

SYNTHESIS AND PHOTOPOLYMERIZATIONS
OF NEW METHACRYLATE CROSSLINKERS AND ANTIBACTERIAL
QUATERNARY AMMONIUM MONOMERS

by

Burcu Sunam Ayfer

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to my husband

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ABSTRACT

SYNTHESIS AND PHOTOPOLYMERIZATIONS OF NEW METHACRYLATE CROSSLINKERS AND ANTIBACTERIAL QUATERNARY AMMONIUM MONOMERS

In the first part of this work, new amine monomers were synthesized from the reaction of 3-(acryloyloxy)-2-hydroxypropylmethacrylate (AHM), acrylamide and methacrylamide with various amines [(3-Dimethylamino)propylamine, N,N,N'-trimethylethylenediamine, 3,3-iminobis (N,N-dimethylpropylamine), 3-(Aminomethyl pyridine)] and then reacted with various alkylhalides to give six new quaternary ammonium monomers (QACs). The photopolymerization of the monomers was investigated by photo-DSC at 30 °C. The reactivities of quaternary ammonium monomers were highly depended on monomer structures. The antibacterial activities of the synthesized amine and quaternary ammonium monomers, their homopolymers and copolymers with 2-hydroxyethylmethacrylate (HEMA) were investigated using *S. aureus* and *E. Coli*. It was found that as the alkyl chain length increased, the antibacterial activities of methacrylamide-pyridine QACs increased.

In the second part of this work, three new ester-linked diacid monomers and two ether-linked diacid monomers were synthesized from the reaction of succinyl chloride, adipoyl chloride and dodecanedioyl dichloride with tert-butyl α -hydroxymethyl acrylate (TBHMA) and Bisphenol A and triethyleneglycol with tert-butyl α -bromomethyl acrylate (TBBBr) followed by hydrolysis of t-butyl groups with CF₃COOH. The structure-reactivity relationship of the monomers was investigated using photo-DSC. The monomers were copolymerized with 2-hydroxyethylmethacrylate (HEMA) (99.5:0.5) at 40 °C and 60 °C. Rate of polymerizations and conversions were determined. TBHMA-Succinyl diacid monomer had highest reactivity and conversion at 40 °C. All monomers showed higher rates of polymerization at 60 °C than the those of 40 °C. Incorporation of 2 per cent crosslinker to HEMA increased the rate of polymerization.

ÖZET

YENİ METAKRİLİK ÇAPRAZ BAĞLAYICILAR VE ANTİBAKTERİYEL KUVARTER AMONYUM MONOMERLERİN SENTEZLENMESİ VE IŞIKLA POLİMERİZASYONU

Bu çalışmanın ilk bölümünde, yeni amin monomerleri 3-(akriloksi)-2-hidroksipropilmetakrilat (AHM), akrilamid ve metakrilamidin çeşitli aminlerle [(3-Dimetilamino) propilamin, N,N,N'-trimetiletilendiamin, 3,3-iminobis (N,N-dimetilpropilamin), 3-(Aminometil) piridin] reaksiyonundan sentezlenmiştir ve çeşitli alkilhalojenlerle reaksiyonundan 6 yeni kuvarter amonyum monomeri elde edilmiştir. Amin monomerlerinin 30 °C de foto-DSC kullanılarak polimerizasyonu incelenmiştir. Kuvarter amonyum monomerlerinin reaktiflikleri önemli ölçüde monomer yapısına bağlıdır. Sentezlenen amin ve kuvarter amonyum monomerlerinin, homopolymerlerinin ve 2-hidroksietilmetakrilat (HEMA) ile kopolimerlerinin antibakteriyel aktiviteleri *S. aureus* ve *E.coli* bakterileri kullanılarak incelenmiştir Alkil zincir uzunluğu arttıkça metakrilamid-piridin kuvarter amonyum bileşiklerinin antibakteriyel aktivitelerinin arttığı bulunmuştur.

Bu çalışmanın ikinci bölümünde, üç yeni ester-diasit ve iki eter-diasit monomeri süksinil, adipoil ve dodekandioil diklorürün t-bütül α -hidroksimetil akrilat (TBHMA) ve Bisfenol A, trietilenglikolün t-bütül α -bromometil akrilat (TBB_r) ile reaksiyonundan sentezlenmiştir. Monomerlerin t-bütül grupları CF₃COOH ile hidrolize olmuştur. Monomerlerin yapı-reaktiflik ilişkileri foto-DSC kullanılarak incelenmiştir. Monomerler HEMA ile 40 °C ve 60 °C de kopolimerleştirilmiştir. Polimerizasyon hızları ve dönüşümler hesaplanmıştır. TBHMA-Succinyl diasit 40 °C de en fazla reaktivite ve dönüşüme sahip olan monomerdir. 60 °C de bütün monomerler 40 °C dekine göre daha yüksek polimerizasyon hızı göstermişlerdir. HEMA' ya yüzde 2 çapraz bağlayıcı ilave ettiğimizde polimerizasyon hızı artmıştır.

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LIST OF ABBREVIATIONS

ACRY	Acrylamide
AHM	3-(acryloyloxy)-2-hydroxypropylmethacrylate
DMAPA	(3-Dimethylamino) propylamine
DSC	Differential Scanning Calorimetry
DPC	Differential Photocalorimeter
IDPA	3,3-iminobis(N,N-dimethylpropylamine)
IR	Infrared Spectroscopy
METH	Methacrylamide
NMR	Nuclear Magnetic Resonance Spectroscopy
Photo-DSC	Photo Differential Scanning Calorimetry
PYR	3-(Aminomethyl) pyridine
TMEDA	N,N,N'-trimethylethylenediamine
UV	Ultra Violet Spectroscopy

1. INTRODUCTION

1.1. Introduction to Antibacterial Monomers and Polymers

An antibacterial is an agent that interferes with the growth and reproduction of bacteria. Antibacterials are now most commonly described as agents used to disinfect surfaces and eliminate potentially harmful bacteria [1].

Antibacterials may be divided into two groups according to their speed of action and residue production: The first group contains those that act rapidly to destroy bacteria, but quickly disappear (by evaporation or breakdown) and leave no active residue behind. Examples of this type are the alcohols, chlorine, peroxides and aldehydes (Figure 1.1) [1].

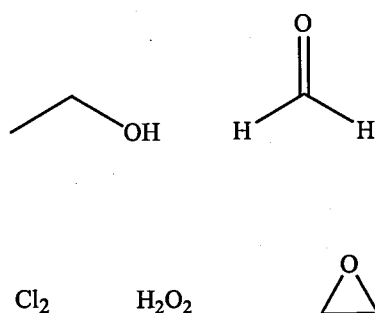


Figure 1.1. The examples of volatile antibacterial agents

The second group consists mostly of newer compounds that leave long-acting residues on the surface to be disinfected and thus have a prolonged action. Common examples of this group are anilides, biguanides, bisphenols, halophenols, heavy metals and quaternary ammonium compounds (Figure 1.2) [1].

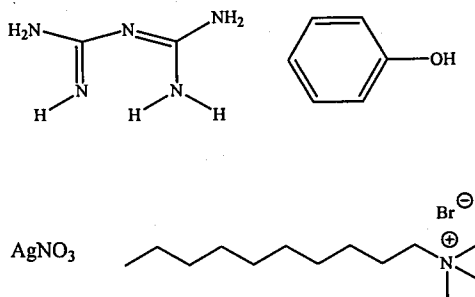


Figure 1.2. The examples of non-volatile antibacterial agents

1.1.1. Quaternary Ammonium Compounds

Quaternary ammonium compounds (QACs) are widely used as effective antibacterial agents. Their common features are the possession of positive charge and hydrophobicity [2]. QACs have the general formula of $\text{R}_4\text{N}^+\text{X}^-$ (Figure 1.3). In a quaternary structure nitrogen atom is covalently bonded to four groups and the positive charge is balanced by a negative counterion. The number of nitrogen atoms can vary in the molecule depending on the starting materials used in the synthesis. Both mono and bis-quaternary ammonium compounds are currently in use. Any anion may be attached to the cation to form a salt, although the chloride and bromide salts are most commonly used [3, 4].

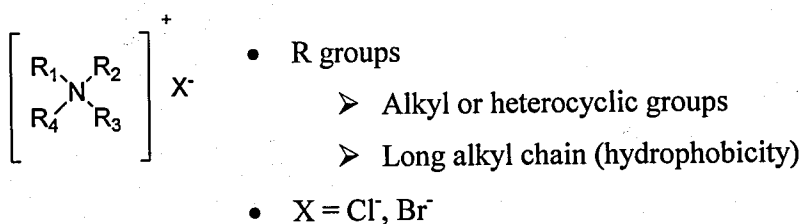


Figure 1.3. General structures of quaternary ammonium compounds (QACs)

QACs antibacterial activity is resulted from their amphiphilic structure and surfactant property which was first reported by Dogmak [5]. Classification and biological activity of QACs depend upon the nature of the organic groups attached to nitrogen, the number of nitrogen present, and the counterion [6]. The organic substituents are either

alkyl, aryl, or heterocyclic [7]. At least one of the organic substituents should be a long alkyl chain in order to provide a hydrophobic segment compatible with the bilayer of the outer cell wall [8, 9, 10]. It has been shown that an increase of the alkyl chain length of an amphiphilic compound, i.e. to 14 carbon alkyl chains, is followed by an increase in the hydrophobic interaction with the lipid bilayer of the cell wall, which in turn increases the antibacterial activity of the compound [3, 10]. QACs containing one long alkyl chain substituent of at least eight carbon atoms have been shown to be very active biocides in water (Figure 1.4) [11].

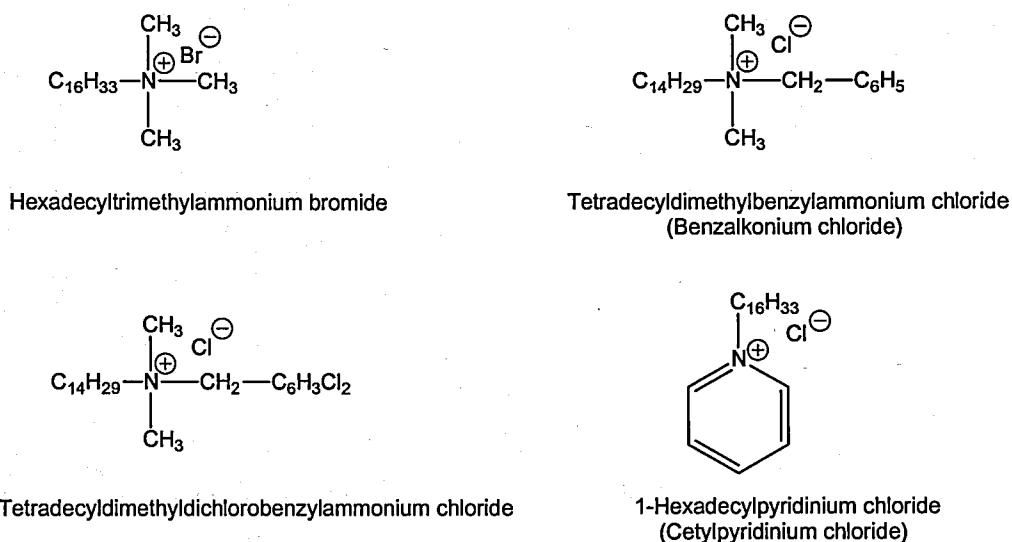


Figure 1.4. The examples of quaternary ammonium antimicrobial compounds

The sequence of elementary events in the mode of action of the cationic disinfectants can be summarized as follows [2]:

- adsorption onto the bacterial cell surface
- diffusion through the cell wall
- binding to the cytoplasmic membrane
- disruption of the cytoplasmic membrane
- release cytoplasmic constituents such as K^+ ions, DNA, and RNA
- precipitation of cell contents and death of the cell

The electrostatic interaction between the positive charge of an antibacterial and the negative charge of bacterial cells, as well as the hydrophobic interaction between the antibacterial and the cell surfaces, appears to be important [12]. As quaternary ammonium functionalized surfaces have a high positive surface charge, they exert a strong adhesive force on negatively charged bacteria, which has been proposed to physically inhibit surface growth of rod-shaped bacteria [13].

QACs are usually white, crystalline powders that are very soluble or dispersible in water. As the chain lengths of the substituents increase, the solubility of QACs in polar solvents decreases, whereas their solubility in non-polar solvents increases [14]. QACs have a broad spectrum of antimicrobial activity and often display extended biological activity because they may leave long-lived residues on treated surfaces [4].

QACs have some advantages over other antibacterial agents [4] such as;

- excellent penetration properties
- extended residence time of biological activity
- low toxicity
- least corrosive of disinfectants
- more stable
- bacteriostatic or bactericidal activity
- non-irritating to the skin

Quaternary structures are effective on both gram positive and gram negative bacteria at medium concentrations [10], but they have a stronger antibacterial effect on gram positive ones, since gram negatives have an extra protective membrane [5].

1.1.2. Types of Bacteria

There are two types of bacteria. These are Gram-positive and Gram-negative bacteria. The terms positive and negative have nothing to do with electrical charge, but simply designate two distinct morphological groups of bacteria. Bacteria can be classified according to the accessibility of their cell wall to the dye crystal violet [15].

The gram stain is the most widely used staining procedure in bacteriology. Gram-positive and gram-negative bacteria stain differently because of fundamental differences in the structure of their cell walls (Figure 1.5, 1.6) [15]. The bacterial cell wall serves to give the organism its size and shape as well as to prevent osmotic lysis. The material in the bacterial cell wall which confers rigidity is peptidoglycan [16].

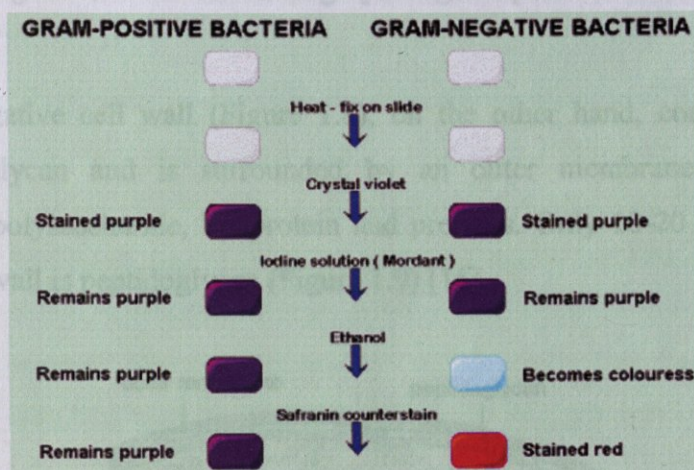


Figure 1.5. Schematic representation of the gram staining procedure

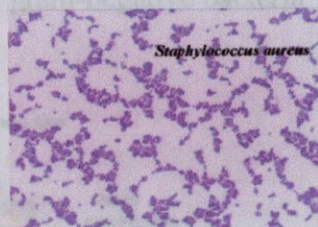
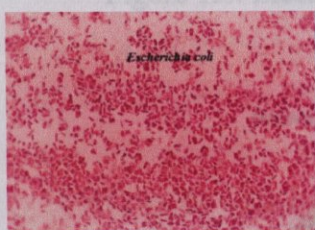
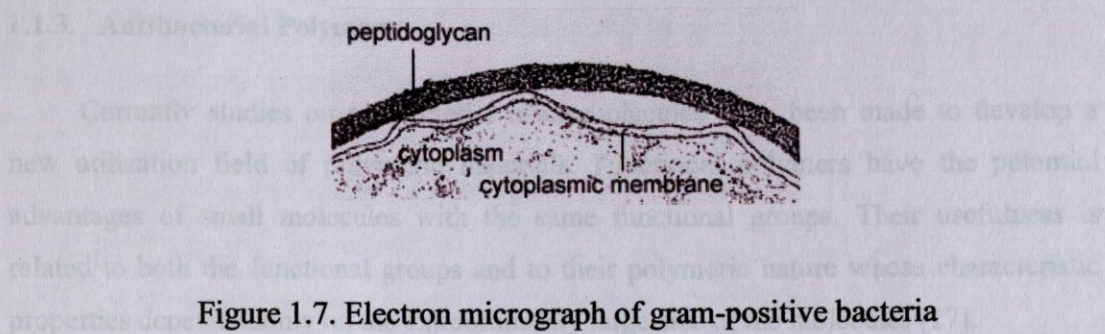
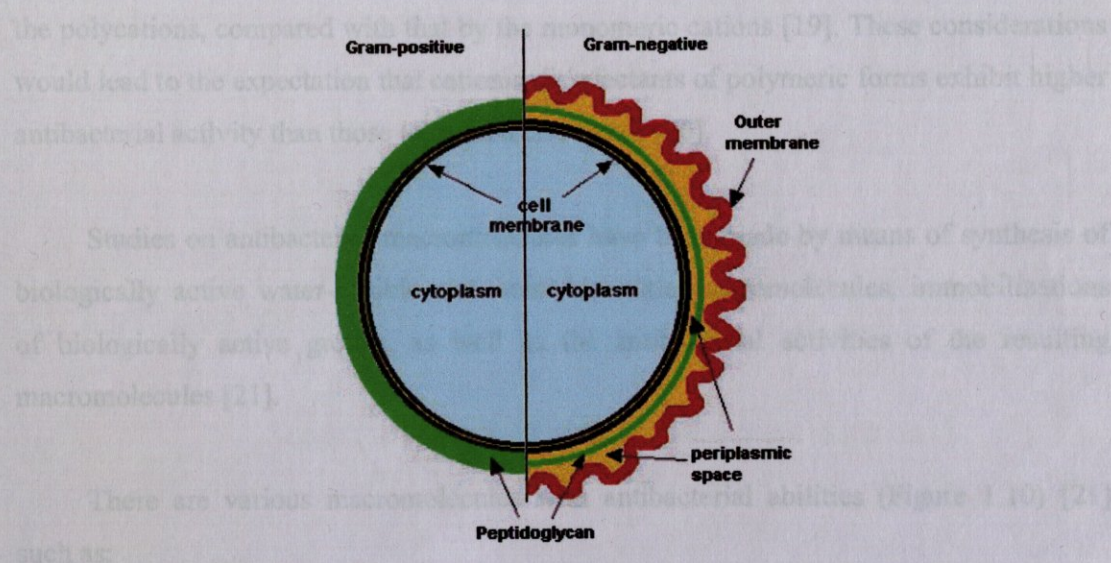
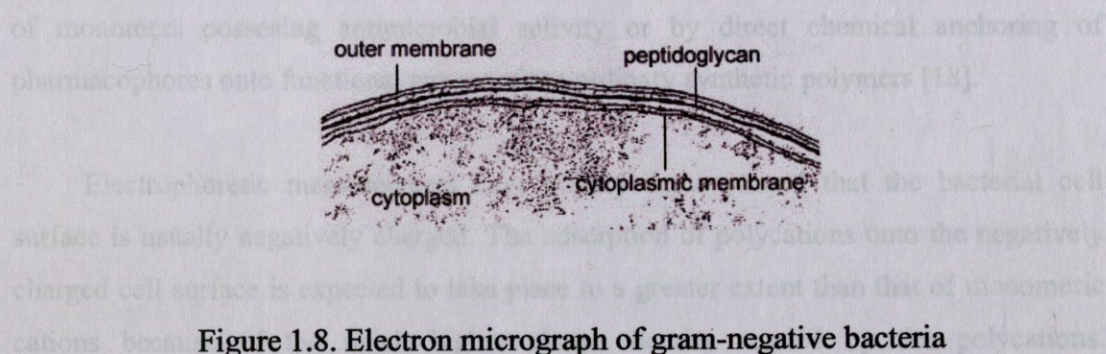


Figure 1.6. The view of gram-negative (*Escherichia coli*) and gram-positive (*Staphylococcus aureus*) bacteria

In electron micrographs, the gram-positive cell wall appears as a thick, dense wall 20-80 nm thick and consisting of numerous interconnecting layers of peptidoglycan. Chemically, 60 to 90 per cent of the gram-positive cell wall is peptidoglycan (Figure 1.7) [16].



