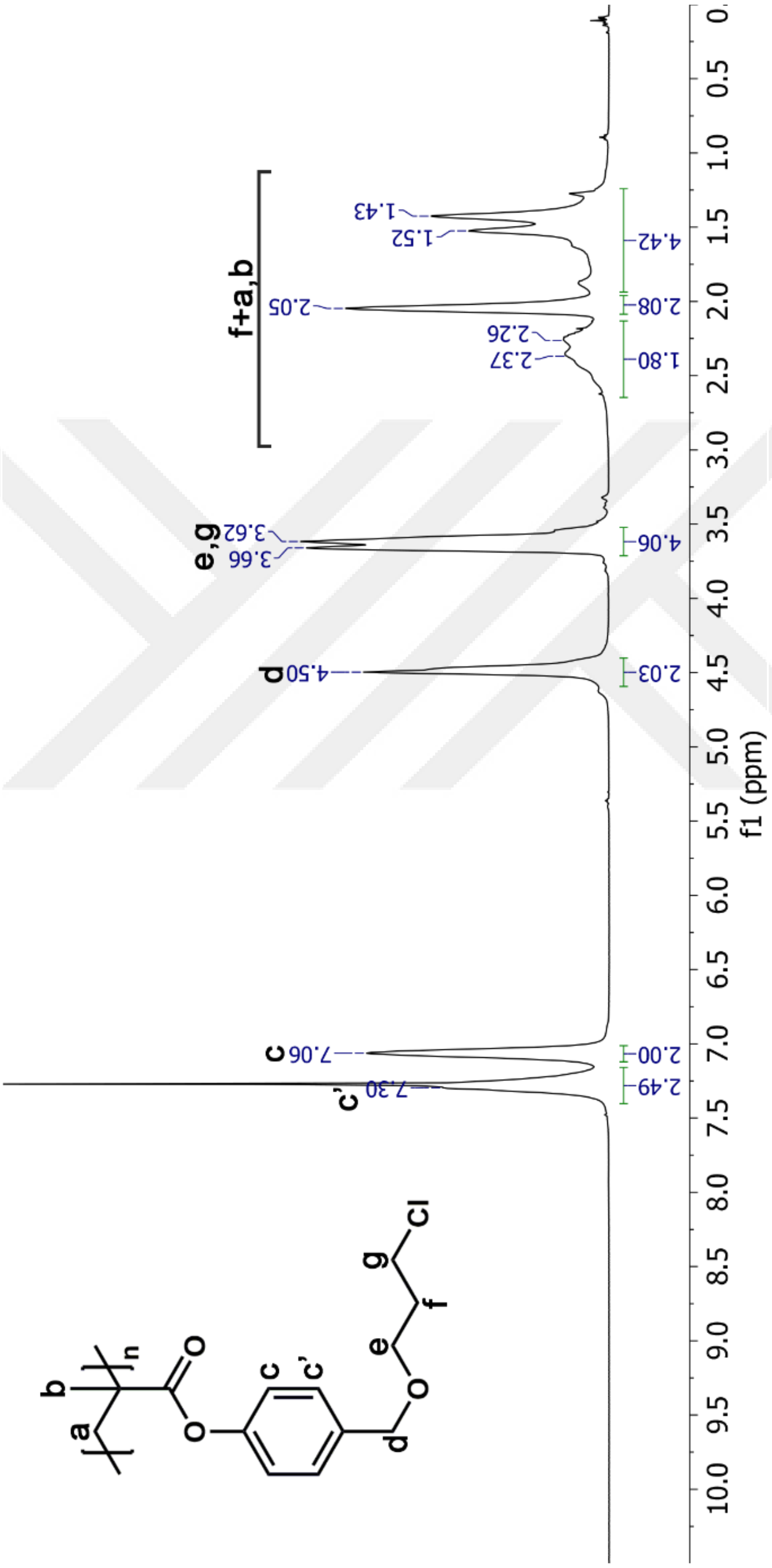

Figure 4.24: ^{1}H NMR spectrum of P8 in $CDCl_3$ (500 MHz).

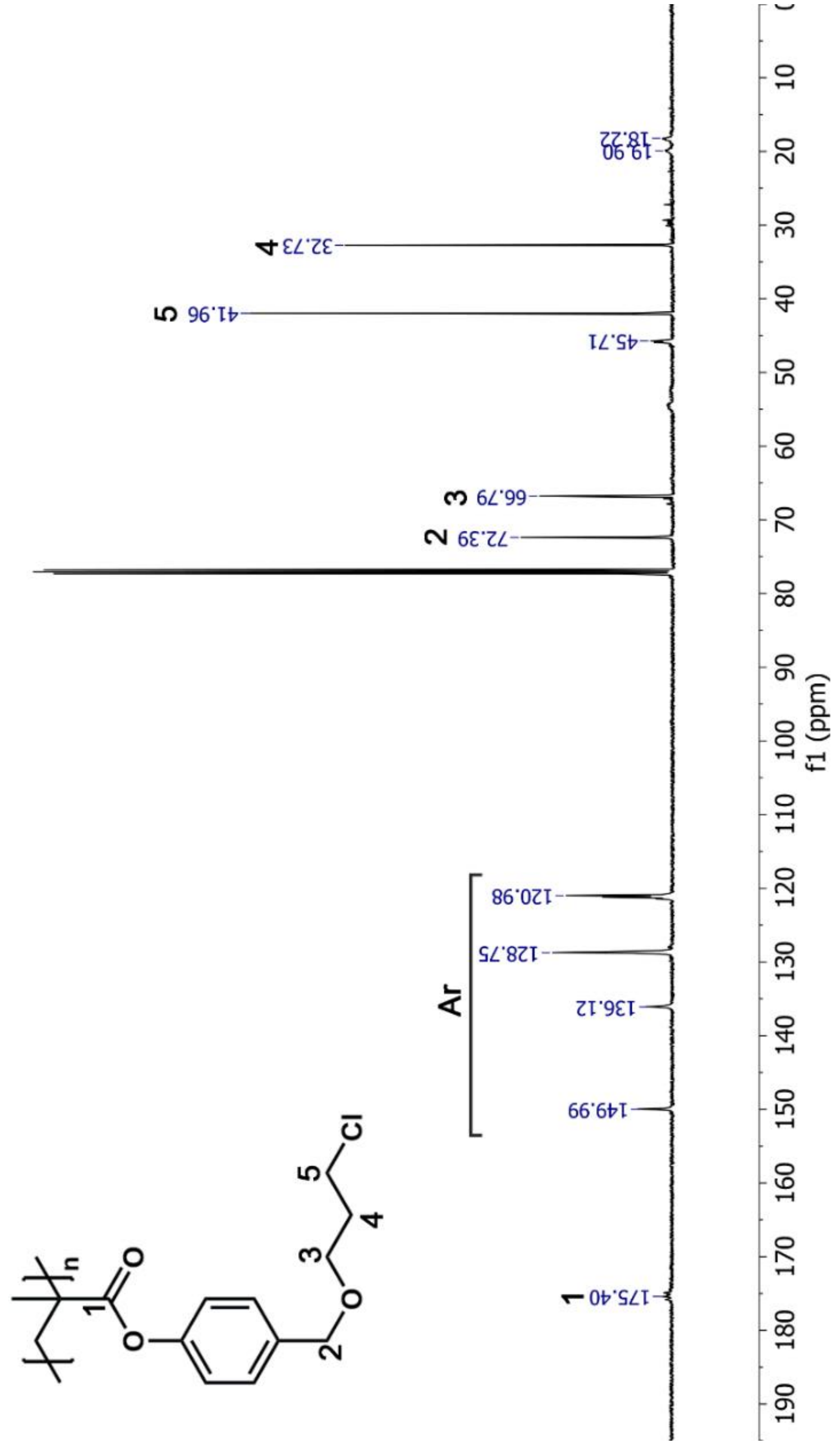

Figure 4.25: ^{13}C NMR spectrum of P8 in $CDCl_3$ (125 MHz).

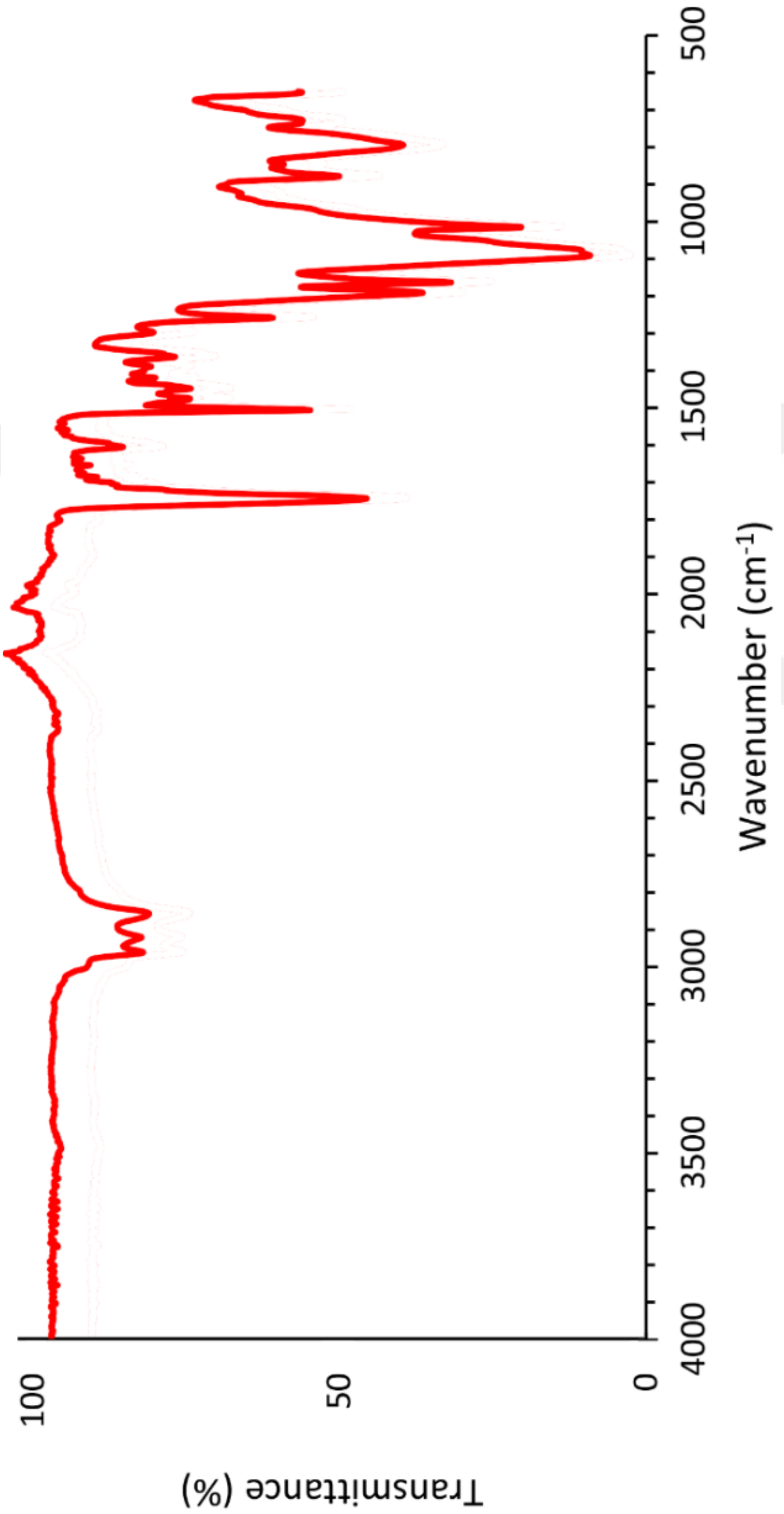

Figure 4.26: FT-IR spectrum of P8.

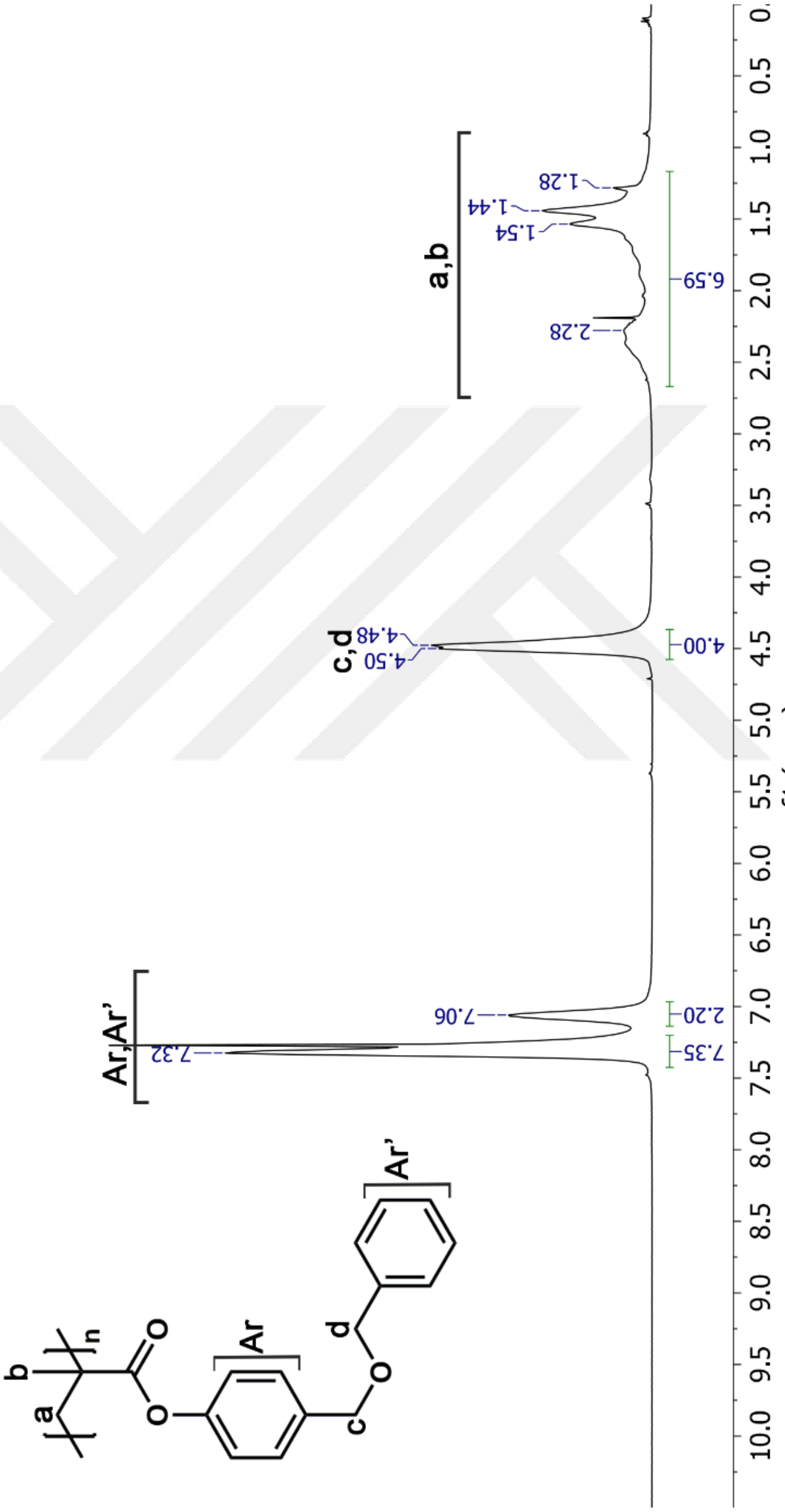

Figure 4.27: ^{1}H NMR spectrum of P9 in $CDCl_3$ (500 MHz).

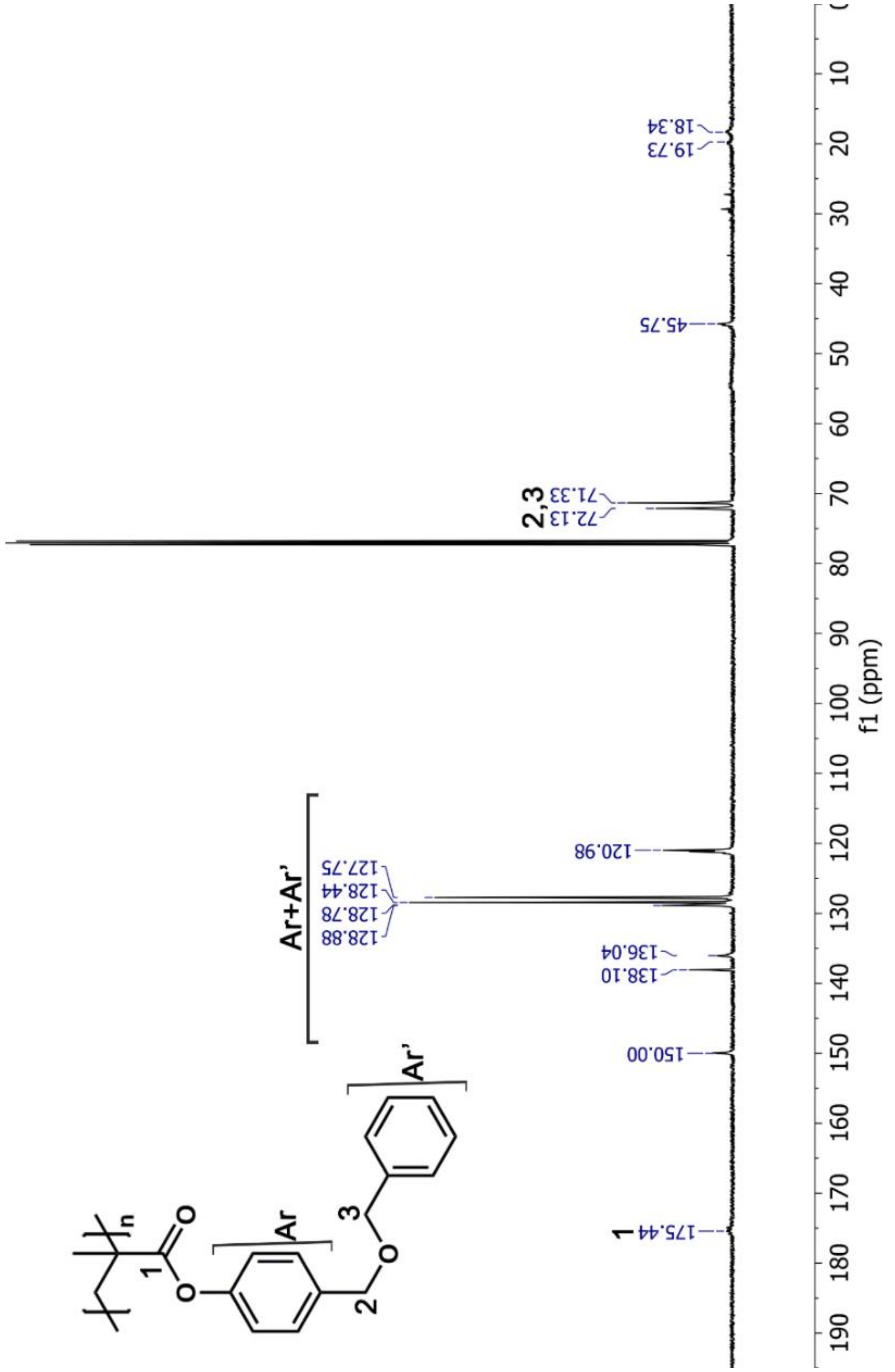

Figure 4.28: ^{13}C NMR spectrum of P9 in $CDCl_3$ (125 MHz).