The gram-negative cell wall (Figure 1.8), on the other hand, contains only 2-3 layers of peptidoglycan and is surrounded by an outer membrane composed of phospholipids, lipopolysaccharide, lipoprotein and proteins. Only 10-20 per cent of the gram-negative cell wall is peptidoglycan (Figure 1.9) [16].



1.1.3. Antibacterial Polymers

Currently studies on antibacterial macromolecules have been made to develop a new utilization field of polymeric materials. Functional polymers have the potential advantages of small molecules with the same functional groups. Their usefulness is related to both the functional groups and to their polymeric nature whose characteristic properties depend mainly on the extraordinarily large size of the molecules [17].

Polymers with antimicrobial activity have usually been prepared by compounding antimicrobial agents into ordinary synthetic polymers. However, many of the antimicrobial agents steadily permeate out from the polymer matrices, damaging human cells. Covalent bonding of antimicrobial pharmacophores to polymer matrices would reduce or eliminate the permeation problems, which can be done either by polymerization of monomers possessing antimicrobial activity or by direct chemical anchoring of pharmacophores onto functional groups of the ordinary synthetic polymers [18].

Electrophoretic measurements have clearly demonstrated that the bacterial cell surface is usually negatively charged. The adsorption of polycations onto the negatively charged cell surface is expected to take place to a greater extent than that of monomeric cations because of the much higher charge density carried by the polycations. Furthermore, binding to the cytoplasmic membrane is also expected to be facilitated by the polycations, compared with that by the monomeric cations [19]. These considerations would lead to the expectation that cationic disinfectants of polymeric forms exhibit higher antibacterial activity than those of monomeric forms [20].

Studies on antibacterial macromolecules have been made by means of synthesis of biologically active water-soluble and water-insoluble macromolecules, immobilizations of biologically active groups, as well as the antibacterial activities of the resulting macromolecules [21].

There are various macromolecules with antibacterial abilities (Figure 1.10) [21] such as;

- Water soluble polymers with quaternary ammonium salts
- Polymers with biguanide groups
- Water-soluble polymers with quaternary pyridinium salts
- Polymers with phosphonium groups
- Polymers with sulfonium salts
- Water-insoluble polyurethane with quaternary ammonium salts
- Epoxy resins containing QACs

Polymeric antimicrobial agents also have the advantage that they are nonvolatile, chemically stable, and do not permeate through the skin [3].

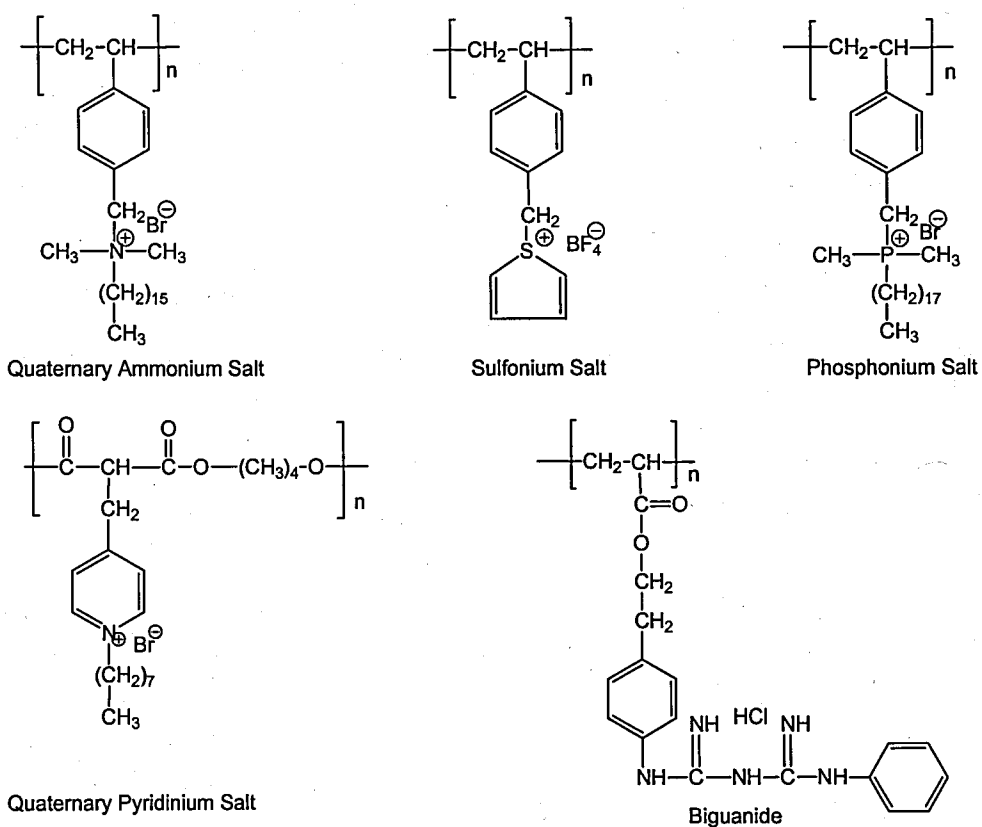


Figure 1.10. Some examples of antibacterial polymers

1.1.4. Polymers with Quaternary Ammonium Groups

Continuous effort has been made during the last two decades to synthesize polymers with quaternary ammonium substituents. The literature suggests that the polymers containing quaternary ammonium groups either in the backbone or as pendant groups show enhanced efficacy over corresponding small molecule QACs plus reduced residual toxicity, increased efficiency and selectivity, and prolonged lifetime [6, 7].

The biocidal groups must act by contact with the cell membrane of the microorganisms. Quaternary ammonium compounds (QACs) containing at least a long alkyl chain (at least eight carbon atoms) are good candidates for this function, because they are known to be effective against a large spectrum of microorganisms such as bacteria, algae, fungi, etc [22].

Polymeric QACs do not release low-molecular weight biocides. They have been described as surface active, that means not migrating, antimicrobials. It is assumed that no release of biocidal substances into the environment occurs. There are however indications that at least poly quats having chain length of eight to ten carbon atoms do release biocidal components yielding a zone of inhibition in agar plate tests [23].

The polymers (Figure 1.11) are in general more active against Gram-positive bacteria than against Gram-negative bacteria [3]. This fact is due to the difference in the cell walls between Gram-negative and Gram-positive bacteria. The former have more complicated cell walls compared with the later ones.

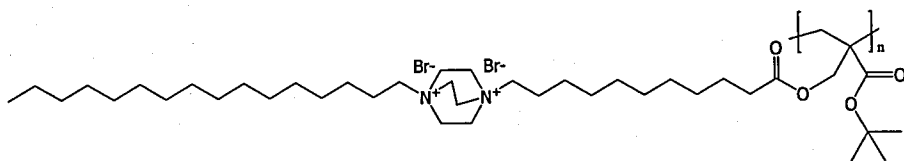


Figure 1.11. Antibacterial polymers containing quaternary ammonium moieties based on 1,4-diazobicyclo[2.2.2.]octane (DABCO)

1.1.5. Antibacterial Activities of Polymers

The microbiological activity of antimicrobial polymers is based on their special constitution and the three dimensional structure of the polymers. The antibacterial efficacy is attributed only to the final polymer itself, not to leaching low molecular additives or the initial monomers [23].

There are various parameters that influence the activities of antimicrobial polymers in solution such as [24];

- Charge density
- Molecular weight
- Concentration
- Alkyl chain length
- Counter ion
- Bacteria type

It has been reported that the target site of cationic disinfectants is the cytoplasmic membranes of microbes [25]. The main constituents of the cytoplasmic membrane are membrane proteins and phospholipids [26]. Poly cations cause aggregation and phase separation in the phospholipids [24].

Active cationic biocides possess a feature as surfactants since they have hydrophilic and hydrophobic moieties in a single molecule. Hydrophobic group effects the micelle size and solubilization efficiency. The solubilization ability was improved with increasing side-chain length and degree of polymerization [24].

However, cationic biocides must overcome the bacterial cell wall to reach to cytoplasmic membrane. Biocides of a small size are expected to diffuse freely through the cell wall but not molecules with large molecular size [24]. Such molecular weight dependence on antibacterial activity has been investigated for the polycationic biocides against intact cells and protoplasts that are freed from the cell wall [27]. The bell-shaped dependence of the antibacterial activity on the molecular weight was observed for the

intact cells, whereas the antibacterial activity against protoplasts monotonously increased with increasing molecular weight [24]. These results clearly indicate that the exclusion at the cell walls operates for polymers possessing high molecular weight (large molecular size). Polycationic biocide possessing an optimal size of assembly is expected to show the maximum antibacterial activity [24].

1.1.6. Application Areas of Antibacterial Polymers

Antimicrobial polymers have been used as in many areas such as food processing [28], filters [29], biomedical devices [30], coatings, disinfectants and preservatives in pharmaceuticals [31].

Antimicrobial polymers have been used as a coating material for common objects such as doorknobs, children's toys, computer keyboards and telephones to prevent transmission of microbial infections. These polymers can be used as additives for antifouling paints on hospital room walls [32].

In the field of biomedical polymers, infections associated with biomaterials represent a significant challenge to the more widespread application of medical implants [33]. Infection is the most common cause of biomaterial implant failure in modern medicine [34]. Antibacterial polymers play an important role; catheters made from a polymer that slowly releases an antibiotic could prevent thousands of hospital patients from dying from infections every year. Antimicrobial polymers could also thwart infections around more permanent implants, such as pacemakers [35].

In the field of textiles, work has been performed with the aim of developing new textile products with antimicrobial finishes for medical applications [36]. Other likely uses of these polymers are as cleaning solutions for contact lenses [37] as well as coatings and chemically bound components of biomaterials [38].

1.2. Introduction to Photopolymerization

Photopolymerization of monomers or oligomers has become a well-accepted process which has found a large variety of industrial applications because of unique advantages [39].

The main advantages of photopolymerizations, in comparison with thermally cured systems, are the very fast curing speed, solvent free formulations, the ability to deal with heat sensitive substrates and the energy savings [40]. UV and/or visible light radiation are used to induce polymerization or crosslinking of a monomer, oligomer or prepolymer in the presence of an initiator. The initiator is used to absorb the light energy, which transforms it into active species, such as radicals or ions, capable of inducing reactions.

Photopolymerization is considered to be the most effective way to rapidly transform a multifunctional monomer or polymer with polymerizable functions into a dense three-dimensional polymer network at ambient temperature (Figure 1.12). These crosslinked networks have some advantages such as; high thermal stability, high mechanical strength and resistance to solvent absorption.

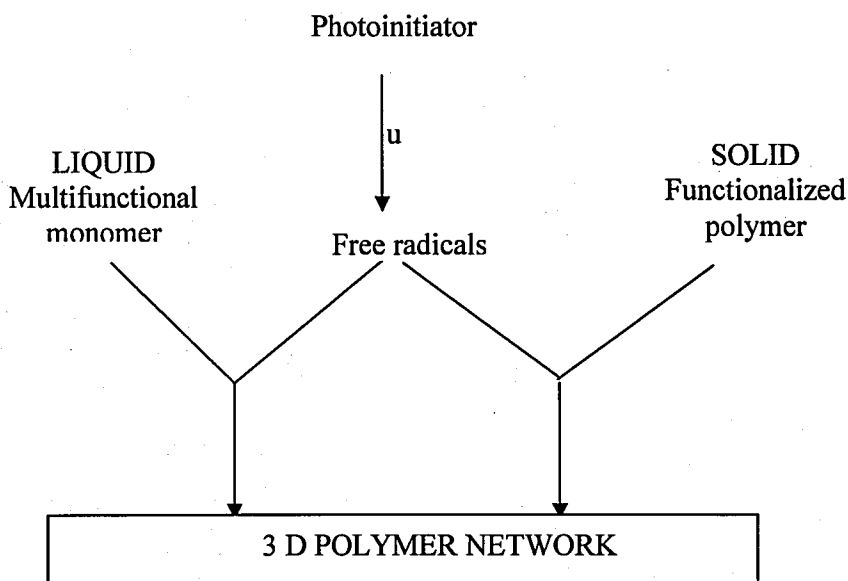


Figure 1.12. Photoinitiated crosslinking polymerization

There are two main classes of photopolymerization reactions, depending whether the reaction proceeds by a radical-type or cationic-type mechanism.

1.2.1. Photoinitiated Cationic Polymerization

Cationic polymerizations are usually initiated by electrophilic compounds such as Bronsted or Lewis acids, onium salts and organometallic complexes. Onium salts contain diaryliodonium or triarylsulfonium cations (Ar_2I^+ , Ar_3S^+) and fluorinated anions such as BF_4^- , PF_6^- , AsF_6^- or SbF_6^- . Protonic acids are readily generated by photolysis of onium salts in the presence of a hydrogen donor molecule (Figure 1.13) [41].

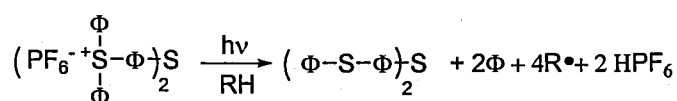


Figure 1.13. An example of photoinitiated cationic polymerization

The two distinct features of photoinitiated cationic polymerization are its lack of sensitivity toward atmospheric oxygen and its living character, due to the fact that the propagating polymer cations are not reacting among themselves. By contrast to radical initiated polymerization, the chain reaction will continue to proceed effectively after UV exposure [42].

Photoinitiated cationic polymerization is being increasingly used to cure multifunctional monomers that are inactive towards radical species, in particular epoxides and vinyl ethers.

1.2.2. Photoinitiated Radical Polymerization

Radical polymerizations are initiated by free radicals that are produced upon UV irradiation of aromatic carbonyl compounds, either by homolytic cleavage of C-C bonds, or by hydrogen abstraction from a H-donor molecule [43].

The most efficient photoinitiators of the first type are the benzoin derivatives, the benzyl ketals, the acetophenone derivatives, and the hydroxyalkylphenones [44].



Figure 1.14. The structures of acetophenone derivatives and hydroxyalkylphenone

The benzoyl radical has been shown to be the major initiating species. The other radical fragments may, in some cases, also contribute to the initiation but to a lesser extent (figure 1.15) [45].

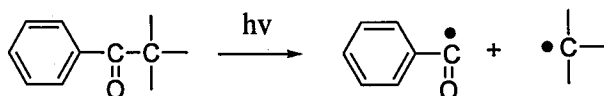


Figure 1.15. Decomposition of one initiator to give a benzoyl radical

Other initiators of the photocleavage type have been developed recently and appear to be very efficient in promoting UV curing, in particular the acylphosphine oxides and the substituted aminoketones.

Aromatic ketones like benzophenone or thioxanthone (Figure 1.16), when promoted to their excited states by UV irradiation, do not undergo a fragmentation but rather abstract a hydrogen atom from a H-donor molecule to generate a ketyl radical and a donor radical (Figure 1.17) [44]:

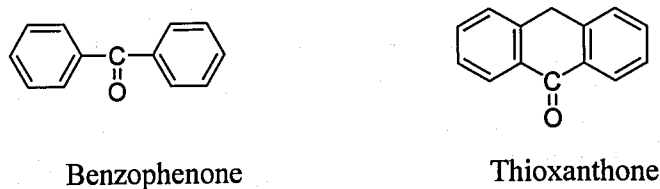


Figure 1.16. Structures of benzophenone and thioxanthane

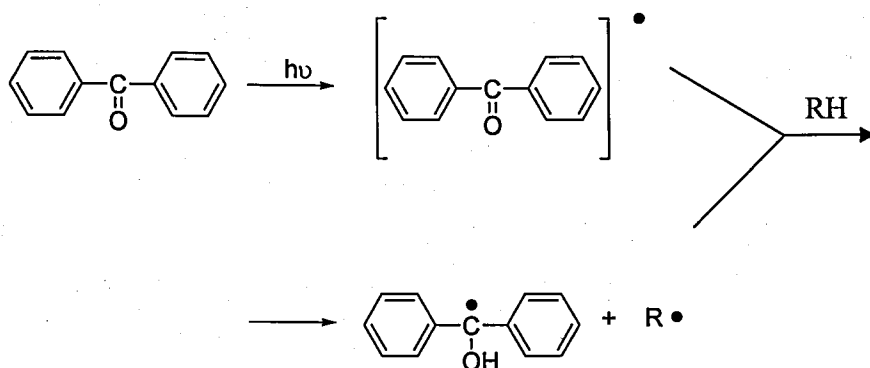


Figure 1.17. Mechanism of radical generation by hydrogen abstraction

An efficient photoinitiator must exhibit a large absorption in the emission range of the light source and generate initiating species with the highest possible quantum yields [43]. A great number of photoinitiators have been developed for UV-curing applications. Their photolysis mechanisms and performances have been extensively studied [45].

There are three main classes of UV-curable resins that polymerize by a radical mechanism [43] : unsaturated polyester/styrene, thiol-polyene, acrylate monomers.

1.2.3. Light Sources

The light source is a critical factor in the UV curing process. In general, two major kinds are used [46]:

- arc light
- laser light

The basic arc light has clear fused quartz tubing in which a gas is enclosed. When a direct current is applied through two electrodes to generate an arc, the gas is discharged and light is emitted. The output of the lamp depends on the pressure and the type of gas used. The most common gases are mercury and xenon. A small amount of another gas pressure can be either low (10⁻³ torr), medium (1-2 atm), or high (> 2 atm). The medium-pressure mercury lamp is the single most important light source used in the radiation

curing industry. This is due to its high power (200-300 W/in.) and important emission lines, which are absorbed by most commercial photoinitiators (i.e., 254, 280, 303, 313, 334, and 365 nm) [46].

High-pressure xenon lamps provide a broad and continuous output from 290 nm in the UV region to >800 nm in the IR region. Both the xenon arc and medium-pressure mercury lamps can be doped with Zn, Cd, or TlI_2 to change their output spectra.

In recent years, new lamp designs have been introduced in which the electrodes have been replaced by microwave or other rf (radio-frequency) sources. The advantages of electrodeless lamps are longer lamp life, short warmup times, and highly efficient UV output-40 per cent of the energy can be converted to UV light, compared to about 15-20 per cent conversion for a medium-pressure mercury lamp.