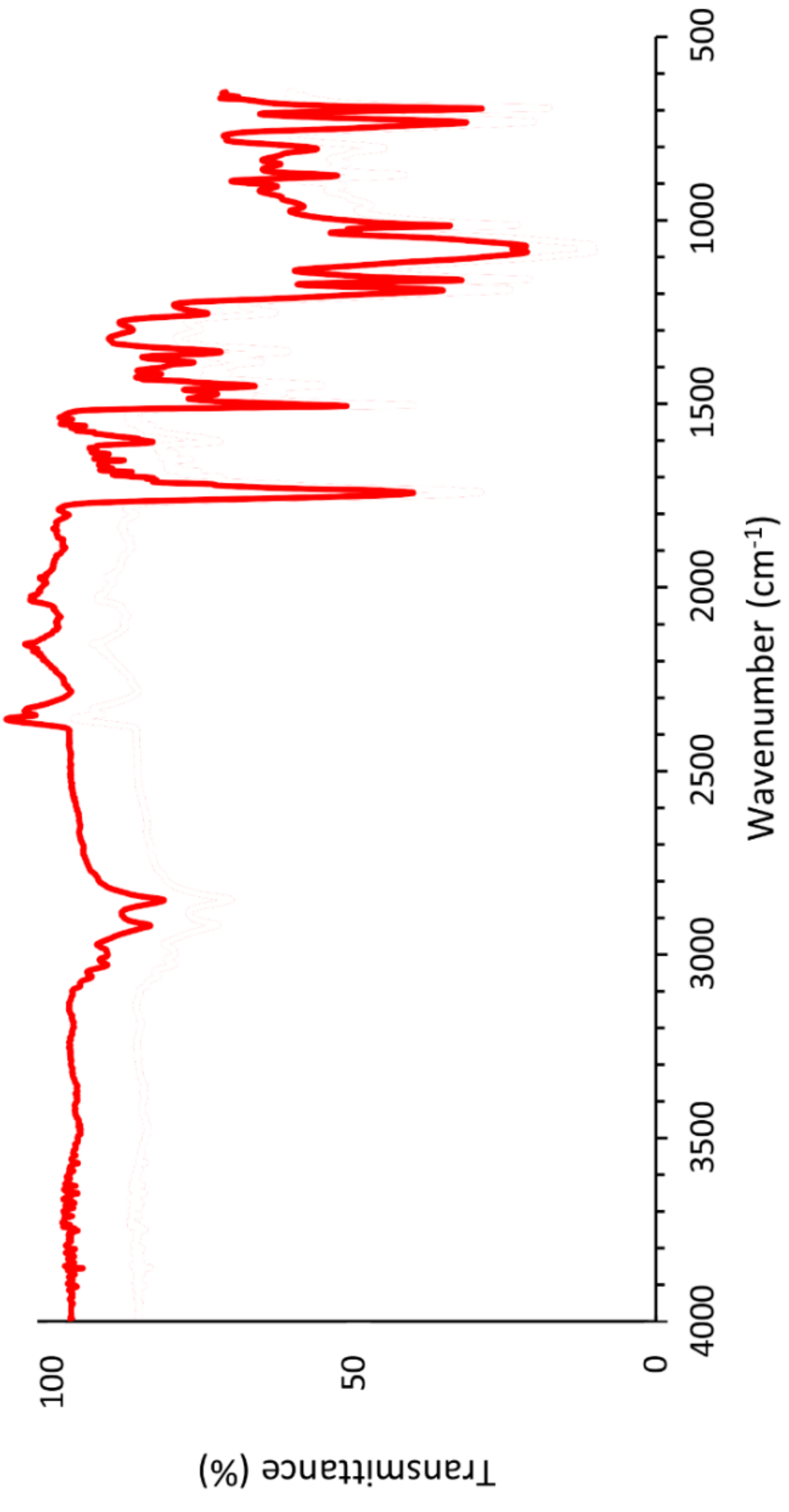

Figure 4.29: FT-IR spectrum of P9.

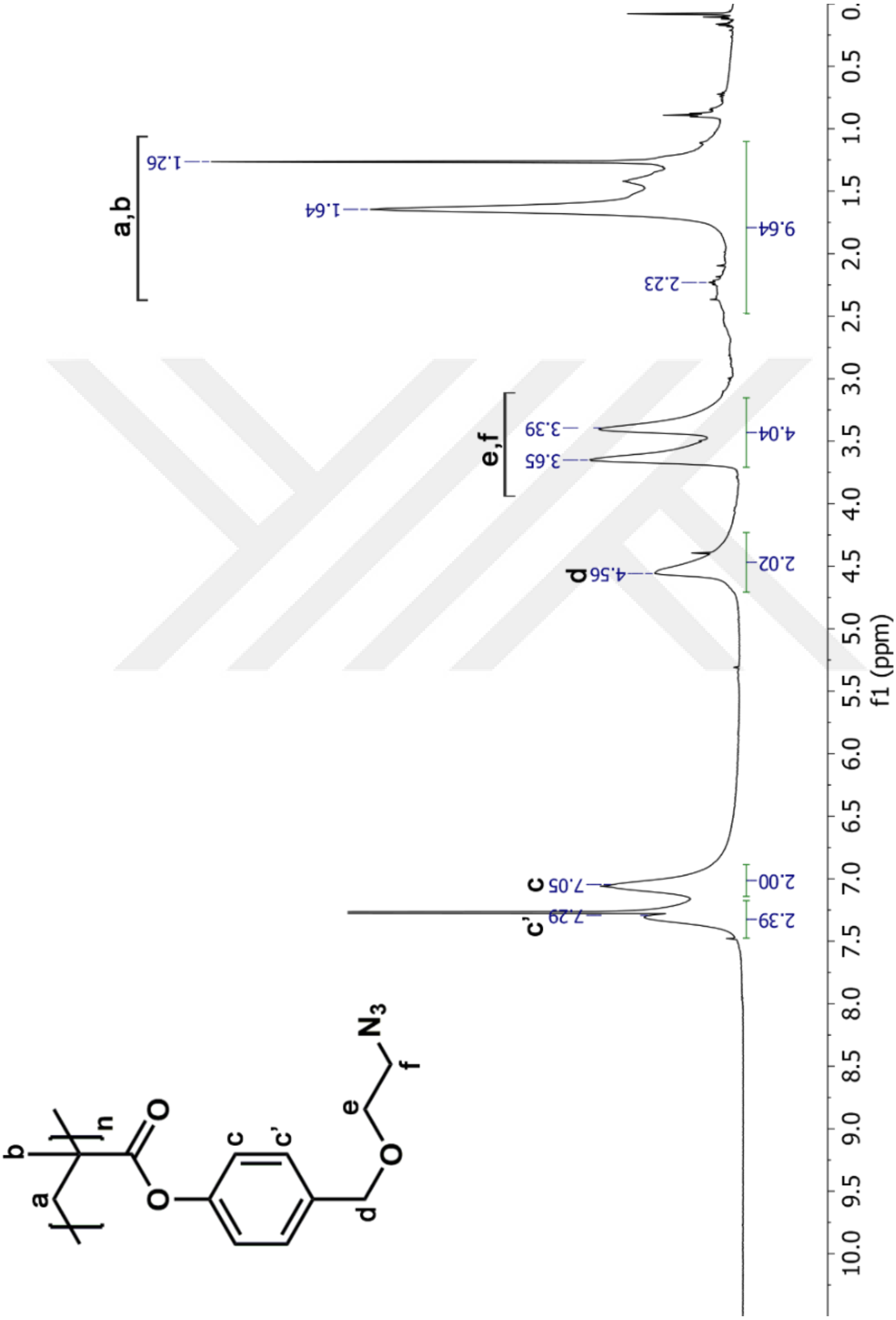

Figure 4.30: ^{1}H NMR spectrum of P10 in $CDCl_3$ (500 MHz).

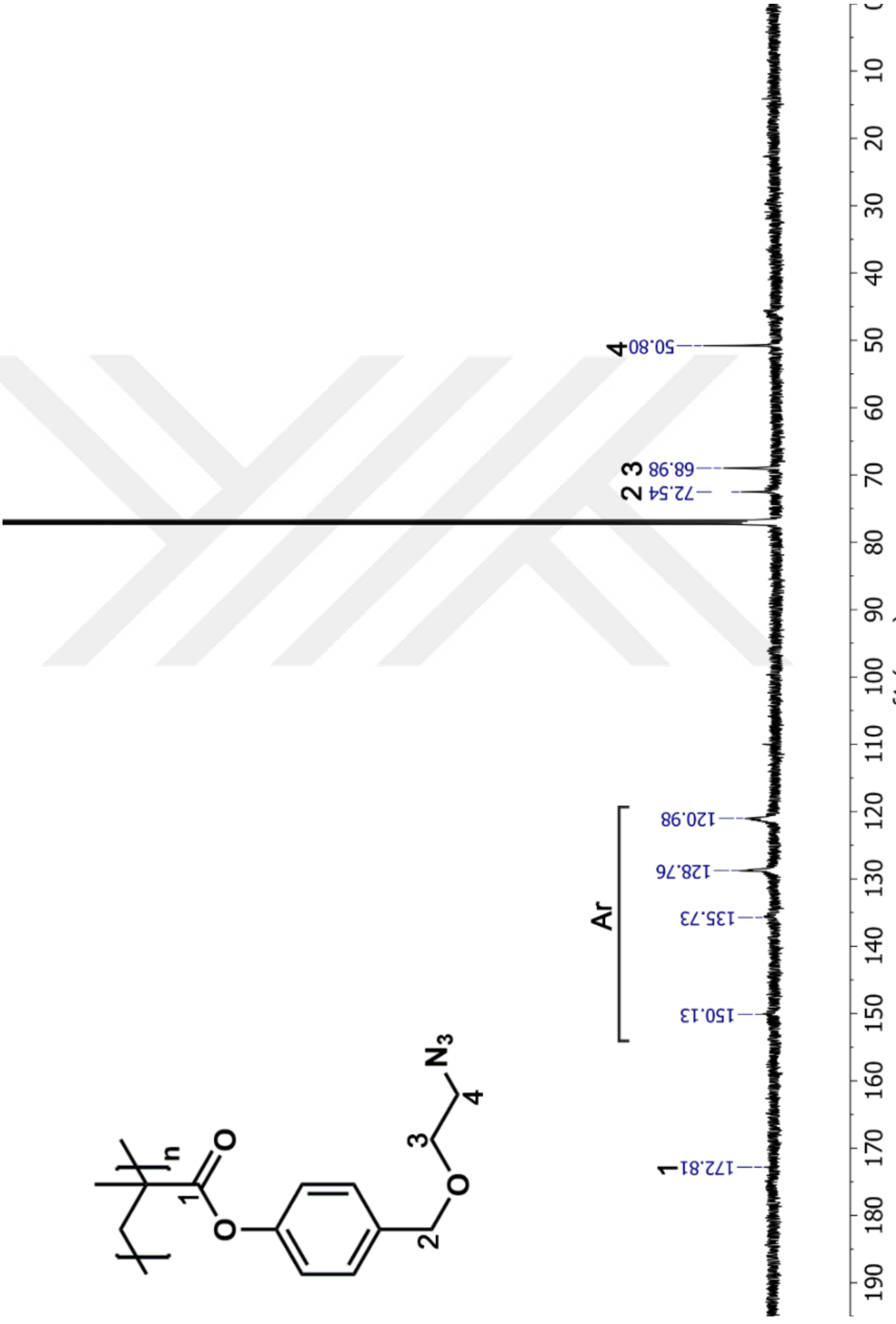

Figure 4.31: ^{13}C NMR spectrum of P10 in $CDCl_3$ (125 MHz).

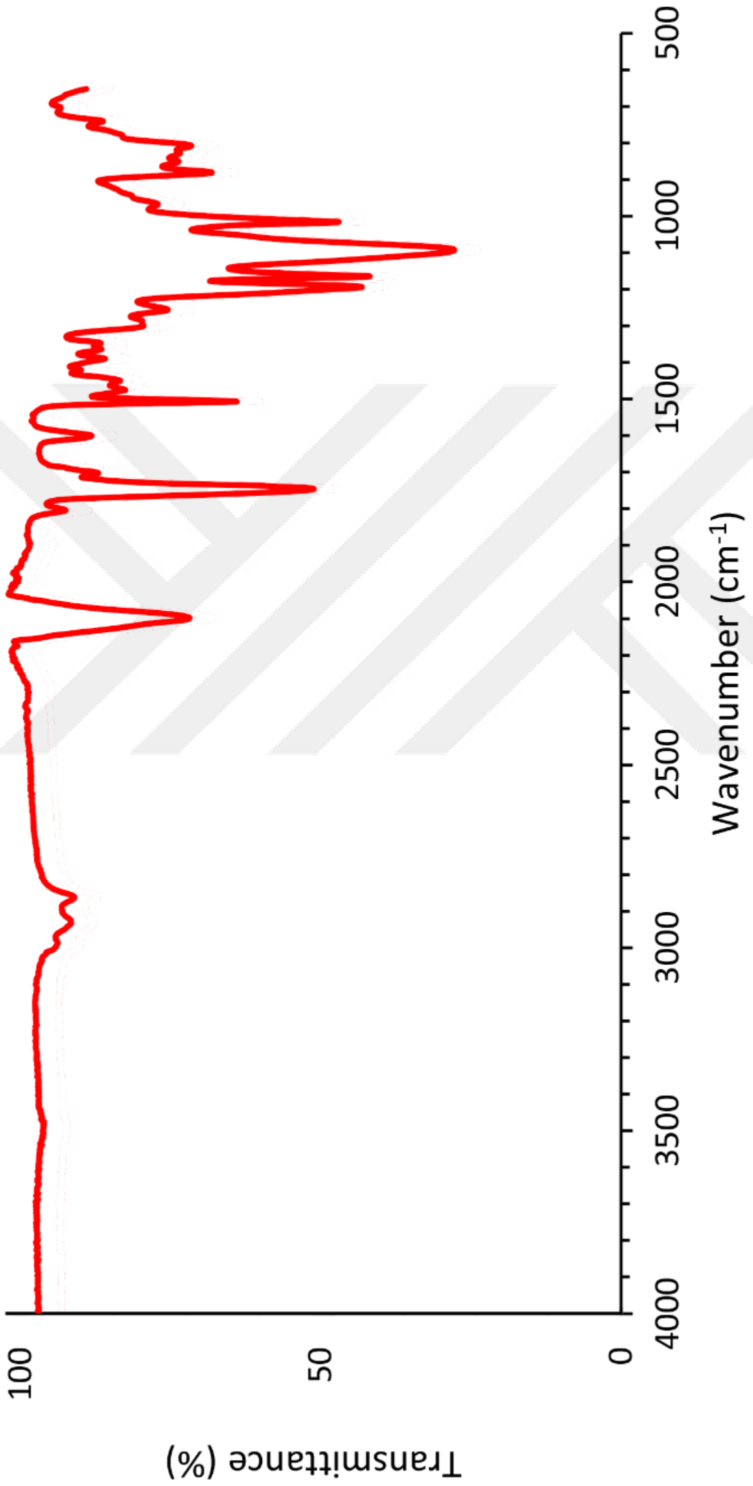

Figure 4.32: FT-IR spectrum of P10.

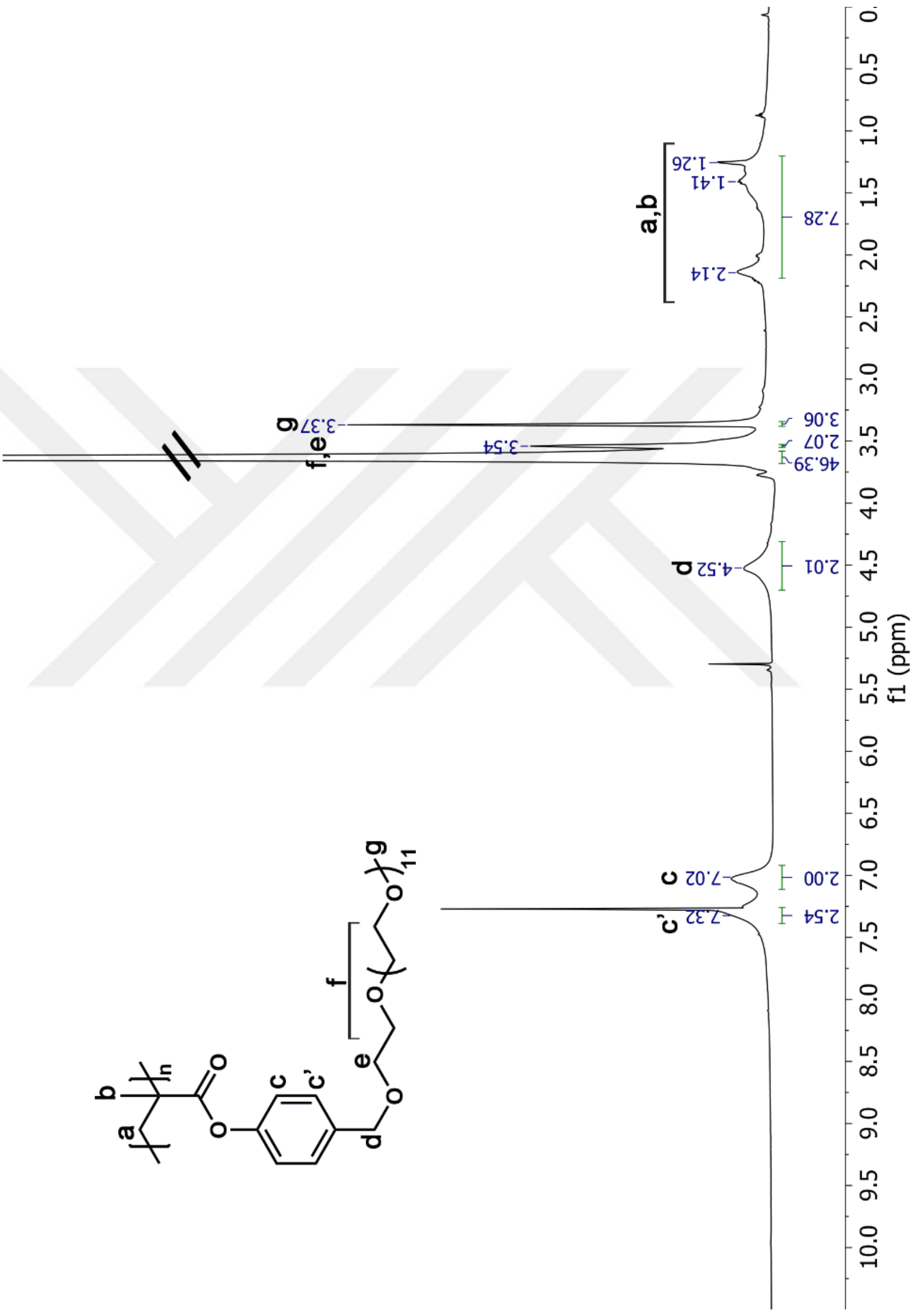

Figure 4.33: ^{1}H NMR spectrum of P11 in $CDCl_3$ (500 MHz).

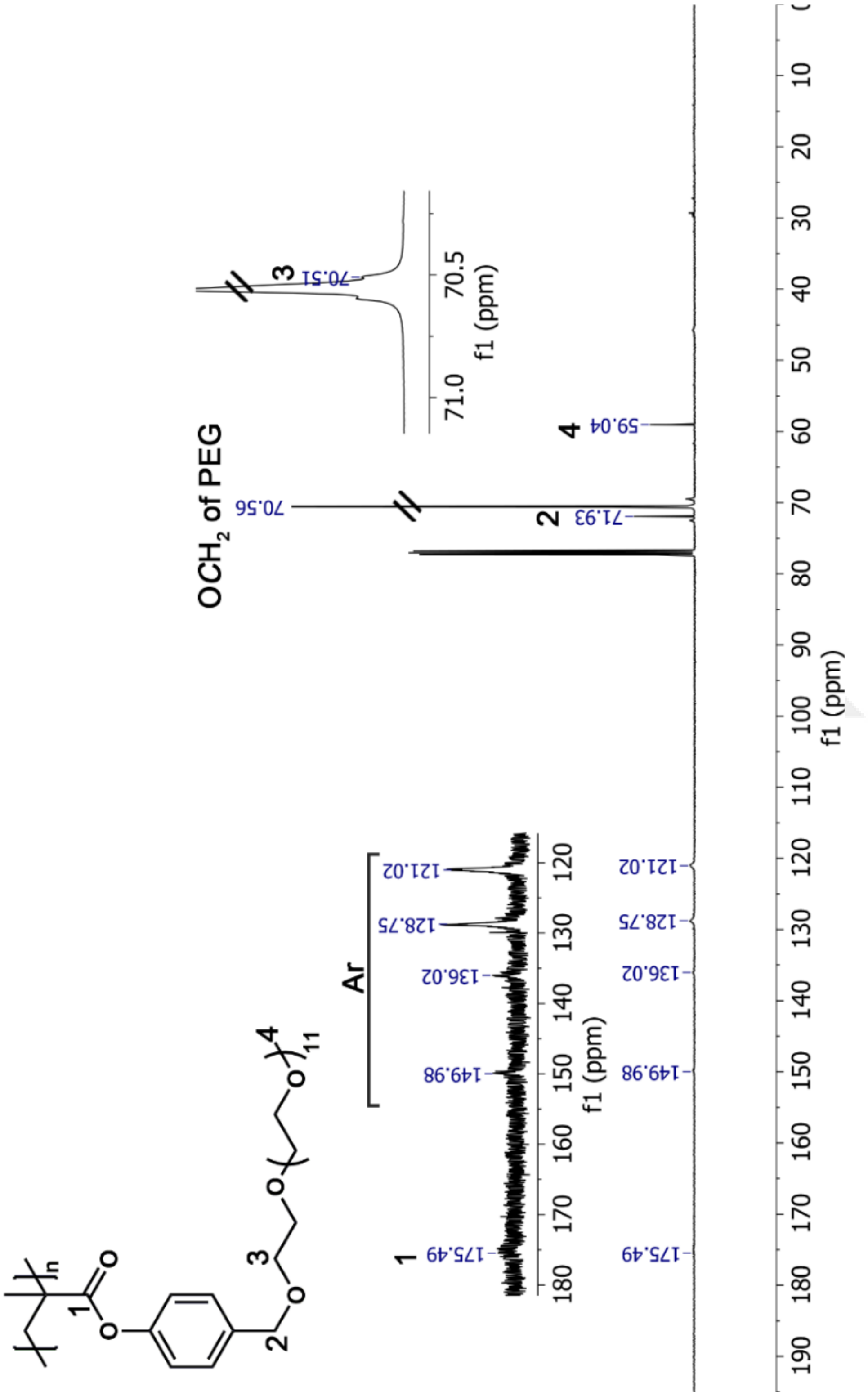

Figure 4.34: ^{13}C NMR spectrum of P11 in CDCl$_3$ (125 MHz).