Lasers (light amplification by stimulated emission of radiation) offer the prospect of an excitation source of exceedingly high intensity (one of their inherent properties) compared to classical light sources. Their output is available in both UV and visible wavelengths. Lasers can be operated in either pulsed or continuous mode. Some lasers offer fixed wavelength, and others offer tunable wavelengths [46].

The correct choice of lamp system is the first step toward success of a radiation curing process. Emission spectra of the lamps must match the absorption spectra of the chosen photoinitiators, sensitizers, or charge transfer complexes. Stable output over a period of time and the intensities of the various emission lines are also important [46].

1.2.4. Mono- or Multifunctional Monomers

The chemical structure and functionality of both monomer and oligomer determine the final degree of polymerization, as well as the physical and chemical characteristics of the cured polymer [39].

The monomers that are most widely used for photopolymerization are multifunctional acrylates and methacrylates because of their high reactivity and moderate to low volatility. Acrylates are known to be among the most reactive monomers polymerizing by a free-radical mechanism. This feature, together with the remarkable chemical, optical and mechanical properties of the polymers obtained, account for the great commercial success of acrylate-based UV-curable resins [47]. It also explains why the photoinitiated polymerization of multifunctional acrylate monomers and oligomers has been so thoroughly investigated, mainly from the kinetic and mechanistic points of view [48]. The polymerization of a diacrylate monomer, initiated by UV-generated benzoyl radicals, is assumed to develop according to the following scheme (Figure 1.18) [44]:

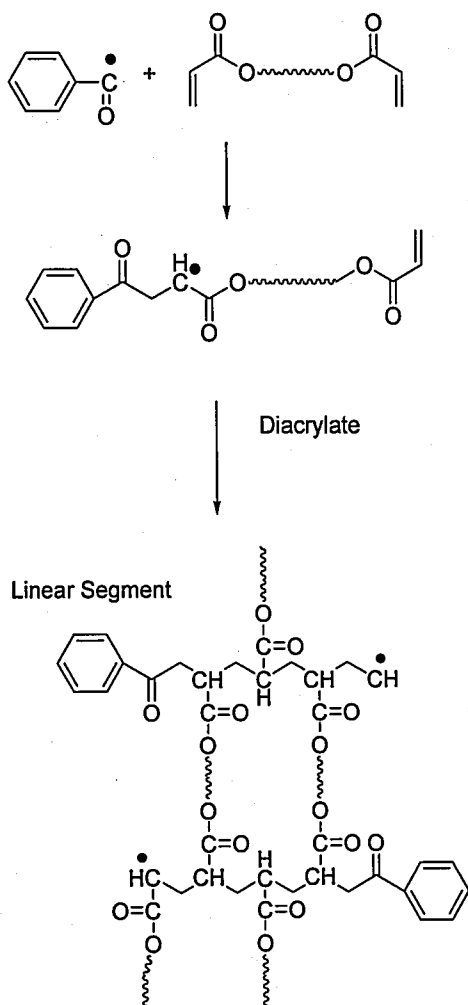


Figure 1.18. Mechanism of polymerization of a diacrylate monomer

Multifunctional monomer polymerizations exhibit many complex features including autoacceleration and autodeceleration [49], limiting double bond conversion [50], trapping of radicals in networks, unequal reactivities of different functional groups [51] and a reaction diffusion-controlled termination mechanism [52]. All of this behavior occurs because of the extremely low mobility of reacting species in the crosslinked network [53].

For any real-world application, it is essential to understand the relationships between the monomer/polymer structure and reaction conditions with the properties of network materials formed [54]. For example, the number of functional groups, plus the distance and flexibility between functional groups, combine to affect the crosslinks density versus the primary and secondary cyclic structures that can form during polymerization [55]. A primary cycle occurs when a growing polymer radical loops on itself and polymerizes through a pendant double bond on the same chain, leading to reduced crosslink density, and generation of microgels and heterogeneity in the polymer. This heterogeneity causes reduction in physical properties such as mechanical strength, solvent resistance and glass transition temperature. A secondary cycle forms when a polymer chain forms more than one crosslink with another polymer chain [56].

Different type of structures can be used for the telechelic polymer or oligomer backbone, such as polyurethanes, polyesters, polyethers and polysiloxanes. The final properties of UV-cured acrylate polymers depend primarily on the chemical structure of the functionalised oligomer. Low-modulus elastomers are generally obtained with aliphatic compounds, whereas hard and glassy materials are formed when aromatic structures are introduced into the polymer chain.

The other types of polymerizable systems commonly used for UV-curing applications are unsaturated polyester resins, thiol-polyene systems, epoxides (by cationic polymerization), etc.

1.2.4.1. Photopolymerization Kinetics of Multifunctional Monomers. The various analytical methods are used to study the kinetics of photopolymerizations. These are differential scanning calorimetry, dilatometry, fluorescence spectroscopy and RT-IR spectroscopy. By these techniques, heat evolved, volume shrinkage, increase in viscosity or disappearance of the reactive group of the monomer are monitored.

The three steps of the curing process become more apparent when the rate of polymerization (R_p) is plotted as a function of the exposure time (Figure 1.19). Rate of polymerization, propagation and termination rate constants can be calculated from heat flow during polymerization according to the following equations :

$$R_p = \frac{(Q/s)M}{n\Delta H_p m} \qquad \frac{k_p}{k_t^{1/2}} = \frac{R_p}{[M](\Theta I_0 \epsilon [A])^{1/2}}$$

(Q/s)	: heat flow per second during reaction
M	: the molar mass of the monomer
n	: number of double bonds per monomer molecule
ΔH_p	: the heat released per mole of double bonds reacted
m	: the mass of monomer in the sample
Θ	: the initiator efficiency
[M]	: the molar concentration of double bonds
I_0	: the incident light intensity
ϵ	: the extinction coefficient of the initiator
[A]	: the initiator concentration

Autoacceleration occurs at the very beginning of the irradiation because of the rapid increase in viscosity until about 5 per cent conversion when the reaction reaches its maximum value $(R_p)_{\max}$. It is followed by a period where the polymerization develops at a sustained pace during 0.3 s (about 30 per cent conversion), the time after which autodeceleration starts to take place when propagation becomes diffusion controlled. Ultimately, vitrification leads to a complete stop of the curing process at about 90 per cent conversion. There remains in the crosslinked polymer a certain amount of unreacted

acrylate double bonds, which may ultimately affect the longterm properties of the UV-cured material [43].

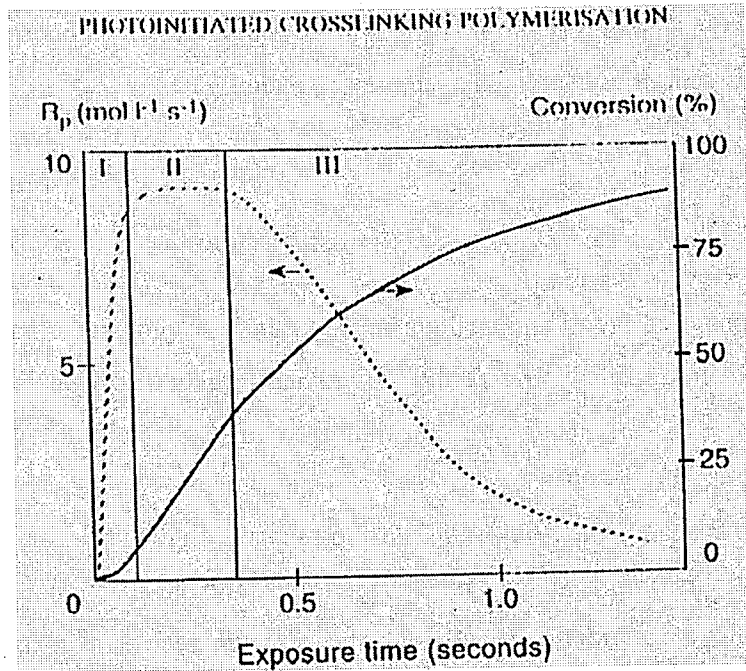


Figure 1.19. The example plot of rate and conversion of a monomer

There are various factors that influence the final conversion such as ;

- Glass transition temperature of the forming network.
- Polymerization temperature
- Crosslinker type (acrylate versus methacrylate)
- Degree of functionality
- Distance and flexibility between functional groups in monomer
- Light intensity

There are also some factors that enhance the polymerization rate such as ;

- The presence of a heteroatom linkage in a monomer
- Dipole moment

- Hydrogen bonding capability
- Light intensity

Hydrogen bonding affects R_p via preorganization of the monomers whereas dipole moment may affect R_p due to a stronger solvent cage combined with increased charge at the propagating radical [57].

1.2.5. Applications of UV-curable Systems

Photocuring technology has found major applications in various industrial sectors because of its distinct advantages, namely an ultrafast polymerization of solvent-free formulations occurring selectively in the illuminated areas [43].

UV curing is used at various stages of printing to substantially speed up ink drying. Another application area is the production of protective coatings for many substrates such as wood, plastics, metals, glass, optical fibers, leather, paper, fabrics, etc [58]. Also, in the field of adhesives, this method is used for quick-setting glues, pressure sensitive adhesives and release coatings [59].

Other promising applications of photo- and laser- induced polymerization include the creation of 3D solid objects by laser stereolithography [60], the recording of holograms by a development-free process [61], the production of optical guides of micronic dimensions [62], the ultrafast curing of dental composites [63] or reinforced plastics [64], molecular imprinting [65] and the manufacture of optical discs [66] and aspherical lenses [67].

Table 1.1. The main areas of today's end uses of UV-radiation curing

Graphic arts	Printing inks Overprint varnishes Printing plates
Coatings	Wood finishing Floor covering Organic glasses Metals Leather, fabrics Optical fibers
Electronics	Printed circuits Patterning(video disc) Sealants(encapsulation) Conformal coatings
Adhesives	Pressure sensitive adhesives Glass laminates Release coatings Quick-setting glues
Miscellaneous	Hologram recording media Optical wave guides Stereolithography Dental composite materials

1.2.5.1. Molecular Imprinting. Molecular imprinting is a facile method for making polymeric artificial receptors that can be tailored toward most small molecules [68]. The strategy for molecular imprinting is outlined in Figure 1.20 where functionalized monomers are bound either covalently or non-covalently to a print molecule or template [69].

The resulting pre-polymer complex is radically copolymerized with an excess of cross-linking monomer in the presence of an equal volume of inert solvent (porogen) to form insoluble porous network polymers [69]. Removal of the template, by extraction or hydrolysis, leaves sites in the polymer that have incorporated the functionalized monomers. These sites are complementary in size and shape to the template molecule, resembling the "lock and key " paradigm of natural receptors such as antibodies and enzymes [70].

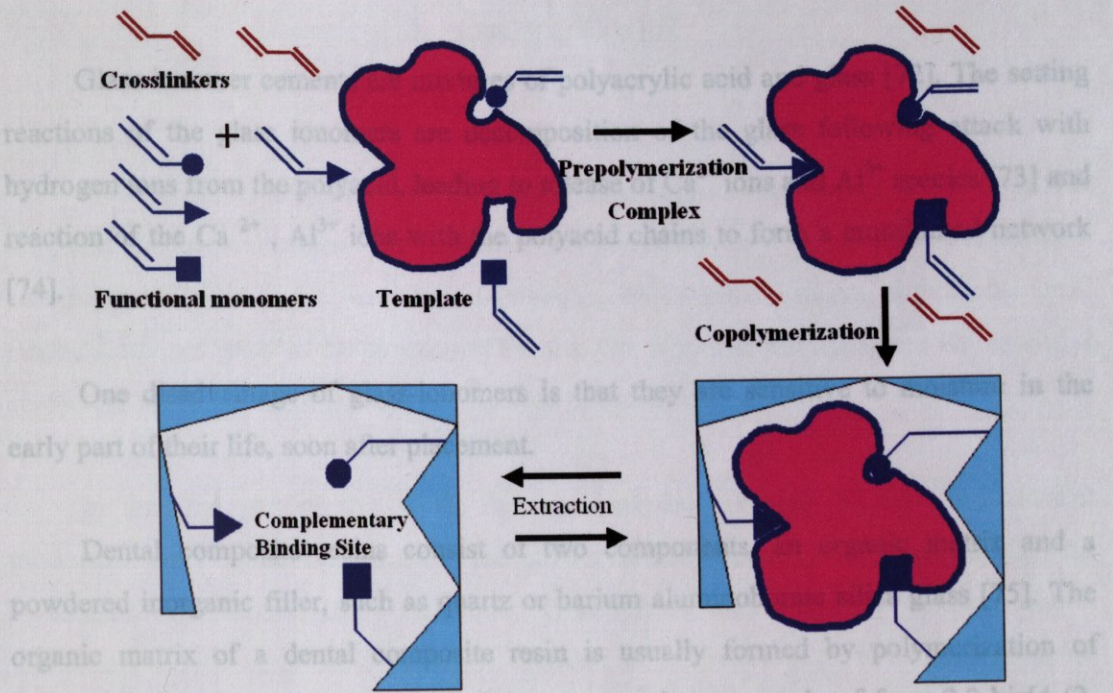


Figure 1.20. Outline of the molecular imprinting strategy in synthetic polymers

In recent years, Efforts have been made for developing new crosslinking materials that exhibit remarkable improvement in binding and selectivity of molecularly imprinted polymers (MIPs). Developing new and better crosslinkers besides functional monomers is a fruitful approach to improve MIP materials, since 80-90 per cent of the MIP is made up of crosslinker [69].

1.2.5.2. Dental Restorative Materials. One of the most interesting developments in the field of biomaterials in recent years has been the photocurable dental filling materials.

In the past 30 years, two contrasting materials, the glass-ionomer cement and the composite resin, have been developed. They have superior aesthetics to amalgams, though they do not yet endure conditions in the mouth quite so well. They have been combined to make hybrid materials (resin-modified glass ionomers). Following placement in the tooth they are cured with visible light, and are white, translucent restorations. From the view of their underlying chemistry, they are interesting in that they combine both water-soluble and water-immiscible components, and when set include both polyelectrolyte and nonionic polymer structures [71].

Glass ionomer cements are mixtures of polyacrylic acid and glass [72]. The setting reactions of the glass ionomers are decomposition of the glass following attack with hydrogen ions from the polyacid, leading to release of Ca^{2+} ions and Al^{3+} species [73] and reaction of the Ca^{2+} , Al^{3+} ions with the polyacid chains to form a crosslinked network [74].

One disadvantage of glass-ionomers is that they are sensitive to moisture in the early part of their life, soon after placement.

Dental composite resins consist of two components, an organic matrix and a powdered inorganic filler, such as quartz or barium aluminoborate silica glass [75]. The organic matrix of a dental composite resin is usually formed by polymerization of aromatic or urethane dimethacrylates. Many composites are made of from 2,2-bis[4-(2-hydroxy-3-methacryloylpropoxy)-phenyl]propane, known as bisGMA. Bis-GMA is used because of its large molecular size, which has the effect of reducing the proportion of the molecule that undergoes polymerization, hence ensuring a low shrinkage [76]. BisGMA does, though, have a high viscosity as the monomer, and low viscosity monomers are added as diluents to improve this. These diluents include ethylene glycol dimethacrylate (EGDMA) and triethylene glycol dimethacrylate (TEGDMA) [77].

Resin-modified glass-ionomer cements were originally developed as hybrids of self-curing glass-ionomers and composite resins [78]. In order to make the aqueous and the organic components miscible, 2-hydroxyethyl methacrylate (HEMA) was added. It acts as both a co-solvent and a photopolymerizable monomer [71].

2. OBJECTIVES

Monomers and polymers with quaternary ammonium functionality and at least one long alkyl chain on nitrogen have antibacterial activities. Also it is known that monomers and polymers with metal chelating functionality make metals unavailable to bacteria. Bacteria can not grow in the absence of Fe, Ca, Cu, Mg, Mo and Zn which are essential co-factors for many bacterial enzymes such as proteinases.

In the first part of this work, the aim was the synthesis of new antibacterial monomers and polymers based on AHM and acrylamide/methacrylamide monomers and investigate their antibacterial activities. Hydroxylated secondary and tertiary amine monomers were synthesized via Michael addition of different amines to acrylate group of AHM and quaternized with various alkylhalides. Acrylamide and methacrylamide derivatives of different amines were synthesized and also quaternized with alkylhalides.

Synthesized hydroxylated amine monomers and their polymers may have metal chelating ability due to the presence of secondary or tertiary nitrogens and hydroxyl groups and may have potential antibacterial activity. Synthesized quaternary ammonium monomers and polymers also are expected to show antibacterial activity. The minimum inhibitory concentration (MIC) values were evaluated to investigate the antibacterial activities of these monomers, homopolymers and copolymers by using the broth dilution method.

Photoinitiated free radical polymerization of multifunctional monomers produces highly crosslinked networks with high thermal stability, mechanical strength and resistance to solvent absorption. The monomers that are most widely used for photopolymerization are multifunctional acrylates and methacrylates. It is essential to understand the effect of monomer structure on the photopolymerization reactivities. For example, the type and the number of functional groups present, the distance and flexibility between functional groups, hydrogen bonding and liquid crystallinity have drastic effects on the reactivity of monomers. Monomers based on alkyl α -hydroxymethyl acrylates (RHMA) offer great versatility for obtaining functionalized monomers.

In the second part of this work, new multifunctional methacrylates based on RHMA monomers were synthesized to investigate the effect of monomer structure on photopolymerization reactivities. The monomers contained acid groups to improve adhesion properties of polymers to metals and dentin. The size of spacer between double bonds were changed to investigate the effect of flexibility between functional groups on the monomer structure. The reactivities of the monomers were investigated using photo-DSC.

3. EXPERIMENTAL

3.1. Antibacterial Monomers and Polymers

3.1.1. Materials

Chemicals used in this study were as follows:

3-(acryloyloxy)-2-hydroxypropylmethacrylate (AHM), (3-Dimethylamino) propylamine (DMAPA), N,N,N'-trimethylethylenediamine (TMEDA), 3,3'-iminobis(N,N'-dimethylpropylamine) (IDPA), 3-aminopyridine, acryloyl chloride, triethylamine (TEA), methacryloyl chloride, MgSO₄, 2-hydroxy-1-[4-hydroxyethoxyphenyl]-2-methyl-1-propane (Irgacure 2959), 2,2-Dimethoxy-2-phenyl acetophenone (Irgacure 651), bromohexane, bromooctane and bromohexadecane were all obtained from Aldrich and used as received. The solvents; acetonitrile, hexane, methylene chloride, diethyl ether, ethanol and chloroform were all obtained from Merck and used as received. Tryptic soy (TSB) was purchased from Difco Laboratories. Bacterial strains used for antibacterial activity tests included *S. aureus* RN4220 and *E. Coli* TOP10 strain.

3.1.2. Apparatus

¹H-NMR and ¹³C-NMR spectra were recorded using a Varian Gemini 200 MHz spectrometer. IR analysis was performed on a FT-IR Mattson 5000 using NaCl windows.

Photopolymerizations were done in a TA Instruments differential photocalorimeter (DPC) with a medium pressure mercury lamp.

3.1.3. Monomer Synthesis

3.1.3.1. Synthesis of AHM-(3-Dimethylamino) propylamine (AHM-DMAPA). AHM (3.2 g, 0.015 mol) and (3-Dimethylamino) propylamine (1.5 g, 0.015 mol) were added into a 50 ml round-bottom flask and the mixture was stirred at room temperature for 24

hours. The product (AHM-DMAPA) was obtained as a colorless, viscous liquid in 90 per cent yield.

$^{13}\text{C-NMR}$ (CDCl_3); δ = 18.2 (CH_3), 27.1 (CH_2), 34.7 ($\text{CH}_2\text{-CO}$), 45.3 [$\text{N-(CH}_3)_2$], 47.9 ($\text{CH}_2\text{-NH}$), 57.7 ($\text{CH}_2\text{-NH}$), 65.1 ($\text{CH}_2\text{-O}$), 65.2 ($\text{CH}_2\text{-O}$), 67.2 (CH-OH), 126.0 ($\text{CH}_2\text{=C}$), 135.7 (C=CH_2), 167.1 (C=O), 172.4 (C=O) ppm.

$^1\text{H-NMR}$ (CDCl_3); δ = 1.9 ($\text{CH}_3\text{-C}$), 2.2 [$\text{N-(CH}_3)_2$], 2.5-3.5 (CH_2), 3.5-4 (CH_2 for esters), 5.56 ($\text{H}_2\text{C=C}$), 6.12 (C=CH_2) ppm.

IR (NaCl) : 1166 (C-O), 1295 (C-N), 1637 (C=C), 2946-2819 (C-H), 3500 (OH , NH) cm^{-1} .

3.1.3.2 Synthesis of AHM-N,N,N'-trimethylethylenediamine (AHM-TMEDA). AHM (3.2 g, 0.015 mol) and N,N,N'-trimethylethylenediamine (TMEDA) (1.5 g, 0.015 mol) were added into a 50 ml round-bottom flask and the mixture was stirred at room temperature for 24 hours. The product (AHM-TMEDA) was obtained as a colorless, viscous liquid in 94 per cent yield.

$^{13}\text{C-NMR}$ (CDCl_3); δ = 18.0 (CH_3), 32.6 ($\text{CH}_2\text{-CO}$), 41.7 (N-CH_3), 45.4 [$\text{N-(CH}_3)_2$], 53.5 ($\text{CH}_2\text{-N}$), 55 ($\text{CH}_2\text{-N}$), 56.5 ($\text{CH}_2\text{-N}$), 65.0 ($\text{CH}_2\text{-O}$), 65.3 (CH-OH), 66.8 ($\text{CH}_2\text{-O}$), 125.9 ($\text{CH}_2\text{=C}$), 135.7 (C=CH_2), 166.9 (C=O), 172.2 (C=O) ppm.

$^1\text{H-NMR}$ (CDCl_3); δ = 1.94 ($\text{CH}_3\text{-C}$), 2.1 [$\text{N-(CH}_3)_2$], 2.3 (N-CH_3), 2.5-3.5 (CH_2), 3.5-4 (CH_2 for esters), 5.49 ($\text{H}_2\text{C=C}$), 6.03 (C=CH_2) ppm.

IR (NaCl) : 1168 (C-O), 1295 (C-N), 1637 (C=C), 1725 (C=O), 2952-2817 (C-H), 3435 (OH , NH) cm^{-1} .

3.1.3.3. Synthesis of AHM-3,3-iminobis(N,N-dimethylpropylamine) (AHM-IDPA). AHM (1.6 g, 0.015 mol) and 3,3-iminobis(N,N-dimethylpropylamine) (1.4 g, 0.015 mol) were added into a 50 ml round-bottom flask and the mixture was stirred at room

temperature for 24 hours. The product (AHM-IDPA) was obtained as a colorless, viscous liquid in 89 per cent yield.

$^{13}\text{C-NMR}$ (CDCl_3): δ = 18.1 (CH_3), 25.0 (CH_2), 33.1 ($\text{CH}_2\text{-O}$), 45.1 [$\text{N-(CH}_3)_2$], 49.5 ($\text{CH}_2\text{-N}$), 51.6 ($\text{CH}_2\text{-N(CH}_3)_2$), 57.5 ($\text{CH}_2\text{-N}$), 65.3 ($\text{CH}_2\text{-O}$), 65.7 (CH-OH), 66.6 ($\text{CH}_2\text{-O}$), 125.7 ($\text{CH}_2\text{=C}$), 135.7 (C=CH_2), 166.9 (C=O), 172.3 (C=O) ppm.

$^1\text{H-NMR}$ (CDCl_3): δ = 1.8 ($\text{CH}_3\text{-C}$), 2.1 [$\text{N-(CH}_3)_2$], 2.5-3.5 ($\text{CH}_2\text{-N}$), 3.5-4 (CH_2 for esters), 5.45 ($\text{H}_2\text{C=C}$), 5.99 (C=CH_2) ppm.

IR (NaCl) : 1164 (C-O), 1295 (C-N), 1637 (C=C), 1724 (C=O), 2948-2813 (C-H), 3500 (OH, NH) cm^{-1} .

3.1.3.4. Synthesis of AHM-[3-(Aminomethyl) pyridine] (AHM-PYR). AHM (3.2 g, 0.015 mol) and 3-(Aminomethyl) pyridine (1.6 g, 0.015 mol) were added into a 50 ml round-bottom flask and the mixture was stirred at room temperature for 24 hours. The product (AHM-PYR) was obtained as a colorless, viscous liquid in 90 per cent yield.

$^{13}\text{C-NMR}$ (CDCl_3): δ = 18.0 (CH_3), 34.1 ($\text{CH}_2\text{-CO}$), 44.1 ($\text{CH}_2\text{-NH}$), 50.5 ($\text{CH}_2\text{-NH}$), 65.0 ($\text{CH}_2\text{-O}$), 66.8 ($\text{CH}_2\text{-O}$), 72.3 (CH-OH), 123.3 (CH-CH), 125.8 ($\text{CH}_2\text{=C}$), 135 (C-CH), 135.9 (C=CH_2), 147.8 (CH-N), 148.9 (CH-N), 166.8 (C=O), 172.2 (C=O) ppm.

$^1\text{H-NMR}$ (CDCl_3): δ = 1.8 (CH_3), 2.4 ($\text{CH}_2\text{-CO}$), 2.7 ($\text{CH}_2\text{-NH}$), 3.7 ($\text{CH}_2\text{-C}$), 4.1 ($\text{CH}_2\text{-O}$), 5.45 ($\text{H}_2\text{C=C}$), 5.99 (C=CH_2), 7.15 (CH=C), 7.5 (CH=CH), 8.3 (CH=N), 8.4 (CH-N) ppm.

IR (NaCl) : 1072 (C-O), 1214 (C-N), 1643 (C=C), 1785 (C=O), 2976-2857 (C-H), 3285 (OH, NH) cm^{-1} .

3.1.3.5. Synthesis of Acrylamide-3,3-iminobis(N,N-dimethylpropylamine) (ACRY-IDPA). Acryloyl chloride (1.5 g, 0.1 mol) in dry acetonitrile (5.0 ml) was added dropwise to 3,3-iminobis(N,N-dimethylpropylamine) (6.2 g, 0.2 mol) in dry acetonitrile (33.3 ml) in an ice bath. The mixture was stirred in the ice bath for 4 hours and then at room

temperature for 20 hours. After evaporation of the solvent, the crude product was purified with column chromatography using methylene chloride and methanol (95:5) as eluent. The pure product was obtained as a yellow, viscous liquid in an 30 per cent yield.

$^{13}\text{C-NMR}$ (CDCl_3): δ = 27.4 (CH_2), 45.3 [$\text{N}-(\text{CH}_3)_2$], 45.9 ($\text{CH}_2\text{-N}$), 56.9 ($\text{CH}_2\text{-[N}-(\text{CH}_3)_2]$), 127.6 ($\text{CH}_2=\text{C}$), 127.7 ($\text{C}=\text{CH}_2$), 166.1 ($\text{C}=\text{O}$) ppm.

IR (NaCl) : 1250 (C-N), 1619 (C=C), 1654 (C=O), 2952-2762 (C-H) cm^{-1} .

3.1.3.6. Synthesis of Methacrylamide-[3-(Aminomethyl) pyridine] (METH-PYR). To a solution of 3-(Aminomethyl) pyridine (7.2 g, 0.0819 mol) and triethylamine (TEA) (5.7 ml, 0.0819 mol) in methylene chloride (25 ml) at 0 $^\circ\text{C}$ methacryloyl chloride (4 ml, 0.041 mol) was added dropwise and the solution was allowed to come to room temperature and stirred for 40 min. Then 25 ml of water was added and the solution was stirred for 30 min. The organic layer was separated and the aqueous layer was extracted with chloroform. The organic layers were dried with magnesium sulfate and solvent was evaporated. The crude product was purified with column chromatography using methylene chloride:methanol (95:5) as eluent. The pure product was obtained as a colorless liquid.

$^{13}\text{C-NMR}$ (CDCl_3): δ = 18.2 (CH_3), 40.4 ($\text{CH}_2\text{-NH}$), 119.7 ($\text{CH}=\text{CH}$), 123.2 ($\text{CH}_2=\text{C}$), 134.2 ($\text{CH}=\text{CH}$), 135.2 ($\text{C}=\text{CH}$), 139.2 ($\text{C}=\text{CH}_2$), 147.7 (CH-N), 148.3 (CH-N), 168.5 ($\text{C}=\text{O}$) ppm.

$^1\text{H-NMR}$ (CDCl_3): δ = 1.7 (CH_3), 4.2 ($\text{CH}_2\text{-NH}$), 5.1 ($\text{C}=\text{CH}_2$), 5.5 ($\text{C}=\text{CH}_2$), 7.0 ($\text{CH}=\text{CH}$), 7.4 (CH-CH), 7.7 (CH-N), 8.2 (CH=N) ppm.

3.1.4. Quaternization of Monomers

3.1.4.1. Quaternization of AHM-TMEDA with Bromohexane. AHM-TMEDA (1.1 g, 0.028 mol), bromohexane (1.8 g, 0.044 mol) and 13.75 ml dry acetonitrile were heated at 60 $^\circ\text{C}$ for 3 days under nitrogen. After evaporation of the solvent the product was purified by dissolving in methanol and precipitation into diethylether to give an oily liquid AHM-TMEDA QAC in an 54 per cent yield.

^{13}C NMR (CDCl_3): δ = 13.8 (CH_3), 18.2 (CH_3), 22.3 (CH_2), 25.7 (CH_2), 31.14 (CH_2), 32.5 ($\text{CH}_2\text{-CO}$), 41.3 (CH_2), 51.4 [$\text{N-(CH}_3)_2$], 51.8 ($\text{CH}_2\text{-N}$), 53.3 ($\text{CH}_2\text{-N}$), 60.1 ($\text{CH}_2\text{-N}$), 65.0 ($\text{CH}_2\text{-O}$), 65.7 (CH-OH), 66.8 ($\text{CH}_2\text{-O}$), 126.1 ($\text{CH}_2\text{=C}$), 135.7 (C=CH_2), 165.1 (C=O), 172.1 (C=O) ppm.

^1H -NMR (CDCl_3): δ = 0.8 ($\text{CH}_3\text{-CH}_2$), 1.3 (CH_2), 1.7 (CH_2), 1.8 (CH_2), 1.87 ($\text{CH}_3\text{=C}$), 2.3 (CH_2), 2.5 (CH_2), 2.9 (CH_2), 3.3 ($\text{CH}_2\text{-N}$), 5.5 (C=CH_2), 6.0 (C=CH_2) ppm.

IR (NaCl) : 1125 (C-O), 1250 (C-N), 1650 (C=C), 1750 (C=O), 2995 (C-H stretchings), 3350 (OH) cm^{-1} .

3.1.4.2. Quaternization of AHM-PYR with Bromohexane. AHM-PYR (1.0 g, 0.028 mol), bromohexane (3.2 g, 0.17 mol) and 12.2 ml dry acetonitrile were heated at 60°C for 24 hours under nitrogen. After evaporation of the solvent the product was purified by dissolving in methanol and precipitation into diethylether to give an oily liquid AHM-PYR QAC.

^{13}C -NMR (CDCl_3): δ = 13.4 ($\text{CH}_3\text{-CH}_2$), 17.8 ($\text{CH}_3\text{-C}$), 21.8 (CH_2), 25.2 (CH_2), 26.4 ($\text{CH}_2\text{-CO}$), 30.5 (CH_2), 31.1 ($\text{CH}_2\text{-N}$), 43.3 ($\text{CH}_2\text{-N}$), 47.4 ($\text{CH}_2\text{-N}$), 48.7 ($\text{CH}_2\text{-N}$), 53.4 ($\text{CH}_2\text{-N}$), 54.2 ($\text{CH}_2\text{-N}$), 57.1 ($\text{CH}_2\text{-N}$), 125.7 ($\text{CH}_2\text{=C}$), 135.2 (C=CH_2), 166.6 (C=O), 172.0 (C=O) ppm.

^1H -NMR (CDCl_3): δ = 1.9 ($\text{CH}_3\text{-C}$), 2.3 ($\text{CH}_2\text{-CO}$), 3.6 ($\text{CH}_2\text{-N}$), 4.2 (CH_2 for esters), 5.0 ($\text{CH}_2\text{=C}$), 5.5 ($\text{CH}_2\text{=C}$), 7.6 (CH-C), 7.9 (CH=CH), 8.7 (CH-N), 9.1 (CH=N) ppm.

IR (NaCl) : 1175 (C-O), 1250 (C-N), 1625 (C=C), 1725 (C=O), 2910-2850 (C-H), 3250 (OH) cm^{-1} .

3.1.4.3. Quaternization of ACRY-IDPA with Bromohexane. Acrylamide-IDPA monomer (0.24 g, 0.028 mol), bromohexane (0.517 g, 0.088 mol) and 3.9 ml dry acetonitrile were heated for 24 h under nitrogen. After evaporation of acetonitrile, the liquid product was

purified by dissolution in methanol and precipitation into diethylether to give a white oily liquid ACRY-IDPA QAC.

^{13}C -NMR (CDCl_3): δ = 13.5 (CH_3), 21.9 (CH_2), 22.2 ($\text{CH}_2\text{-CH}_3$), 22.9 (CH_2), 25.4 (CH_2), 30.7 (CH_2), 44.3 ($\text{CH}_2\text{-N}$), 50.6 [$\text{N-(CH}_3)_2$], 61.5 ($\text{CH}_2\text{-N}$), 64.6 ($\text{CH}_2\text{-N}$), 127.5 ($\text{CH}_2\text{=C}$), 128.5 (C=CH_2), 166.3 (C=O) ppm.

^1H -NMR (CDCl_3); δ = 0.8 ($\text{CH}_3\text{-CH}_2$), 1.3 (CH_2), 1.7 (CH_2), 2.3 [$\text{N-(CH}_3)_2$], , 3.4 ($\text{CH}_2\text{-N}$), 5.8 ($\text{CH}_2\text{=CH}$), 6.3 ($\text{CH}_2\text{=CH}$), 6.8 (CH-CO) ppm.

IR (NaCl) : 1075 (C-O), 1625 (C=C), 1675 (C=O), 2928-2856 (C-H), 3428 (OH) cm^{-1} .

3.1.4.4. Quaternization of METH-PYR with Bromohexane. To a solution of METH-PYR (0.2593 g, 0.001473 mol) in dried acetonitrile bromohexane (0.382 g, 0.00231 m) was added and the mixture was heated to 55 $^\circ\text{C}$ for 24 h under nitrogen. After evaporation of the solvent residual solid was washed with diethylether to give pure product METH-PYR/1 QAC as a white solid.

^{13}C NMR (CDCl_3): δ = 13.7 (CH_3), 18.7 (CH_3), 22.2 (CH_2), 25.6 (CH_2), 30.0 (CH_2), 31.5 (CH_2), 40.1 ($\text{CH}_2\text{-NH}$), 62.1 ($\text{CH}_2\text{-N}$), 121.6 (CH=N), 127.6 ($\text{CH}_2\text{=C}$), 138.4 (CH-C), 141.7 (C-CH_2), 142.3 (C=CH_2), 144.5 (CH-N), 145.4 (CH-N), 168.7 (C=O) ppm.

^1H -NMR (CDCl_3); δ = 0.8 ($\text{CH}_3\text{-CH}_2$), 1.3 ($\text{CH}_3\text{-C}$), 1.9 (CH_2), 4.7 ($\text{CH}_2\text{-CO}$), 5.3 ($\text{CH}_2\text{=CH}$), 6.0 ($\text{CH}_2\text{=CH}$), 7.9 (CH-CH), 8.7 (CH=C), 9.1 (CH-N), 9.4 (CH=N) ppm.

IR (NaCl) : 1225(C-N), 1625 (C=C), 1675 (C=O), 3021-2862 (C-H), 3287 (OH , NH) cm^{-1} .

3.1.4.5. Quaternization of METH-PYR with Bromooctane. To a solution of METH-PYR (0.2593 g, 0.001473 m) in dried acetonitrile bromooctane (0.43 g, 0.00231 m) was added and the mixture was heated to 55 $^\circ\text{C}$ for 24 h under nitrogen. After evaporation of the

solvent residual solid was washed with diethylether and pure product METH-PYR/2 QAC was obtained as a white solid.

$^{13}\text{C-NMR}$ (CDCl_3): δ = 13.9 (CH_3), 18.8 ($\text{CH}_3\text{-C}$), 22.5 ($\text{CH}_2\text{-CH}_3$), 26.0 (CH_2), 28.9 (CH_2), 31.5 (CH_2), 40.2 ($\text{CH}_2\text{-NH}$), 62.3 ($\text{CH}_2\text{-N}$), 121.9 (CH=CH), 125.3 ($\text{CH}_2\text{=C}$), 126.5 (CH=C), 127.5 (C-CH), 138.3 (C=CH_2), 141.7 (CH-N), 145.6 (CH-N), 168.8 (C=O) ppm.

$^1\text{H-NMR}$ (CDCl_3); δ = 0.8 ($\text{CH}_3\text{-CH}_2$), 1.3 ($\text{CH}_3\text{-C}$), 1.9 (CH_2), 2.6 (CH_2), 4.7 ($\text{CH}_2\text{-CO}$), 5.4 ($\text{CH}_2\text{=CH}$), 6.0 ($\text{CH}_2\text{=CH}$), 7.9 (CH-CH), 8.6 (CH=C), 8.8 (CH-N), 9.5 (CH=N) ppm.

IR (NaCl) : 1225(C-N), 1613 (C=C), 1675 (C=O), 2950 (CH), 3275 (OH, NH) cm^{-1} .

3.1.4.6. Quaternization of the METH-PYR with Bromohexadecane. To a solution of METH-PYR (0.2593 g, 0.001473 m) in dried acetonitrile bromohexadecane (0.7 g, 0.00231 m) was added and the mixture was heated to 55 $^\circ\text{C}$ for 24 h under nitrogen. After evaporation of the solvent residual solid was washed with diethylether to give a white solid (METH-PYR/3 QAC).