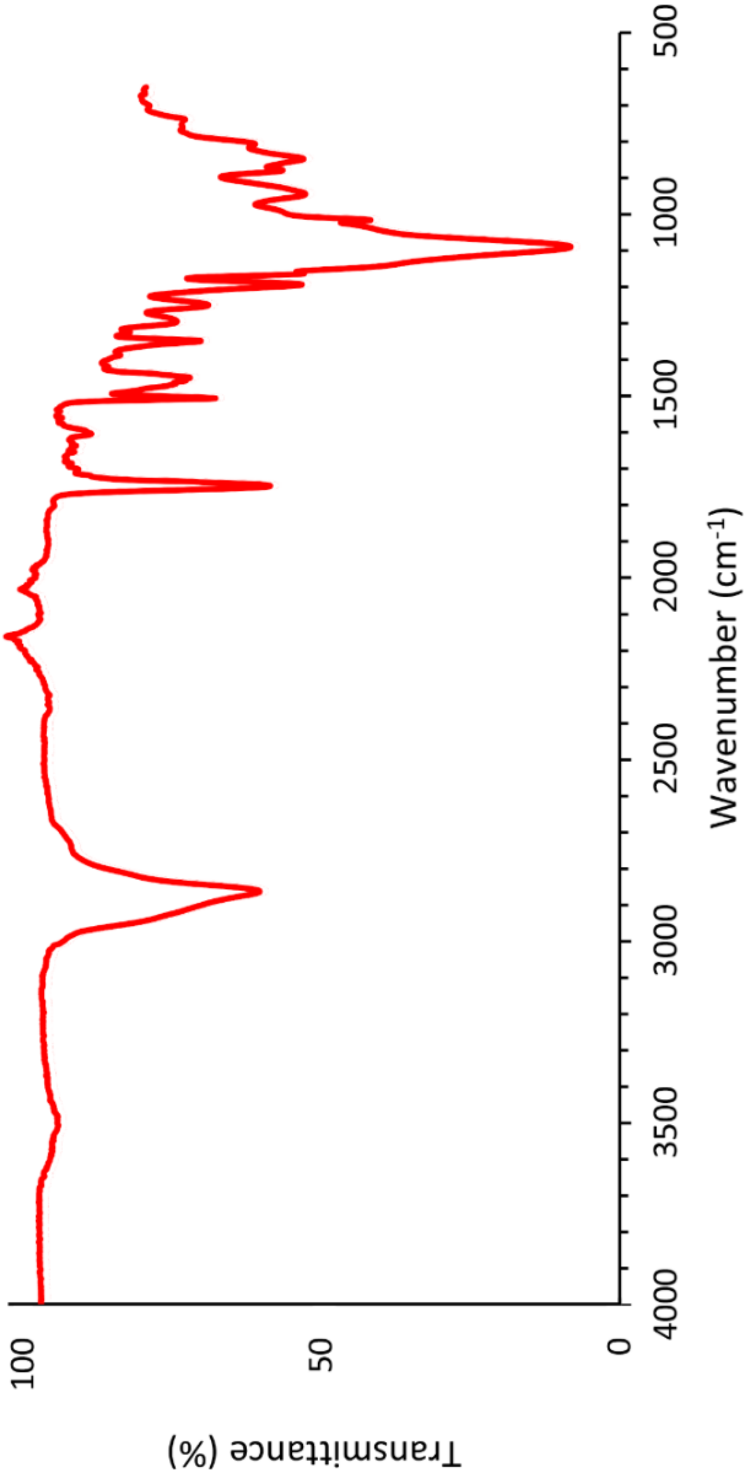

Figure 4.35: FT-IR spectrum of P11.

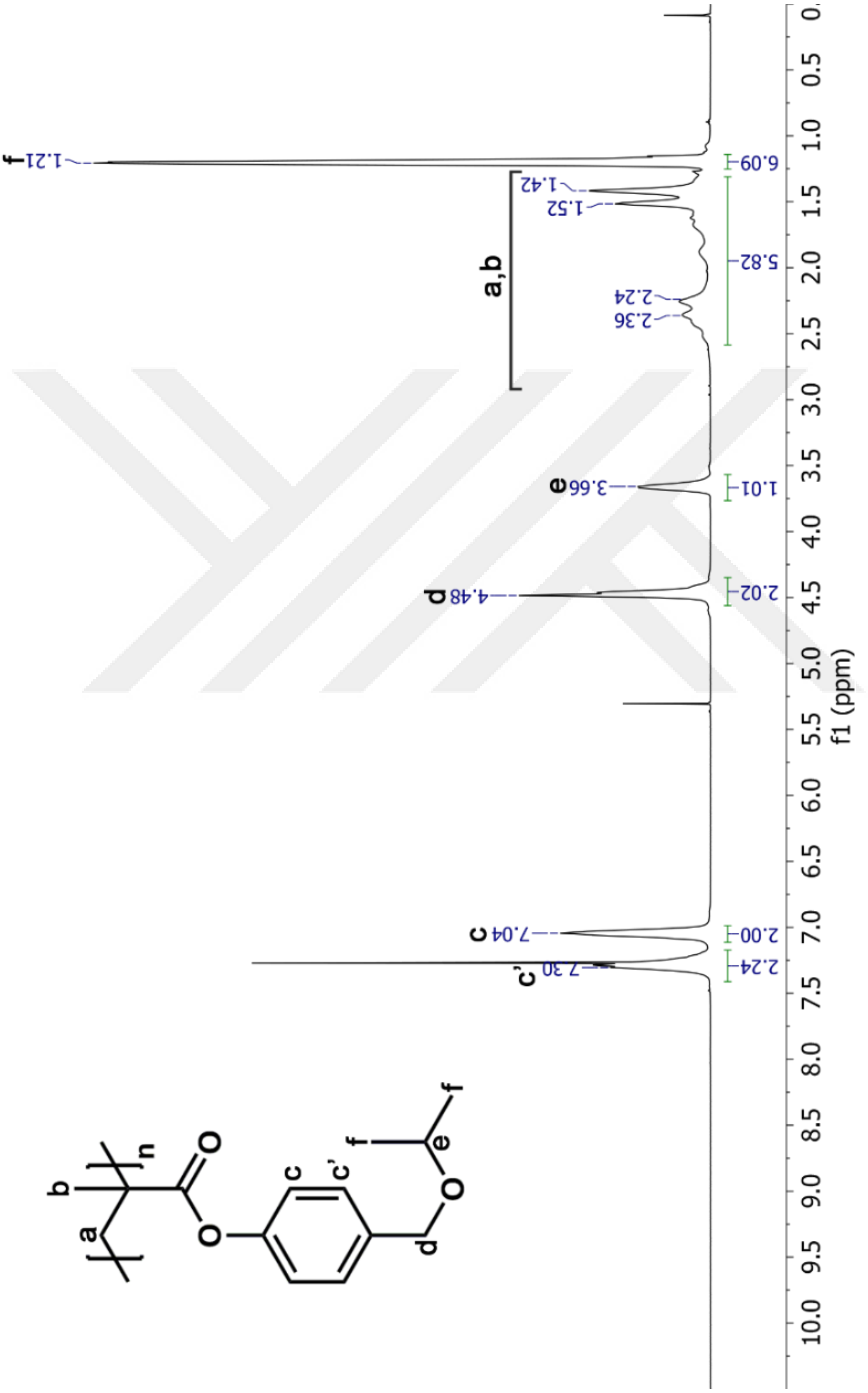

Figure 4.36: ^{1}H NMR spectrum of P12 in $CDCl_3$ (500 MHz).