$^{13}\text{C-NMR}$ (CDCl_3): δ = 14.1 (CH_3), 18.8 ($\text{CH}_3\text{-C}$), 22.6 ($\text{CH}_2\text{-CH}_3$), 26 (CH_2), 29.3 (CH_2), 29.6 (CH_2), 31.5 (CH_2), 31.8 (CH_2), 40.2 ($\text{CH}_2\text{-NH}$), 62.3 ($\text{CH}_2\text{-N}$), 121.9 (CH=CH), 127.5 ($\text{CH}_2\text{=C}$), 138.3 (CH=C), 141.6 (C-CH), 142 (C=CH_2), 145 (CH-N^+), 145.6 (CH-N^+), 168.8 (C=O) ppm.

$^1\text{H-NMR}$ (CDCl_3); δ = 0.8 ($\text{CH}_3\text{-CH}_2$), 1.2 ($\text{CH}_3\text{-C}$), 1.9 (CH_2), 2.4 (CH_2), 4.7 ($\text{CH}_2\text{-CO}$), 5.4 ($\text{CH}_2\text{=CH}$), 6.0 ($\text{CH}_2\text{=CH}$), 7.9 (CH-CH), 8.6 (CH=C), 8.8 (CH-N), 9.5 (CH=N) ppm.

IR (NaCl) : 1220(C-N), 1621 (C=C), 1667 (C=O), 3044-2850 (C-H stretchings), 3286 (OH-NH) cm^{-1} .

3.1.5. Polymer Synthesis

3.1.5.1. Photopolymerization of Amine Monomers. Photopolymerization of monomers were carried out on a TA Instruments Photo-DSC using 2,2-Dimethoxy-2-phenyl acetophenone (Irgacure 651) as initiator.

Initiator (0.0090 g, 2 mol per cent) was first dissolved in dichloromethane (2 ml) and a specific amount of this solution was added to neat monomers. Approximately 3.0 mg of the monomer was placed in a aluminum DSC pan (approximately 200 nm thickness) and carefully weighed. Then initiator solution (2 mol per cent) was added and the sample transferred to the sample holder in the photo-DSC. The samples were purged with nitrogen for 10 min to remove air and to allow for complete solvent evaporation prior to the polymerization. Samples were irradiated for 6 min at 30 °C under nitrogen purge and the heat flux as a function of reaction time was monitored. The light shutter was opened at the 30 s after the beginning of data acquisition; i.e. onset of photocure occurred at 30 s.

Monochromatic 365 nm ultraviolet light was used for all of the photopolymerizations, and light intensity was 1.0 mW/cm². Both rate of polymerization and conversion were calculated as a function of time. The heats of reaction (ΔH_p) used were 13.1 kcal/mol for the methacrylate double bond.

AHM-DMAPA, AHM-TMEDA, AHM-IDPA and AHM-PYR monomers were photocured with the same photopolymerization procedure as mentioned above.

3.1.5.2. Photopolymerization of Quaternary Ammonium Monomers. Photopolymerization of the quaternary ammonium salts were carried out on a TA Instruments Photo-DSC using 2-hydroxy-1-[4-hydroxyethoxyphenyl]-2-methyl-1-propane (Irgacure 2959), as the primary water-soluble photoinitiator system.

Irgacure 2959 (0.0090 g, 2 mol per cent) as a water-soluble photoinitiator was first dissolved in water (2 ml) and a specific amount of this solution was added to neat monomers. Approximately 3.0 mg of the mixture was placed in a DSC pan

(approximately 200 nm thickness) and carefully weighed. Then initiator solution (2 mol per cent) was added and the sample transferred to the sample holder in the photo-DSC. The samples were purged with nitrogen for 10 min to remove air prior to the polymerization. Samples were irradiated for 6 min at 30 °C under nitrogen purge and the heat flux as a function of reaction time was monitored using thermal conditions. The light shutter was opened at the 30 s after the beginning of data acquisition; i.e. onset of photocure occurred at 30 s.

Monochromatic 365 nm ultraviolet light was used for all of the photopolymerizations, and light intensity was 1.0 mW/cm². Both rate of polymerization and conversion were calculated as a function of time. The heats of reaction (ΔH_p) used were 13.1 kcal/mol for the methacrylate double bond and 20.6 kcal/mol for the acrylate double bond.

AHM-TMEDA QAC, AHM-PYR QAC, ACRY-IDPA QAC and METH-PYR/1 QAC and METH-PYR/2 QAC, METH-PYR/3 QAC were photopolymerized by using Irgacure 2959 and with the same procedure as described above.

3.1.5.3. General Homopolymerization of Amine and Quaternary Ammonium Monomers.

Irgacure 2959 (0.0184 g, 4 mol per cent) as a water-soluble photoinitiator was first dissolved in water (4 ml) in order to prepare the initiator solution.

AHM derivatives and quaternary ammonium monomers were homopolymerized in 96-well plate by using a UV lamp. Amine monomers AHM-DMAPA (0.0106 g), AHM-TMEDA (0.0105 g), AHM-IDPA (0.0146 g), AHM-PYR (0.0167 g) and quaternary ammonium monomers AHM-TMEDA QAC (0.0122 g), AHM-PYR QAC (0.0138 g), ACRY-IDPA QAC (0.0143 g), METH-PYR/1 QAC (0.0038 g), METH-PYR/2 QAC (0.0071 g), METH-PYR/3 QAC (0.0156 g) were weighed in the Eppendorf tubes. Then the specific amounts of the photoinitiator solution were added in the tubes. After adding the solutions, all these solutions in the Eppendorf tubes were transferred into the 96-well plate that was used in antibacterial tests. Then, all monomers were homopolymerized by light for 10 hours. After photopolymerization, the polymers were washed three times with methanol to remove unreacted monomers.

3.1.5.4. General Copolymerization of Monomers with HEMA. Irgacure 2959 (0.0092 g, 2 mol per cent) as a water-soluble photoinitiator was first dissolved in water (2 ml) in order to prepare the initiator solution.

AHM derivatives and quaternary ammonium monomers were copolymerized with HEMA (20:80) in 96-well plate by using light lamp. AHM-DMAPA (0.050 g, 1.58×10^{-4} mol), AHM-TMEDA (0.050 g, 1.58×10^{-4} mol), AHM-IDPA (0.050 g, 1.58×10^{-4} mol), AHM-PYR (0.01 g, 3.16×10^{-5} mol) monomers and AHM-TMEDA QAC (0.0050 g, 1.58×10^{-5} mol), AHM-PYR QAC (0.01 g, 3.16×10^{-5} mol), ACRY-IDPA QAC (0.0054 g, 1.58×10^{-5} mol), METH-PYR/1 QAC (0.0050 g, 1.58×10^{-5} mol), METH-PYR/2 QAC (0.010 g, 3.16×10^{-5} mol), METH-PYR/3 QAC (0.010 g, 3.16×10^{-5} mol) were weighed in the Eppendorf tubes. Then, 2-hydroxyethylmethacrylate (HEMA) (0.0054 g, 4.15×10^{-5} mol) was weighed into the monomers. The specific amounts of the photoinitiator solution were also added in the tubes. Methanol was added as a solvent to some of the solutions make them homogeneous.

All the solutions prepared in the Eppendorf tubes were transferred into the 96-well plate that was used in antibacterial tests. Then, all monomers were photopolymerized by a UV light for 10 hours. After photopolymerization, the polymers were washed three times with methanol to remove unreacted monomers.

3.1.6. Measurements of Antibacterial Activities of The Monomers and Polymers

Triptic soy agar (TSA) and triptic soy broth (TSB) were used in the antibacterial activity tests. TSA contained 15.0 g pancreatic digest of casein, 5.0 g enzymatic digest of soybean meal, 5.0 g sodium chloride, and 15.0 g agar. (TSB) contained 17.0 g pancreatic digest of casein, 3.0 g enzymatic digest of soybean meal, 2.5 g dextrose, 5.0 g sodium chloride, and 2.5 g dipotassium phosphate.

The screening of the monomers and polymers for antibacterial activity was done using *S. aureus* and *E. coli* as test organisms because they represent gram-positive and gram-negative bacteria, respectively. *S. aureus* and *E. coli* were streaked out on TSA (triptic soy agar) plates and incubated at 37°C for 24 h. A representative colony was

lifted off with a wire loop and placed in a 5 ml of TSB, which was then incubated with shaking at 37 °C for 24 h in an orbital incubator shaker. At this stage, the cultures of *S. aureus* and *E. coli* contained approximately 10^9 colony forming units (CFU) per mL. Cultures of *S. aureus* and *E. coli* containing 10^7 CFU/mL were prepared by dilution with TSB, which were used for antibacterial tests. In order to prepare cultures of *S. aureus* and *E. coli* containing 10^7 CFU/mL, 50 µl from the stock solution and 500 µl from TSB were mixed in two different falcon tubes per different kind of bacteria.

The minimum inhibitory concentration (MIC) values of the new QACs were determined by the broth dilution method using geometric twofold dilutions in TSB [79]. 2 µg sample was added into 200 µL TSB in order to prepare 512 µg/mL solution. The 96-well plate had 12 colon for antibacterial test.

100 µL TSB was added into the first colon and 100 µL TSB and 10 µL bacteria was also added to the second colon of the 96-well plate. In the third and fourth colon, 100 µL sample (from 512 µg/mL solution), 10 µL bacteria and 50 µL sample (from 512 µg/mL solution), 50 µL TSB and 10 µL bacteria were added respectively. 50 µL sample (from 512 µg/mL solution), 50 µL TSB and 10 µL bacteria was also added to the fifth colon and 50 µL mixture was taken from the fifth colon and transferred to the sixth colon. Thus, the concentrations of the third, fourth, fifth and sixth were 512, 256, 128 and 64 µg/mL. The geometric twofold dilutions in TSB was applied to the next six colon and the concentration of the 12th (the last) colon was 1 µg/mL.

The polymer concentrations ranged from 1 mg/mL to 3.9 µg/mL. Each solution in the series was mixed with 10^5 CFU of the test organism in a 96-well microtiter plate. The 96-well plate was incubated at 37°C for 24 h. The MIC test was repeated at least two times for each antibacterial agent.

3.2. Synthesis and Photopolymerization of New Crosslinkers

3.2.1. Materials

Chemicals used in this study were as follows:

Paraformaldehyde, t-butyl acrylate, 1,4-Diazobicyclo [2.2.2] octan (DABCO), dimethyl sulfoxide, CuCl_2 , CaCl_2 , succinyl chloride, N,N-dimethylaminopyridine (DMAP), NaHCO_3 , NaCl , trifluoroacetic acid (TFA), dodecanedioyl dichloride, adipoyl chloride, PBr_3 , Bisphenol A, triethylamine (TEA), triethyleneglycol, triethyleneglycol dimethacrylate, 2,2-Dimethoxy-2-phenylacetophenone (Irgacure 651), trimethylolpropane and 2-hydroxyethylmethacrylate (HEMA) were all obtained from Aldrich Chemical Co. and used as received. The solvents; tetrahydrofuran (THF), CH_2Cl_2 , ethyl acetate, ether, methanol, petroleum ether, CHCl_3 , HCl and hexane were all obtained from Merck and used as received.

3.2.2. Apparatus

^1H -NMR and ^{13}C -NMR spectra were recorded using a Varian Gemini 400 MHz spectrometer. IR analysis was performed on FT-IR Perkin Elmer using NaCl windows.

Photopolymerizations were performed in a TA Instruments (Q 100) differential photocalorimetry accessory containing a high-pressure mercury lamp.

3.2.3. Synthesis of Tert-Butyl α -Hydroxymethyl Acrylate (TBHMA)

Tert-Butyl Acrylate (128.1 g, 1 mol), paraformaldehyde (30 g, 1 mol), 1,4-Diazobicyclo [2.2.2] octan (DABCO) (14 g, 0.125 mol), dimethyl sulfoxide (227 ml) and H_2O (85 ml) were added into a 1000 ml round-bottom flask which was then fitted with a condensor and placed in a preheated oil bath at 70°C . After the solution was heated under nitrogen at $98\text{--}100^\circ\text{C}$ for 30 minutes it was cooled and the aqueous phase was separated. The organic phase was washed with one weight per cent HCl (2x100 ml) and dried with anhydrous CaCl_2 . After evaporation of excess tert-butyl acrylate, the solution was vacuum distilled in the presence of a free-radical inhibitor, CuCl_2 , and pure TBHMA was collected at 75°C head temperature in 30-40 per cent yield.

^{13}C -NMR (CDCl_3); δ = 27.5 (CH_3), 60.87 ($\text{CH}_2\text{-O}$), 80.48 [$\text{C-(CH}_3)_3$], 123.23 (C=CH_2), 140.85 ($\text{CH}_2\text{=C}$), 165.06 (C=O) ppm.

$^1\text{H-NMR}$ (CDCl_3): δ = 1.4 (s, 9H, CH_3), 3.9 (s, 2H, OCH_2), 4.13 (s, 1H, OH), 5.61 (s, 1H, $\text{CH}=\text{C}$), 5.95 (s, 1H, $\text{CH}=\text{C}$) ppm.

IR (NaCl) : 1159-1054 (C-O), 1457-1369 [$\text{C}-(\text{CH}_3)_3$], 1639 (C=C), 1709 (C=O), 2978-2934 (C-H), 3419 (O-H) cm^{-1} .

3.2.4. Synthesis of Tert-Butyl α -Bromomethyl Acrylate (TBBBr)

TBHMA (19.1 g, 0.1213 mol) and ether (115.6 ml) were placed in a round-bottom flask. PBr_3 (5.3 ml) was added dropwise to the solution in an ice bath. Nitrogen gas was purged to remove HBr gas evolved. After complete addition, the solution was allowed to warm to room temperature and stirred for three hours. Then 69 ml of water was added slowly to the flask in an ice bath and the aqueous phase was separated and extracted with hexane (3x23 ml). The organic phases were combined and extracted with saturated NaCl solution (4x25 ml), dried with anhydrous CaCl_2 and filtered. After removal of ether by rotary evaporator, vacuum distillation of the product in the presence of CuCl_2 gave TBBBr as a colorless liquid in 80-90 per cent yield.

$^{13}\text{C-NMR}$ (CDCl_3); δ = 27.88 (CH_3), 29.68 ($\text{CH}_2\text{-Br}$), 81.54 [$\text{C}-(\text{CH}_3)_3$], 127.82 ($\text{C}=\text{CH}_2$), 138.81 ($\text{CH}_2=\text{C}$), 164.06 (C=O) ppm.

$^1\text{H-NMR}$ (CDCl_3): δ = 0.7 (s, 9H, CH_3), 3.9 (s, 2H, CH_2Br), 5.0 (d, 1H, $\text{CH}=\text{C}$), 5.3 (d, 1H, $\text{CH}=\text{C}$) ppm.

IR (NaCl) : 720 (C-Br), 1226-1158 (C-O), 1394-1368 (C-H), 1718 (C=O), 2978-2934 (C-H) cm^{-1} .

3.2.5. Synthesis of Crosslinkers

3.2.5.1. Synthesis of TBHMA-Succinyl ester-diacid Derivative. To a mixture of TBHMA (4.4 g, 0.028 mol) and DMAP (0.0148 g) in THF (28 ml) in an ice bath, succinyl chloride (1.94 g, 0.01252 mol) was added dropwise under nitrogen, and the solution was stirred at 60 $^\circ\text{C}$ for 24 hours. After evaporation of THF, water was added and the solution was

neutralized with 5 per cent NaHCO_3 solution. The solution was extracted with CH_2Cl_2 and the organic phase was separated. Then the organic phase was extracted with saturated NaCl solution, dried with anhydrous CaCl_2 and filtered. Evaporation of methylene chloride gave the intermediate ester as a colorless liquid in 41.5 percent (2.31 g) yield.

To this intermediate ester monomer (1.85 g, 0.0046 mol), trifluoroacetic acid (TFA) (1 ml) was added dropwise in an ice bath under nitrogen. The solution was stirred at room temperature for 24 hours. The excess acid was removed under vacuum and the remaining solid was purified by recrystallization from methanol to give a white solid with a melting point of 169-170 $^\circ\text{C}$ in 15.6 per cent (0.29 g) yield.

^{13}C -NMR (CDCl_3): δ = 29.7 ($\text{CH}_2\text{-CO}$), 63.6 ($\text{CH}_2\text{-O}$), 127.4 ($\text{CH}_2\text{=C}$), 136.9 (C=CH_2), 167.8 (C=O), 172.9 (C=O acid) ppm.

^1H -NMR (CDCl_3): δ = 2.7 (CH_2)₂, 4.8 ($\text{CH}_2\text{-O}$), 5.9 ($\text{CH}_2\text{=C}$), 6.2 (C=CH_2) ppm.

IR (NaCl): 1162 (C-O), 1641 (C=C), 1665 (C=O acid), 1726 (C=O ester), 2930 (C-H), 3403 (OH) cm^{-1} .

3.2.5.2. Synthesis of TBHMA-Adipoyl ester-diacid Derivative. To a mixture of TBHMA (2.2 g, 0.014 mol) and DMAP (0.0074 g) in THF (14 ml) in an ice bath, adipoyl chloride (1.14 g, 0.00626 mol) was added dropwise under nitrogen, and the solution was stirred at 60 $^\circ\text{C}$ for 24 hours. After evaporation of THF, water was added and the solution was neutralized with 5 per cent NaHCO_3 solution. The solution was extracted with CH_2Cl_2 and the organic phase was separated. Then the organic phase was extracted with saturated NaCl solution, dried with anhydrous CaCl_2 and filtered. Evaporation of methylene chloride gave the intermediate ester as a colorless liquid in 89.2 percent (2.66 g) yield.

To the intermediate monomer (2.66 g, 0.0062 mol), trifluoroacetic acid (TFA) (1.3 ml) was added dropwise in an ice bath under nitrogen. The solution was stirred at room temperature for 24 hours. The excess acid was removed under vacuum and the remaining solid was purified by recrystallization from methanol to give a white solid with a melting point of 143-145 $^\circ\text{C}$ in 9 per cent (0.24 g) yield.

^{13}C -NMR (CDCl_3); δ = 25.4 (CH_2), 34.5 ($\text{CH}_2\text{-C=O}$), 63.6 (CH_2O), 127.7 ($\text{CH}_2\text{=C}$), 137.3 (C=CH_2), 168.1 (C=O), 174.1 (C=O acid) ppm.

^1H -NMR (CDCl_3); δ = 1.5 ($\text{CH}_2\text{=CO}$), 2.3 (CH_2)₂, 2.7 (CH_2)₂, 4.6 ($\text{CH}_2\text{-O}$), 5.7 ($\text{CH}_2\text{=C}$), 6.2 (C=CH_2) ppm.

IR (NaCl): 1153 (C-O), 1630 (C=C), 1670 (C=O acid), 1728 (C=O ester), 2923 (C-H), 3420 (OH) cm^{-1} .

3.2.5.3. Synthesis of TBHMA-Dodecanedioyl ester-diacid Derivative. To a mixture of TBHMA (4.4 g, 0.028 mol) and DMAP (0.0148 g) in THF (28 ml) in an ice bath, dodecanedioyl dichloride (3.34 g, 0.01252 mol) was added dropwise under nitrogen, and the solution was stirred at 60 $^{\circ}\text{C}$ for 24 hours. After evaporation of THF, water was added and the solution was neutralized with 5 per cent NaHCO_3 solution. The solution was extracted with CH_2Cl_2 and the organic phase was separated. Then the organic phase was extracted with saturated NaCl solution, dried with anhydrous CaCl_2 and filtered. Evaporation of methylene chloride gave the intermediate ester as a colorless liquid in 58.8 percent (4.2 g) yield.

To the intermediate monomer (2 g, 0.0039 mol), trifluoroacetic acid (TFA) (0.85 ml) was added dropwise in an ice bath under nitrogen. The solution was stirred at room temperature for 24 hours. The excess acid was removed under vacuum and the remaining solid was purified by recrystallization from methanol to give a white solid with a melting point of 114-115 $^{\circ}\text{C}$ in 15 per cent (0.33 g) yield.

^{13}C -NMR (CDCl_3); δ = 23.7 (CH_2), 27.6 (CH_2), 32.6 ($\text{CH}_2\text{-C=O}$), 61.1 (CH_2O), 125.5 ($\text{CH}_2\text{=C}$), 135.2 (C=CH_2), 165.2 (C=O), 171.3 (C=O acid) ppm.

^1H -NMR (CDCl_3); δ = 1.3 (CH_2)₈, 2.3 ($\text{CH}_2\text{=CO}$), 4.7 ($\text{CH}_2\text{-O}$), 5.8 ($\text{CH}_2\text{=C}$), 6.2 (C=CH_2) ppm.

IR (NaCl): 1166 (C-O), 1635 (C=C), 1672 (C=O acid), 1725 (C=O ester), 2911 (C-H), 3419 (OH) cm^{-1} .

3.2.5.4. Synthesis of TBBBr-Bisphenol A diacid Derivative. To a mixture of Bisphenol A (3.2 g, 0.01405 mol) and TEA (5.4 g, 0.05339 mol) in THF (15 ml) in an ice bath, TBBBr (6.2 g, 0.028 mol) was added dropwise under nitrogen. After 24 hours of stirring at 60 °C, THF was evaporated. The residue was diluted with 25 ml of methylene chloride and the solution was extracted with water (3x12 ml). After drying of solution with anhydrous CaCl_2 and evaporation of the solvent, the intermediate ether was obtained as a colorless liquid in 56.3 percent (4.0 g) yield.

To the intermediate monomer (4.0 g, 0.0079 mol), trifluoroacetic acid (TFA) (1 ml) was added dropwise in an ice bath under nitrogen. The solution was stirred at room temperature for 24 hours. The excess acid was removed under vacuum and the remaining solid was purified by recrystallization from methanol to give a white solid with a melting point of 189.1 °C in 56.7 per cent (2.26 g) yield.

^{13}C -NMR (CDCl_3); δ = 30.8 (C-CH_3)₂, 41.3 (C-CH_3), 65.9 ($\text{CH}_2\text{-O}$), 113.9 (CH-CH), 126.0 (C=CH_2), 127.3 (CH-C), 136.8 (C-C), 142.7 (C=CH_2), 155.6 (C-O), 166.3 (C=O) ppm.

^1H -NMR (CDCl_3); δ = 1.6 (C-CH_3)₂, 4.6 ($\text{CH}_2\text{-O}$), 5.9 ($\text{CH}_2\text{=C}$), 6.2 (C=CH_2), 6.8 (CH-CH), 7.1 (CH-C) ppm.

IR (NaCl) : 1171 (C-O), 1648 (C=C), 1725 (C=O), 2933 (C-H), 3380 (OH) cm^{-1} .

3.2.5.5. Synthesis of TBBBr-Triethyleneglycol diacid Derivative. To a mixture of triethyleneglycol (1.5 g, 0.75 mol) and TEA (3.8 g, 1.92 mol) in THF (10 ml) in an ice bath, TBBBr (4.42 g, 0.02 mol) was added dropwise under nitrogen. After 24 hours of stirring at 60 °C, THF was evaporated. The residue was diluted with 25 ml of methylene chloride and the solution was extracted with water (3x15 ml). After drying of solution with anhydrous CaCl_2 and, evaporation of the solvent, the intermediate ether was obtained as a yellow liquid in 18.6 per cent (0.8 g) yield.

To the intermediate monomer (0.8 g, 0.0018 mol), trifluoroacetic acid (TFA) (2.15 ml) was added dropwise in an ice bath under nitrogen. The solution was stirred at room

temperature for 24 hours. The excess acid was removed under vacuum and the remaining solid was purified by recrystallization from methanol to give a viscous liquid.

^{13}C -NMR (CDCl_3): δ = 68.0-72.0 ($\text{CH}_2\text{-O}$), 125.0 ($\text{C}=\text{CH}_2$), 138.5 ($\text{C}=\text{CH}_2$), 166.0 ($\text{C}=\text{O}$) ppm.

^1H -NMR (CDCl_3): δ = 3.5 ($\text{CH}_2\text{-CH}_2\text{-O}$), 4.1 ($\text{CH}_2\text{-O}$), 5.8 ($\text{C}=\text{CH}_2$), 6.1 ($\text{C}=\text{CH}_2$) ppm.

3.2.6. Photopolymerizations

Photopolymerization of the monomers were carried out on a TA Instruments (Q 100) differential photocalorimetry accessory using 2,2-Dimethoxy-2-phenylacetophenone (Irgacure 651), as the primary photoinitiator system.

Irgacure 651 photoinitiator was first dissolved in methylene chloride and a specific amount of this solution was added to neat monomers. The monomers were mixed with HEMA with the mol ratio of 0.5:99.5. The mixture was then placed in a aluminum DSC pan and carefully weighed. Then initiator solution was added and the sample transferred to the sample holder in the photo-DSC. The samples were purged with nitrogen for 10 min to remove air and to allow for complete solvent evaporation prior to the polymerization. Samples were irradiated for 10 min at 40 $^{\circ}\text{C}$ and 60 $^{\circ}\text{C}$ under nitrogen purge and the heat flux as a function of reaction time was monitored using DSC under isothermal conditions, and both the rate of polymerization and conversion were then calculated as a function of time.

The rate formula used in evaluation of the photopolymerization data was:

$$R_p = \frac{(Q/s)M}{n\Delta H_p m}$$

Where Q/s is heat flow per second during reaction, M is the molar mass of the monomer, n is the number of double bonds per monomer molecule, (ΔH_p) is the heat released per mole of double bonds reacted and m is the mass of monomer in the sample.

The total exotherm was taken as the area under the exotherm curve, with the baseline extrapolated back from the end of the exotherm to the initial rise after the lamp was turned on. Conversion-time plots were calculated with a theoretical heat evolved for methacrylate bonds of $\Delta H_{\text{theor}} = 13.1$ kcal/mol. The rates of polymerizations were calculated from the initial slopes of the conversion-time plots.

All the synthesized ester and ether linked diacid monomers were copolymerized with HEMA using the procedure given above.

TBBr-Triethyleneglycol diacid that is the second ether derivative of TBBr was photopolymerized at 40 °C by the same procedure of other acid derivatives. Triethyleneglycoldimethacrylate that is a commercial monomer was also photopolymerized at the same conditions with the bulk TBBr-Triethyleneglycol diacid derivative in order to compare the reactivity of monomers with each other.

4. RESULTS AND DISCUSSION

4.1. Antibacterial Monomers and Polymers

New monomers and polymers with amine and quaternary ammonium groups on the side chain were synthesized. First series of monomers were the derivatives of AHM. Hydroxylated secondary and tertiary amine derivatives were prepared from reaction of AHM with various amines. The amine monomers were quaternized bromohexane to give quaternary ammonium monomers.

Second series of amine and quaternary ammonium monomers were based on acrylamide and methacrylamide derivatives. New acrylamide/methacrylamide monomers with tertiary amine groups were synthesized [80]. The monomers were quaternized with various alkyl halides. The reactivities of the synthesized monomers in photopolymerizations were determined. The antibacterial activities of the monomers and polymers were investigated against both gram-positive and gram-negative bacteria.

4.1.1. Synthesis of AHM Derivatives

AHM is a mixed acrylate/methacrylate crosslinker containing a hydroxyl group. The structure of this monomer allows us to functionalize AHM through the hydroxyl group or through the acrylate double bond.

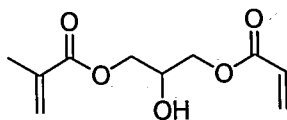


Figure 4.1. Structure of AHM

AHM is a mixture of two isomers in different ratios. These isomers are formed from 1,3 or 1,2 substitution reactions glycerol giving one isomer with primary hydroxyl group (unsymmetrical isomer) and the other with secondary hydroxyl group (symmetrical

isomer). ^{13}C -NMR spectrum of AHM (Figure 4.2) shows methyl carbon attached to double bond at 17.0 ppm, methylenes at 65.5 and 68.3 ppm, CH-OH peak at 72.25 ppm, acrylate double bonds at 128.0 and 131.83 ppm, methacrylate double bonds at 127.55 and 135.5 ppm, two different carbonyls at 165.5 and 167.0 ppm. The peaks at 61.04, 62.42 and 69.33 ppm in the AHM spectrum indicate the presence of a small amount of the 1,2-glycerol diester.

Mathias et al. synthesized a series of new hydroxylated monomers from the Michael addition reaction between ethanolamine, diethyleneglycolamine, triethyleneglycolamine, tetradecylamine, adamantaneamine, and 2-amino-2-(hydroxymethyl)-1,3-propanediol with AHM [81]. These monomers showed high polymerization rates due to preorganization via hydrogen bonding which brings the double bonds close to each other and enhances the rate of polymerization.

In this work, new hydroxylated amine monomers prepared according to the general synthetic route shown in the literature [81]. The synthesis of monomers were carried out via Michael addition of different amines to acrylate group of AHM. The amines chosen for this study were 3-dimethylaminopropyl amine, N,N,N'-trimethylethylenediamine, 3,3-iminobis (N,N-dimethylpropylamine) and 3-aminopyridine. Secondary and tertiary amine based monomers were selectively formed by using equimolar quantities of amine and AHM. The monomers were quaternized with various alkylhalides. The reactivities of the synthesized monomers in photopolymerizations were determined. The antibacterial activities of the monomers and polymers were investigated against both gram-positive and gram-negative bacteria.

4.1.1.1. Synthesis of AHM-(3-Dimethylamino)propylamine (AHM-DMAPA). AHM-DMAPA was synthesized by the reaction of AHM with (3-Dimethylamino)propylamine at room temperature for approximately 24 hours (Figure 4.3). This reaction was clean and giving high yield (90 per cent) of pure product as a clear viscous liquid. The monomer was soluble in water, chloroform and acetone and insoluble in hexane and ether.

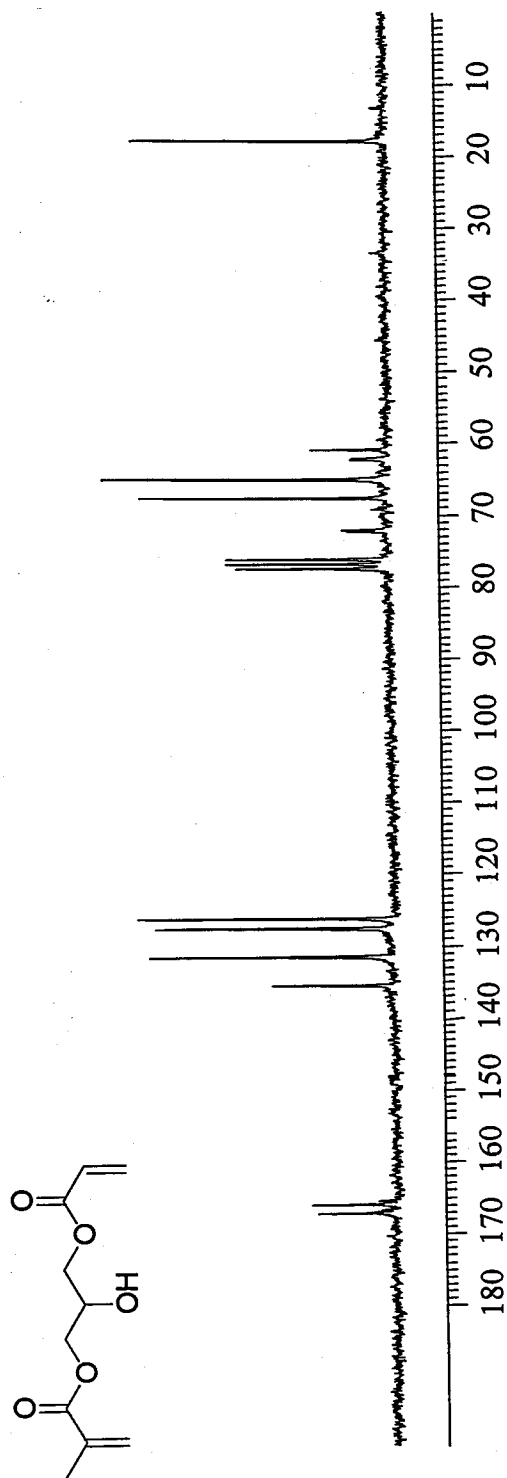


Figure 4.2. ^{13}C -NMR spectrum of AHM

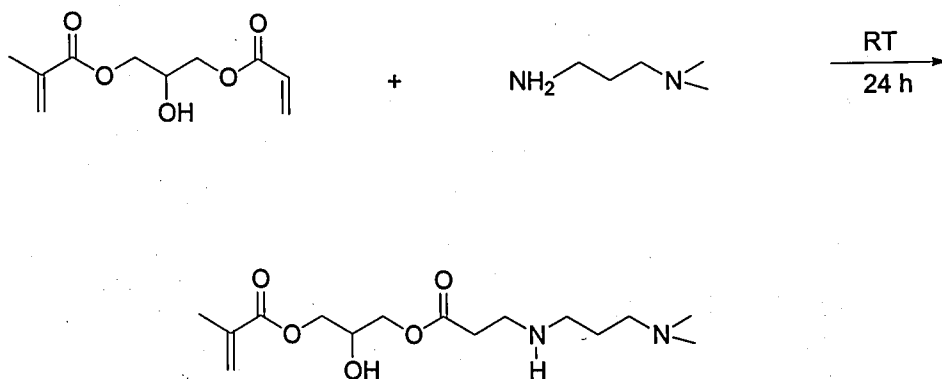


Figure 4.3. Synthesis of AHM-DMAPA monomer

The reaction was monitored using ^{13}C NMR and ^1H NMR spectroscopy (Figure 4.4). No peaks corresponding to acrylate double bonds were seen after the reaction. The methyl carbons attached to nitrogen atom at 45.3 ppm, methylene carbons attached to NH at 57.7 and 47.9 ppm, double bond carbon peaks at 135.7 and 126.0 ppm, and two carbonyl carbon peaks at 172.4 and 167.1 ppm were observed.

^1H NMR (Figure 4.5) spectrum shows methyl protons attached to double bond and nitrogen atom at 1.9 and 2.2 ppm, other methylenes at 2.5-3.5 ppm, methylenes of ester groups at 4.0 ppm. The peaks at 5.56 ppm and 6.12 ppm correspond to double bond protons.

The IR spectrum of the derivative (Figure 4.6) shows C-O vibrations at 1168 cm^{-1} and C-N stretchings between $1300\text{--}1180\text{ cm}^{-1}$ which confirms formation of the product. C=C stretching peak, the ester carbonyl and C-H vibrations appeared at 1637, 1722, 2946- 2819 cm^{-1} , respectively. The broad peak at around 3500 is due to OH and NH.