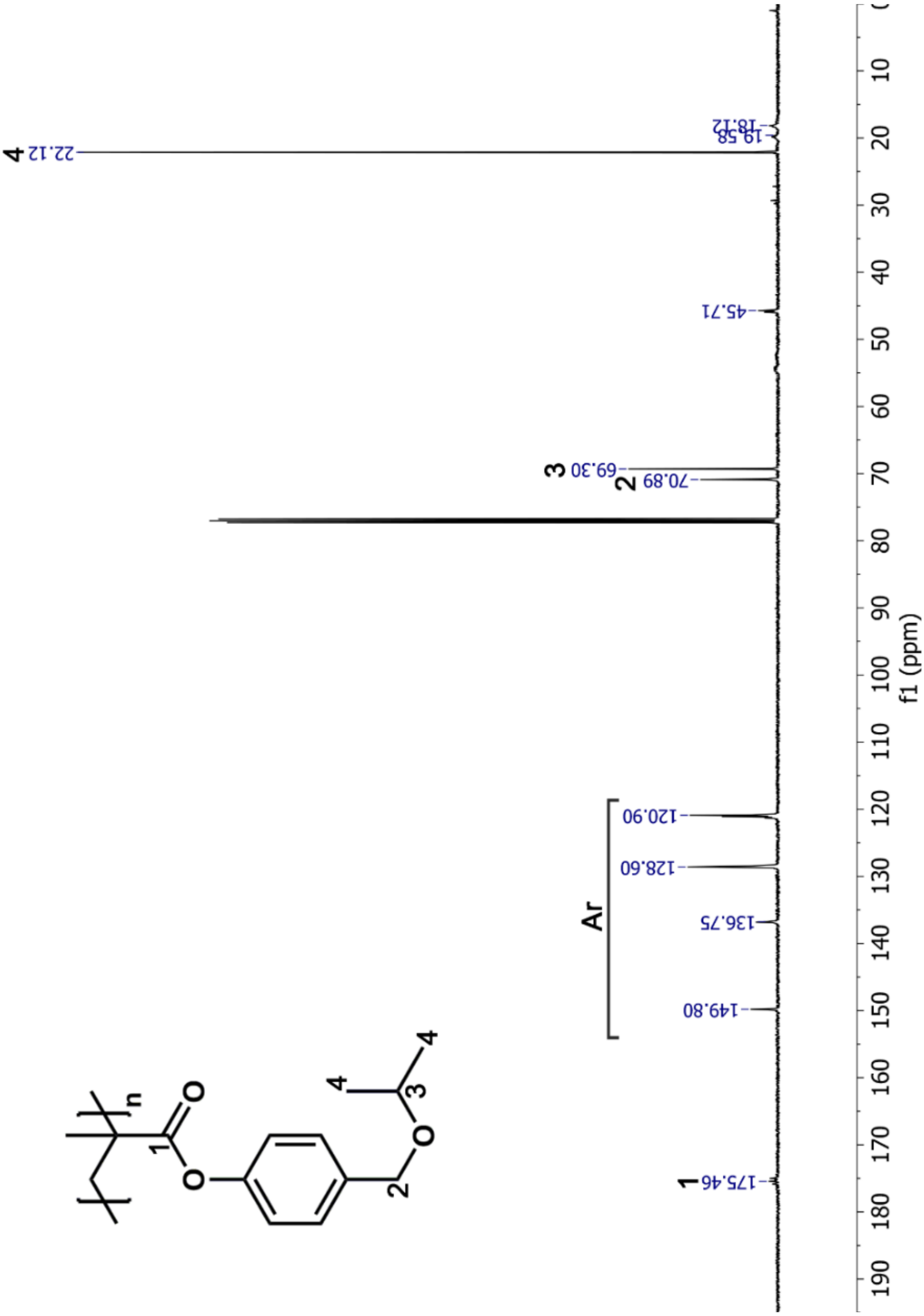

Figure 4.37: ^{13}C NMR spectrum of P12 in $CDCl_3$ (125 MHz).

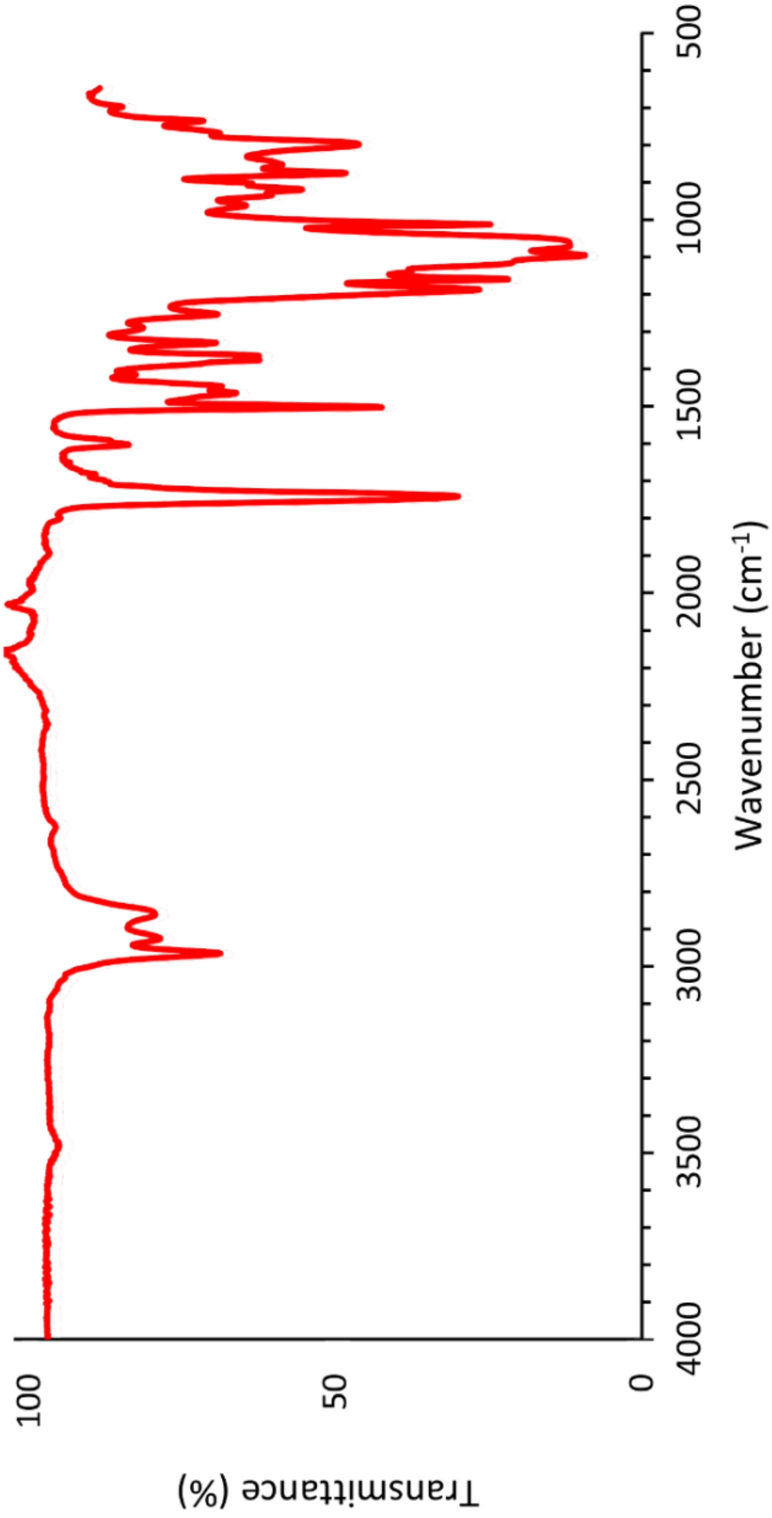

Figure 4.38: FT-IR spectrum of P12.

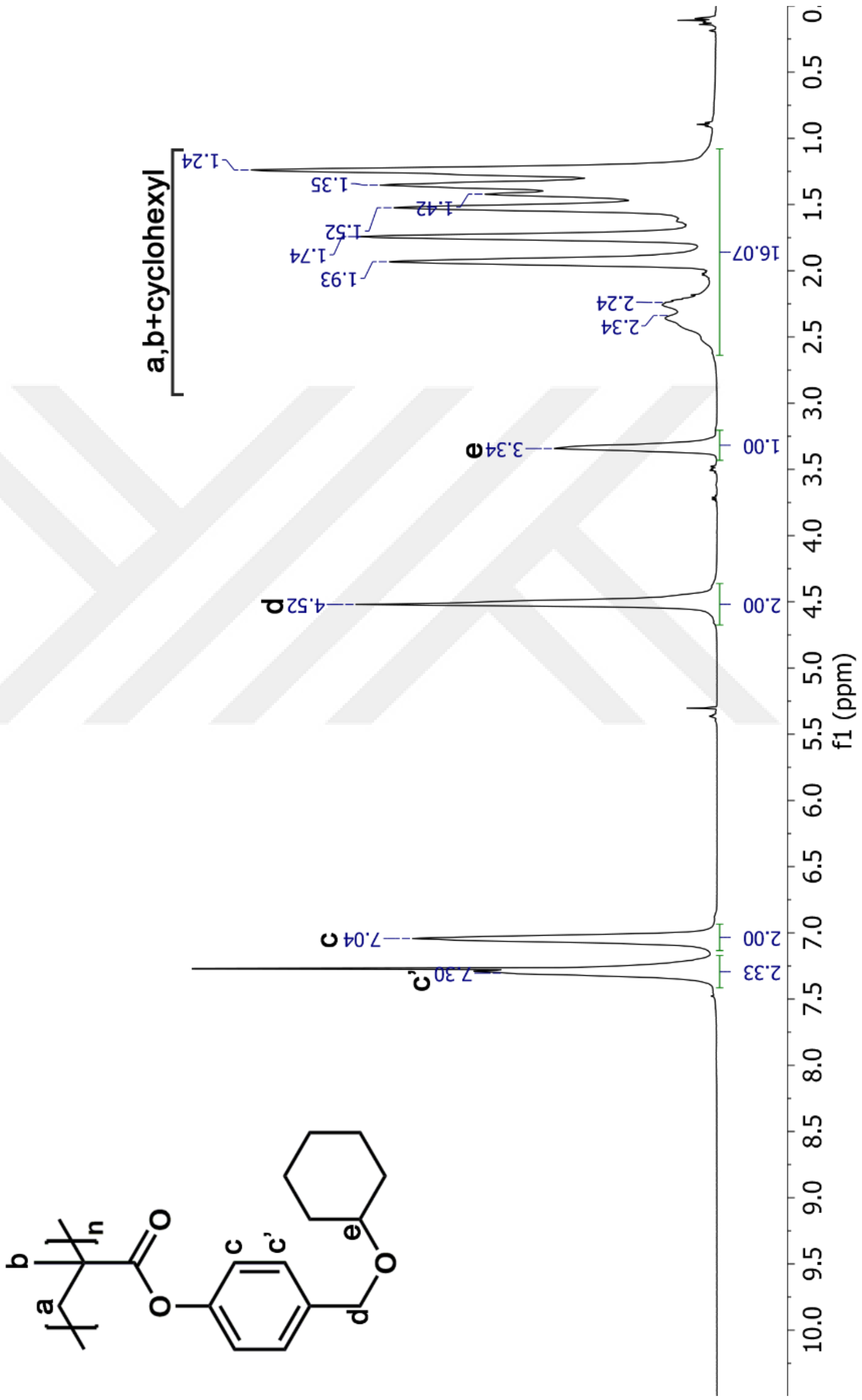

Figure 4.39: ^{1}H NMR spectrum of P13 in $CDCl_3$ (500 MHz).