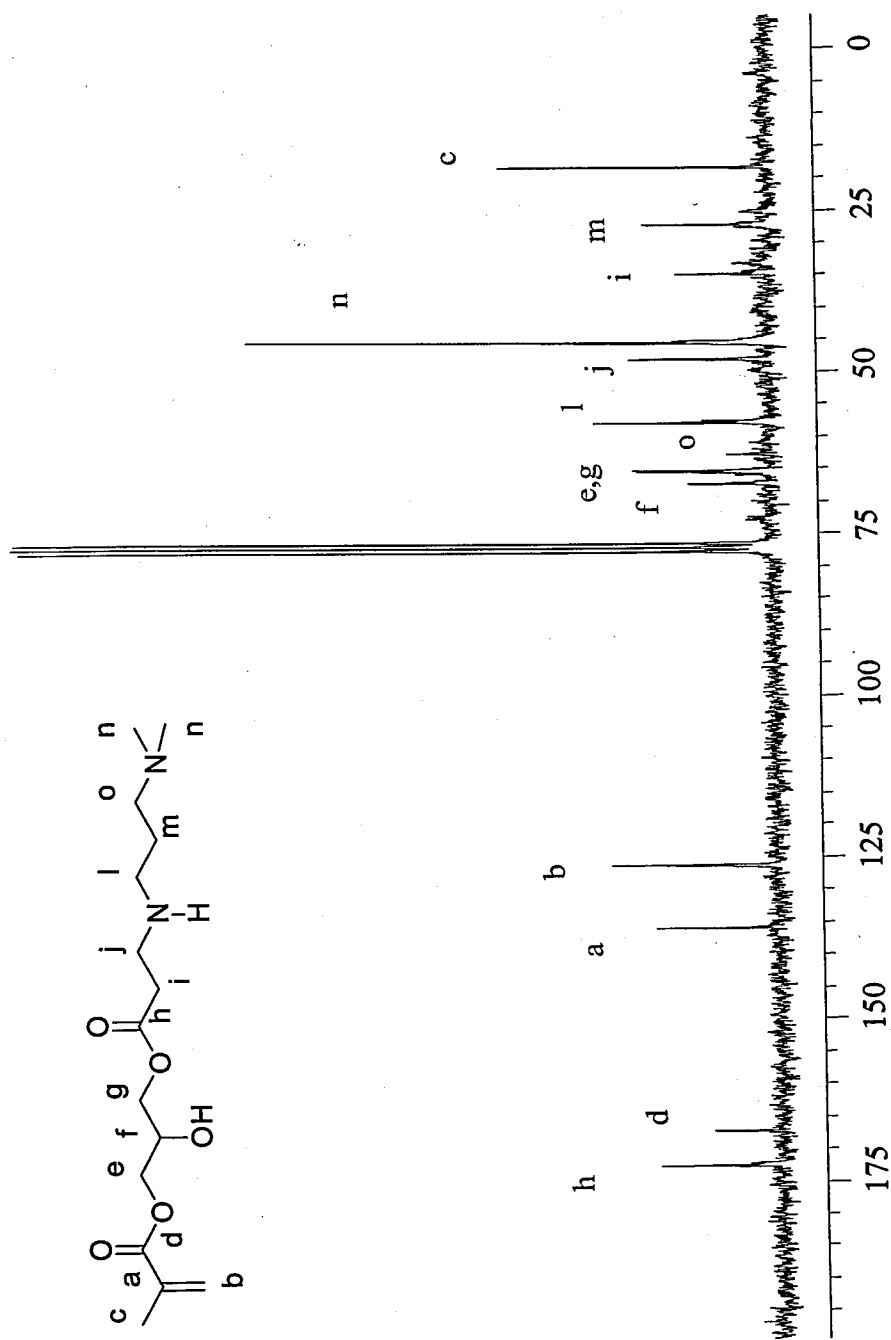


Figure 4.4. ^{13}C -NMR spectrum of AHM-DMAPA monomer

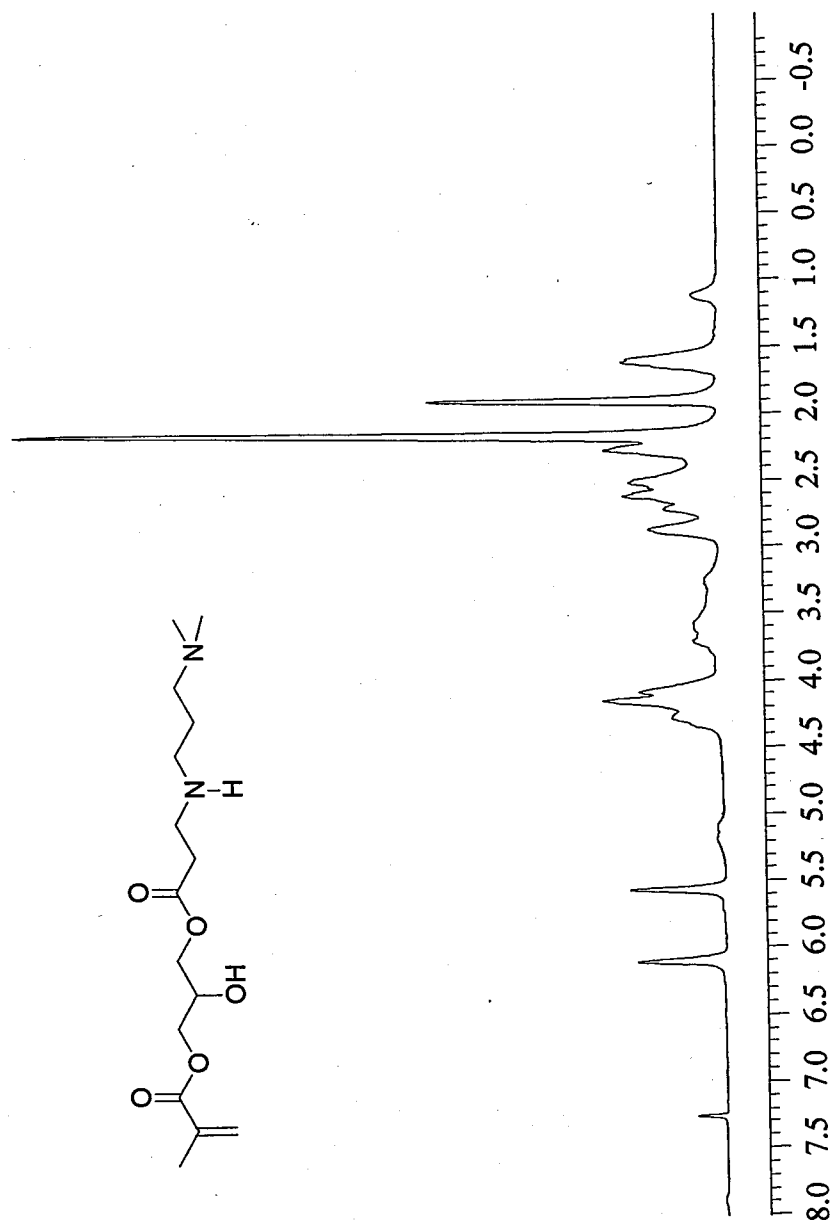


Figure 4.5. ¹H-NMR spectrum of AHM-DMAPA monomer

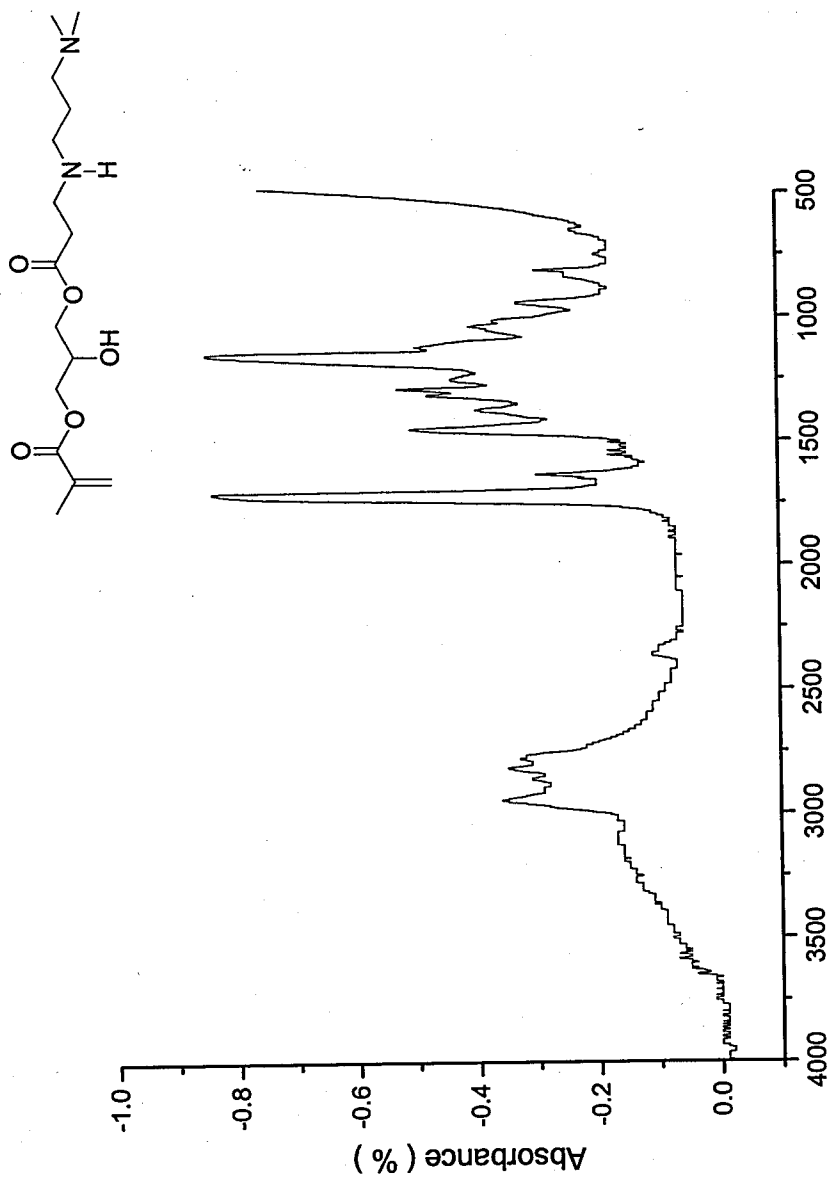


Figure 4.6. IR spectrum of AHM-DMPA monomer

4.1.1.2. Synthesis of AHM-N,N,N'-trimethylethylenediamine (AHM-TMEDA). AHM-TMEDA was synthesized by the reaction of AHM with N,N,N'-trimethylethylenediamine at room temperature using equimolar quantities of reactants for 24 h and without any solvent (Figure 4.7). This reaction was clean and giving high yield (94 per cent) of pure product as a clear viscous liquid. The monomer was soluble in water, acetone, chloroform and ether but insoluble in hexane.

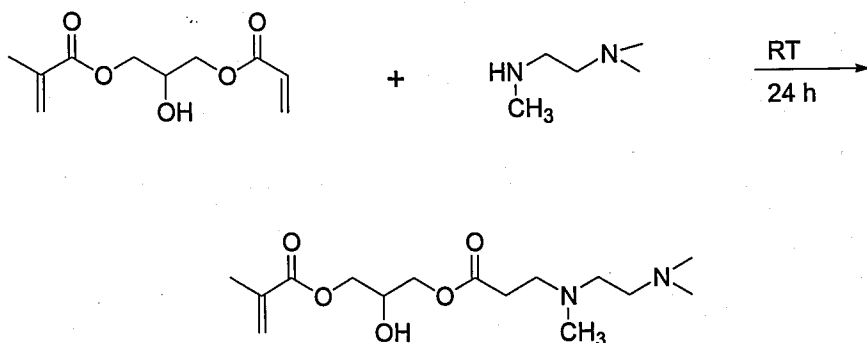


Figure 4.7. Synthesis of AHM-TMEDA

After the reaction the peaks corresponding to acrylate double bond in AHM at 128.0 and 131.83 ppm completely disappeared. New methylene carbon peaks at 32.6, 53.5 55.0 and 56.5 ppm, methyl carbons attached to N atom at 45.4 ppm and a new carbonyl peak at 172.2 ppm were observed (Figure 4.8) as a result of the Michael addition reaction.

^1H NMR (Figure 4.9) spectrum of this monomer is characterized by methyl hydrogens attached to double bond and nitrogen atoms at 1.9, 2.2 and 2.3 ppm, other methylene hydrogens overlapping at 2.5-3.5 ppm, methylenes of ester groups at around 4 ppm and double bond hydrogens at 5.49 ppm and 6.03 ppm.

The FT-IR spectrum of the derivative (Figure 4.10) shows C-N stretchings between $1300\text{-}1180\text{ cm}^{-1}$, confirming formation of the product.

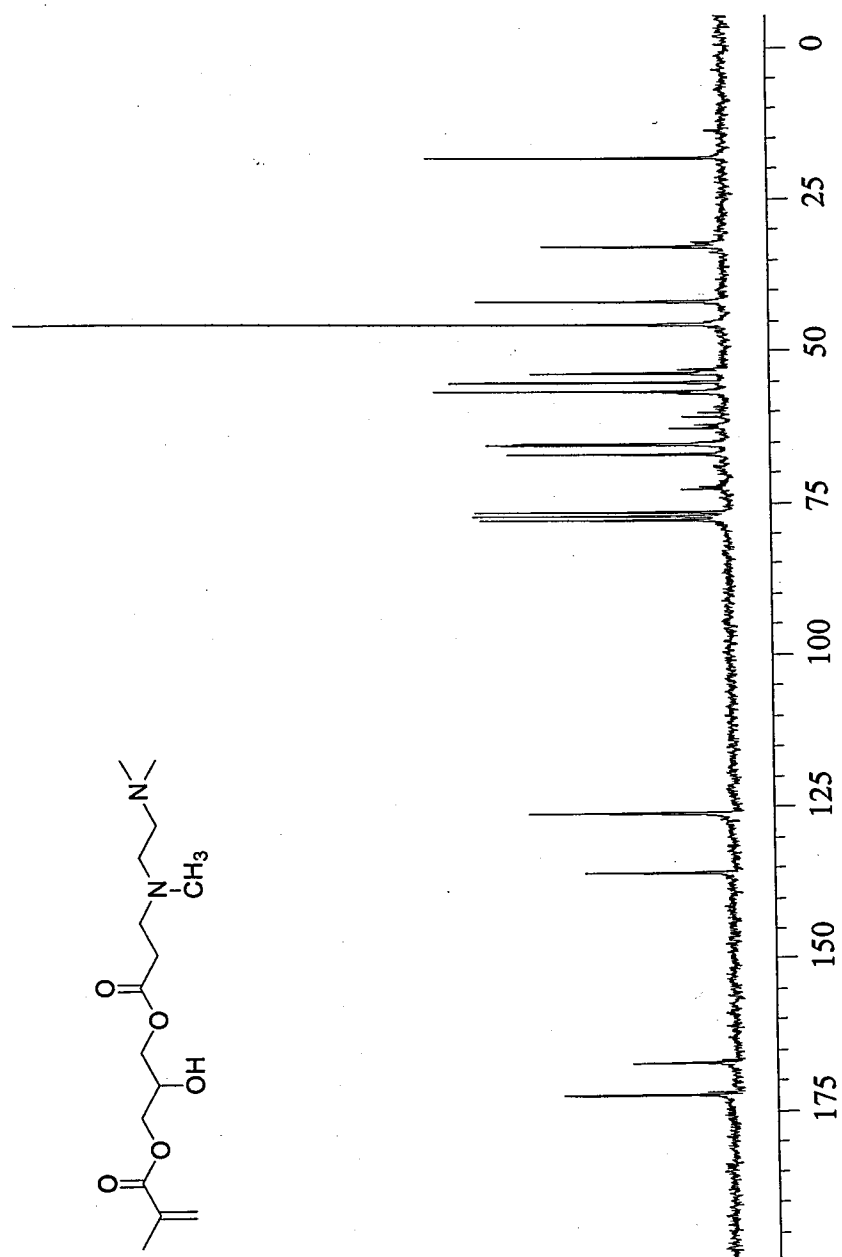


Figure 4.8. ^{13}C -NMR spectrum of AHM-TMEDA monomer

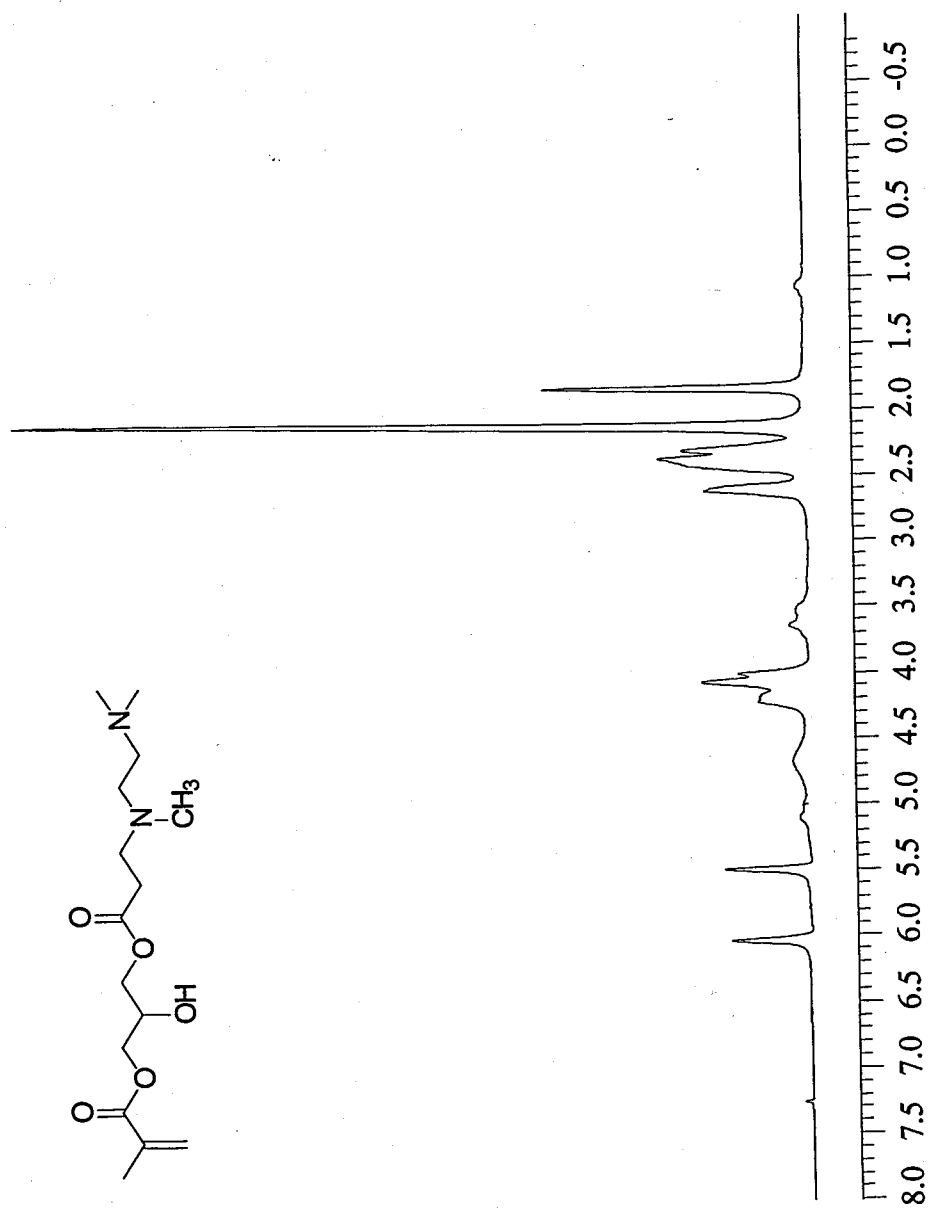
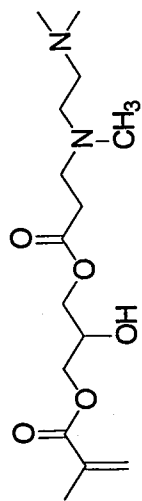


Figure 4.9. ^1H -NMR spectrum of AHM-TMEDA monomer

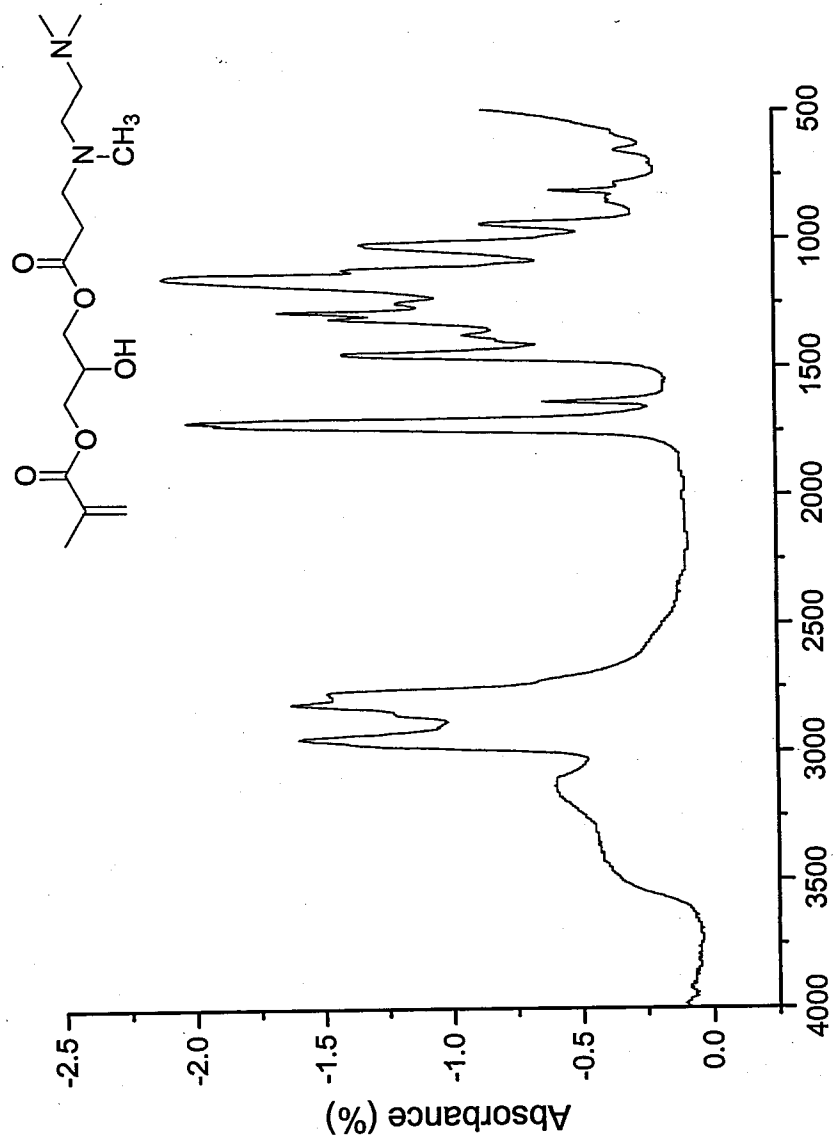


Figure 4.10. IR spectrum of AHM-TMEDA monomer

4.1.1.3. Synthesis of AHM-3,3-iminobis(N,N-dimethylpropylamine) (AHM-IDPA). The reaction of 3,3-iminobis(N,N-dimethylpropylamine) with AHM was carried out at room temperature for approximately 24 hours without using any solvent (Figure 4.11). The pure product appeared as a clear viscous liquid and was soluble in water, acetone, chloroform and ether but insoluble in hexane.