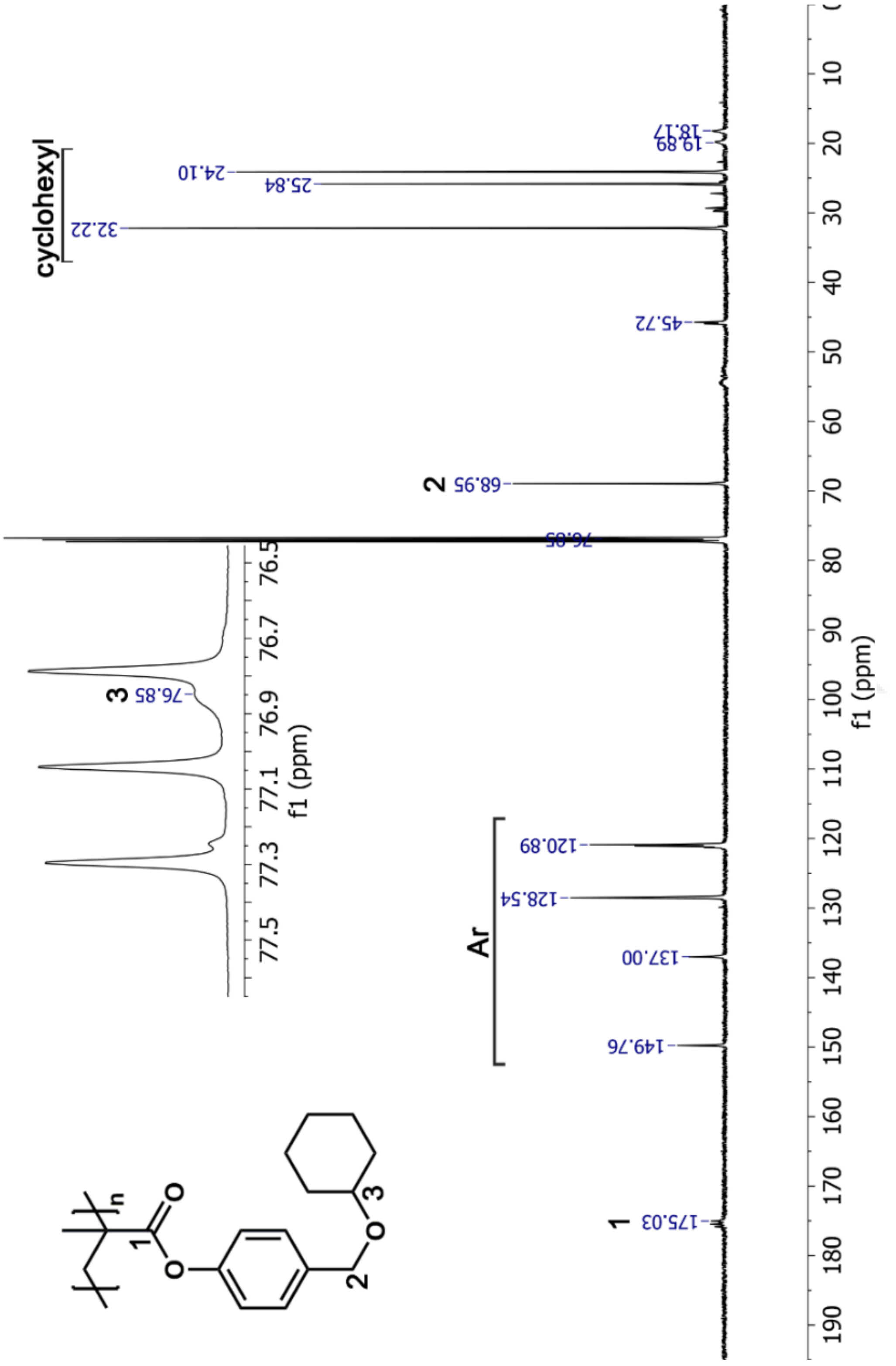

Figure 4.40: ^{13}C NMR spectrum of P13 in CDCl$_3$ (125 MHz).

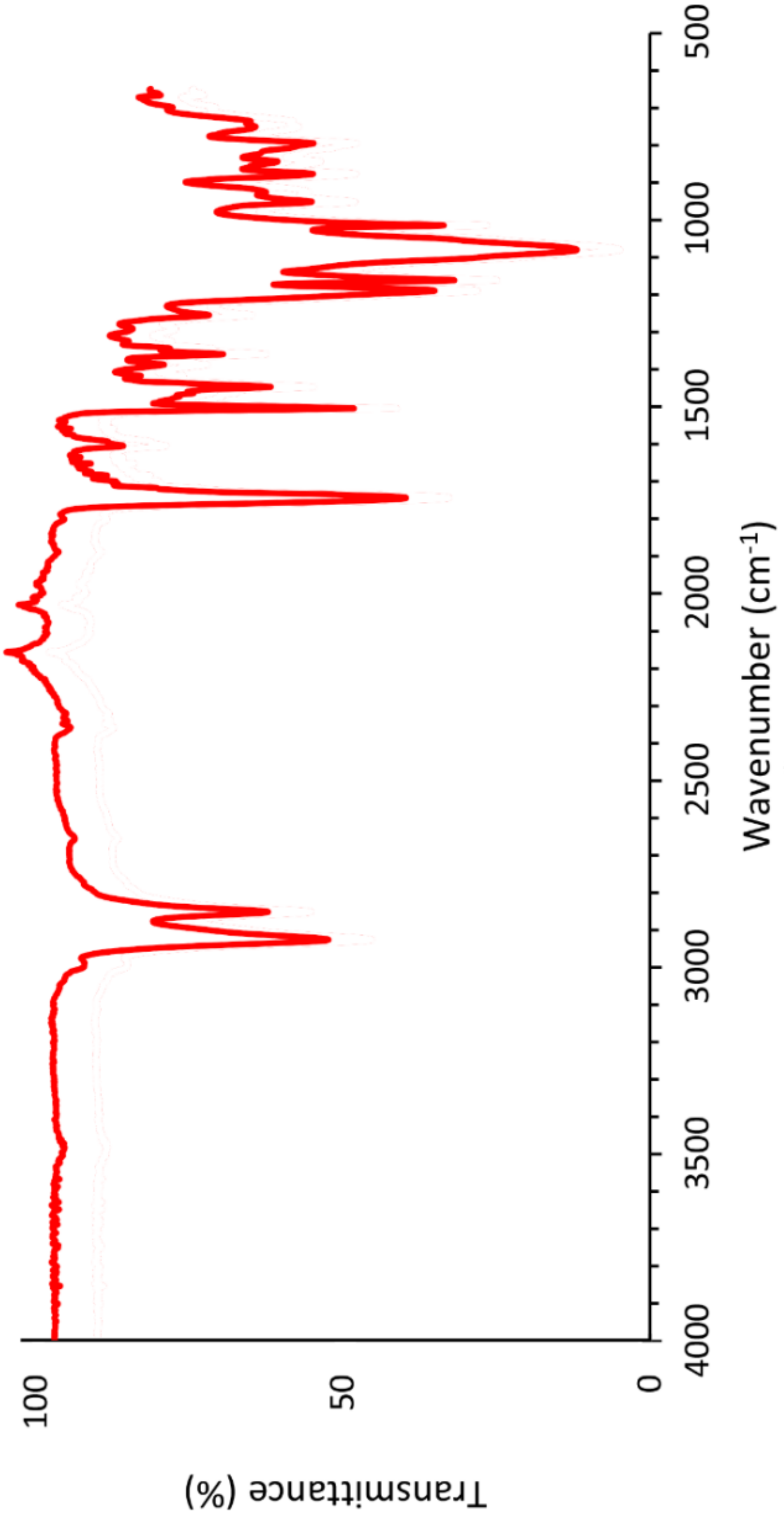

Figure 4.41: FT-IR spectrum of P13.

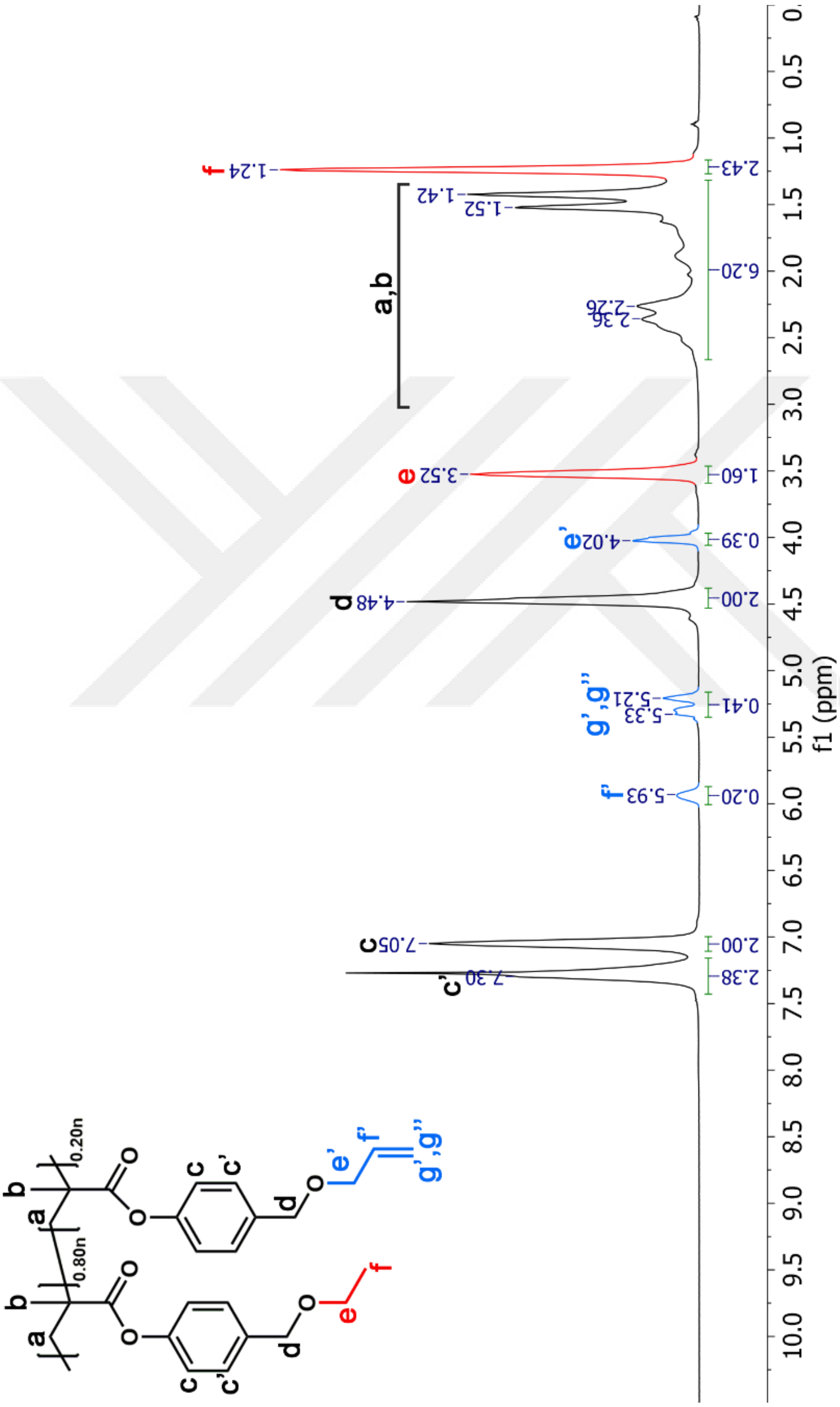

Figure 4.42: ^{1}H NMR spectrum of P14 in $CDCl_3$ (500 MHz).

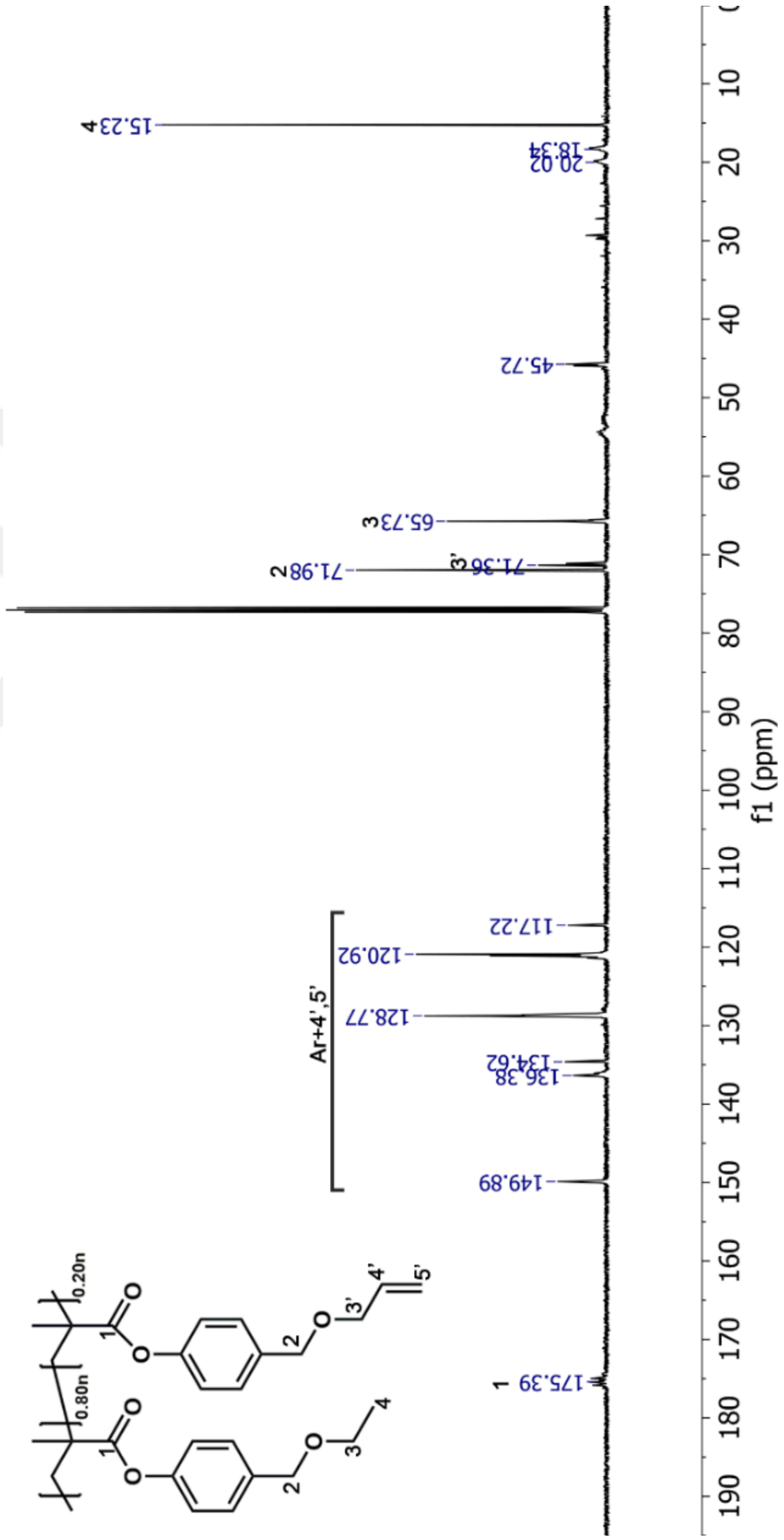

Figure 4.43: ^{13}C NMR spectrum of P14 in $CDCl_3$ (125 MHz).

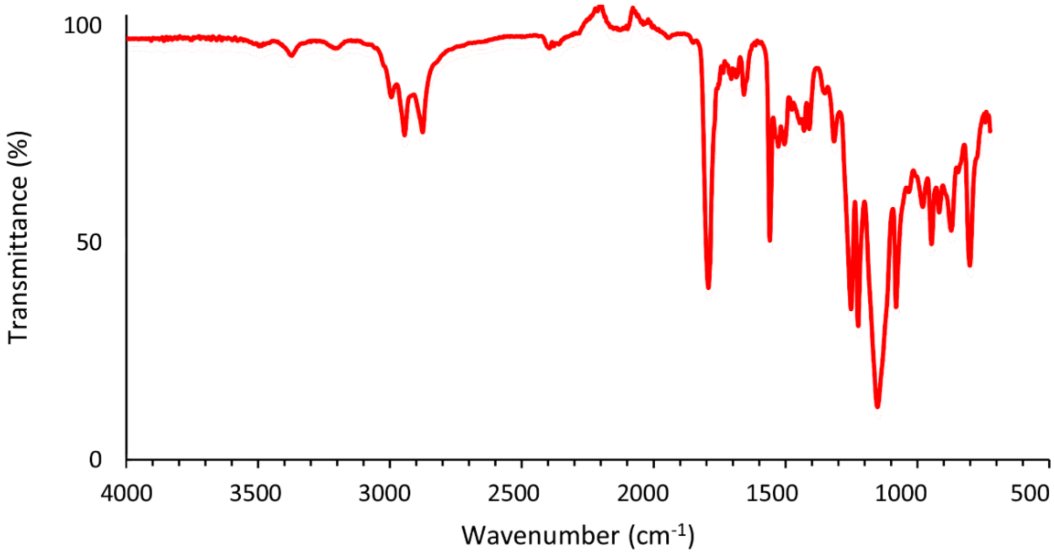

Figure 4.44: FT-IR spectrum of P14.66

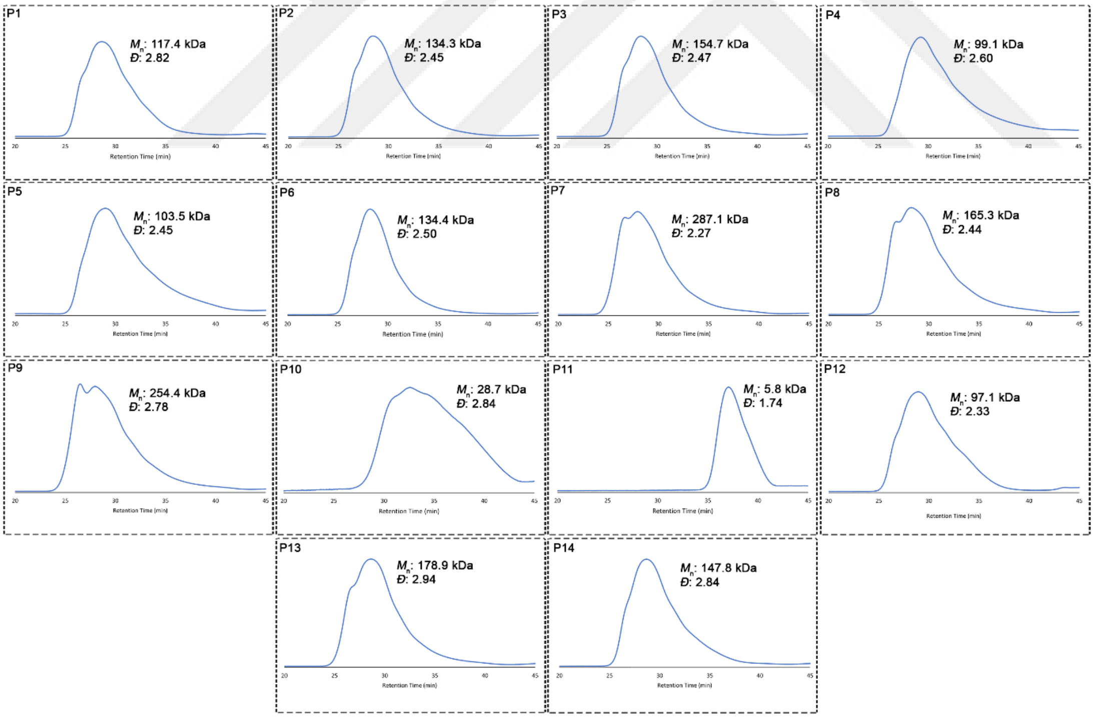

Figure 4.45: GPC chromatograms of P1 – P14.

5. CONCLUSION

In summary the CDMS-mediated RER has been successfully extended to the modification of aldehyde pendant polymers. It was found that the aldehyde-functionalized polymer has been proven to furnish the corresponding ether pendant polymers in quantitative or near quantitative RER efficiencies, regardless of the alcohols examined. The proposed strategy showed good functional group tolerance, allowing for the attachment of several useful functionalities, ranging from double and triple bonds to aromatics and halogens, to polymer chains. Both NMR and FT-IR analyses confirmed the highly efficient transformation of aldehyde units into ether units. It was also observed that almost all polymers shifted to a higher molecular weight region after modification compared to the parent polymer.

This study is believed to make a significant contribution to the development of a practical and easily applicable PPM method for the polymer community. It is also believed the versatility of aldehydes has been widened for polymer functionalization using readily accessible starting materials.

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- **Akar, E., Kandemir, D., Luleburgaz, S., Kumbaraci, V., & Durmaz, H.** (2022). Efficient Post-Polymerization modification of pendant aldehyde functional polymer via reductive etherification reaction. *European Polymer Journal*, 177, 111440. https://doi.org/10.1016/j.eurpolymj.2022.111440
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