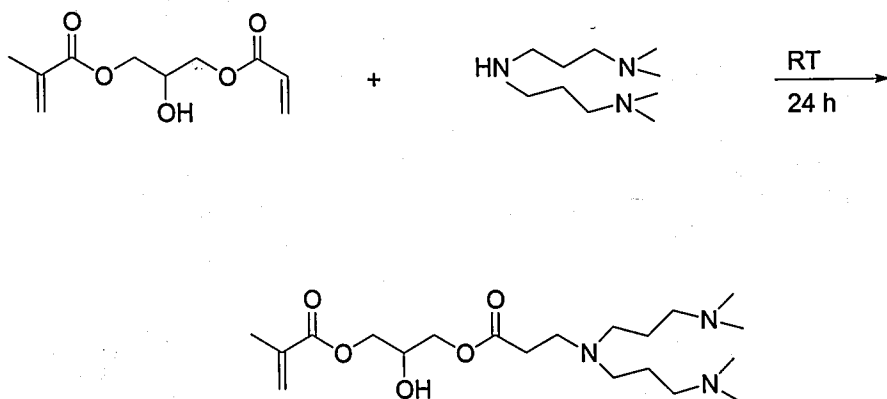


Figure 4.11. Synthesis of AHM-IDPA

Figure 4.12 shows the ^{13}C NMR spectrum of the monomer. The disappearance of acrylate group peaks evidences the formation of the Michael product. The methyl carbon attached to double bond at 18.1 ppm, the methyl carbons attached to nitrogen atoms at 45.1 ppm, methylene carbons attached to N atom 49.5 and 57.5 ppm, double bond carbon peaks at 135.7 and 125.7 ppm and two carbonyl carbon peaks at 172.3 and 166.9 ppm were observed.

^1H NMR (Figure 4.13) spectrum shows methyl protons attached to double bond and nitrogen atoms at 1.8 and 2.1 ppm, other methylene hydrogens attached to nitrogen atoms at 2.6 ppm, methylenes of ester groups at 4 ppm and double bond protons at 5.45 ppm and 5.99 ppm.

The IR spectrum of this monomer (Figure 4.14) shows the characteristic absorptions of C-O, C-N, C=C, C=O, C-H, OH and NH vibrations at 1164, 1300-1180, 1637, 1724, 2948-2813 and 3500 cm^{-1} .

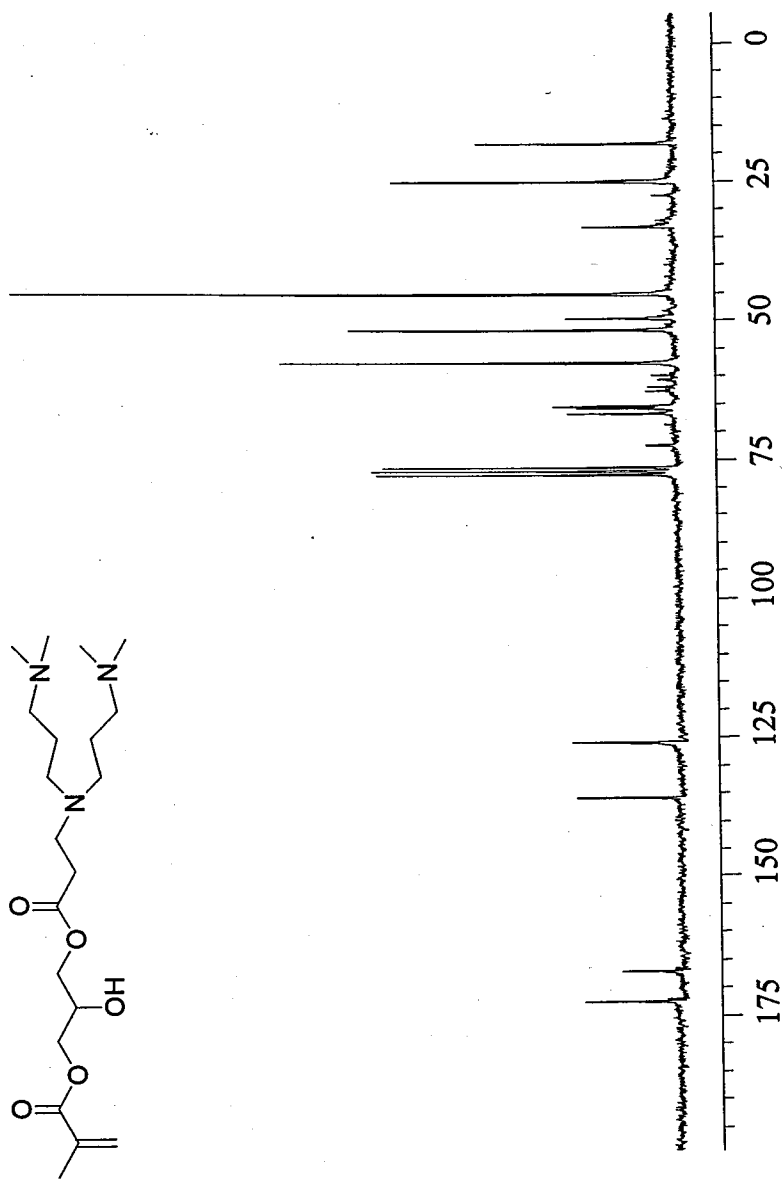


Figure 4.12. ^{13}C -NMR spectrum of AHM-IDPA monomer

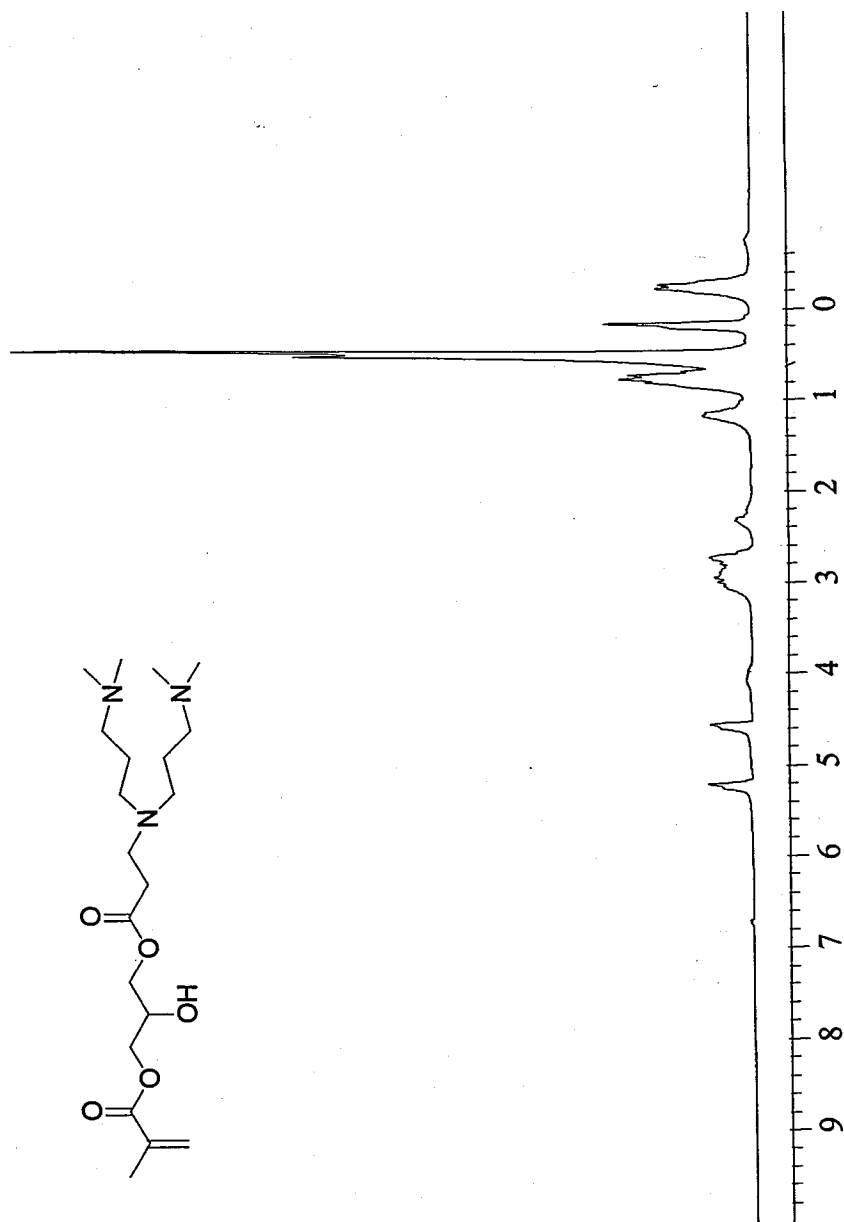


Figure 4.13. ¹H-NMR spectrum of AHM-IDPA monomer

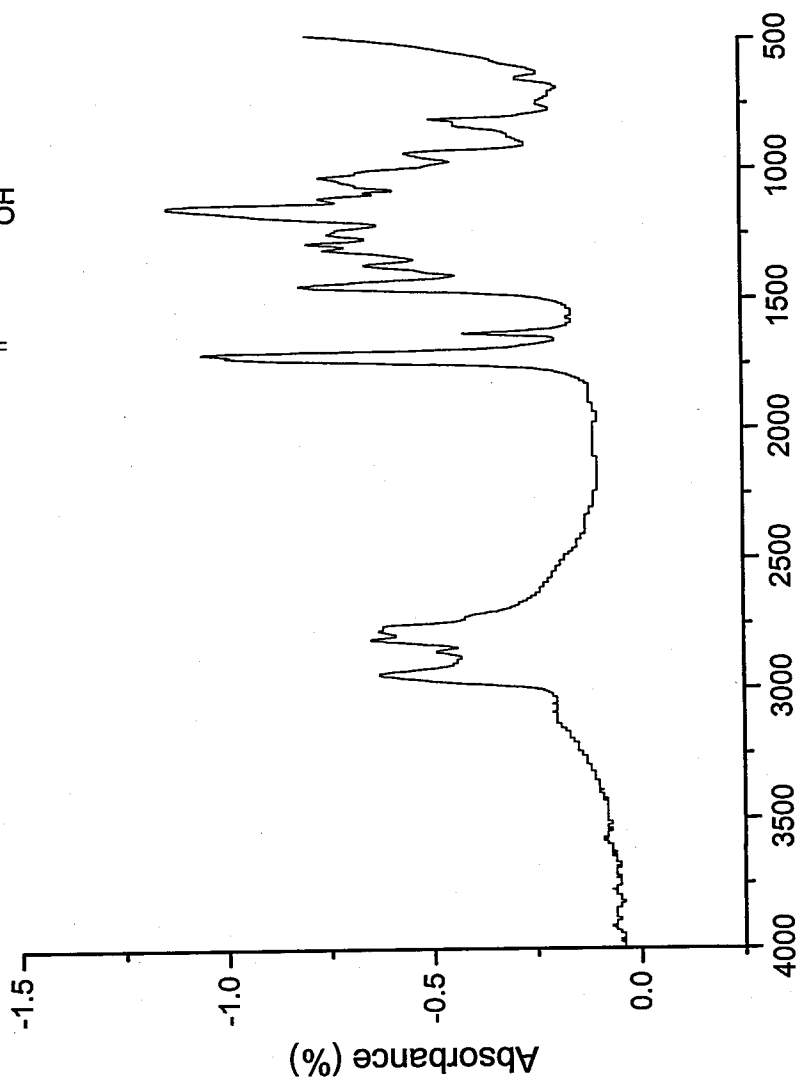
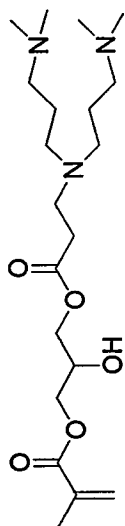


Figure 4.14. IR spectrum of AHM-IDPA monomer

4.1.1.4. Synthesis of AHM-[3-(Aminomethyl) pyridine] (AHM-PYR). A new monomer based on alcohol amine (AHM-PYR) was synthesized by the reaction of AHM with 3-(Aminomethyl) pyridine at room temperature without any solvent or catalyst (Figure 4.15). Selective formation of secondary amine product was obtained by controlling the stoichiometry of the reagents. This reaction was clean and giving high yield (90 per cent) of pure product as a clear viscous liquid. The monomer was soluble in toluene, acetone, benzene, chloroform but insoluble in water.

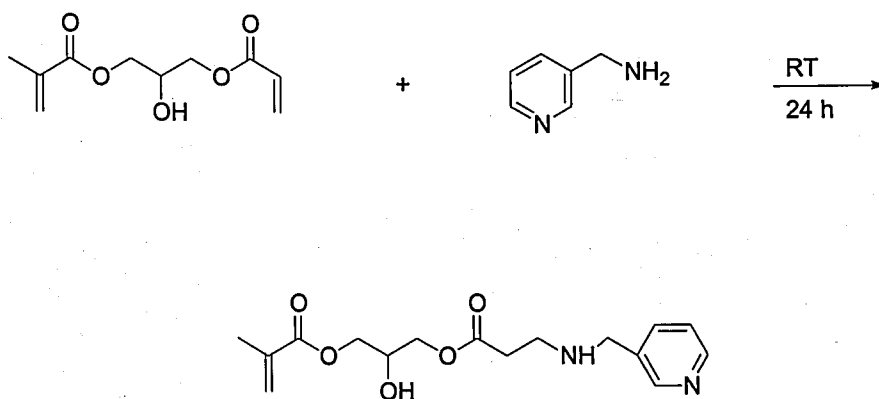


Figure 4.15. Synthesis of AHM-PYR

The completion of reaction was evidenced by the disappearance of the ^{13}C NMR (Figure 4.16) peaks for the acrylate groups and the appearance of new signals corresponding to the methylene carbons of the Michael adduct formed.

^1H NMR (Figure 4.17) spectrum shows methyl proton attached to double bond at 1.8 ppm. Methylene attached to carbonyl is observed at 2.4 ppm. Other methylenes attached to NH appeared at 2.7 and 3.7 ppm. Methylenes of ester groups appeared at around 4.1 ppm. The peaks at 5.45 ppm and 5.99 ppm correspond to double bond protons. The proton peaks due to pyridine ring also appeared at 7.1, 7.5, and 8.4 ppm.

The IR spectrum of the derivative (Figure 4.18) shows OH and NH stretchings at 3300 cm^{-1} , C-H vibrations at $2976\text{--}2857\text{ cm}^{-1}$, the ester carbonyl at 1785 cm^{-1} , C=C stretching peak at 1643 cm^{-1} , C-O vibrations at 1072 cm^{-1} , and C-N at 1214 cm^{-1} .

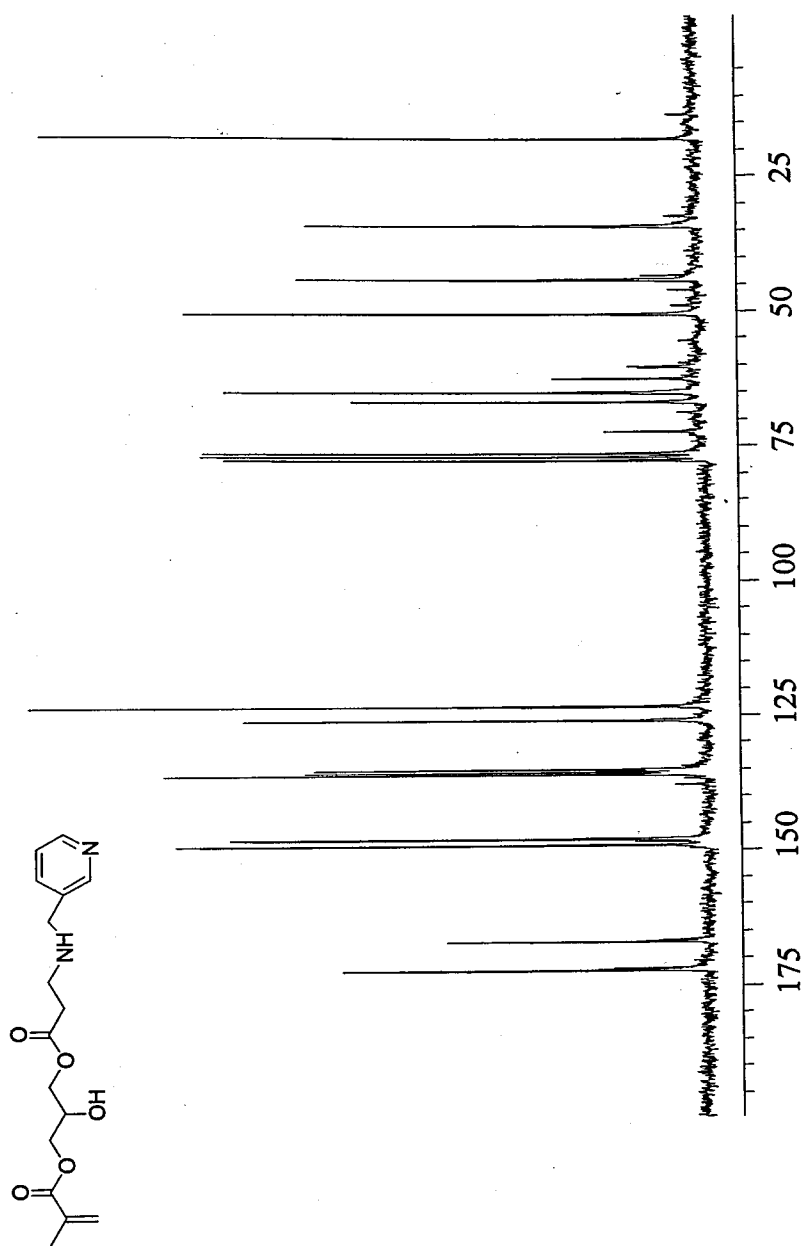


Figure 4.16. ^{13}C -NMR spectrum of AHM-PYR monomer

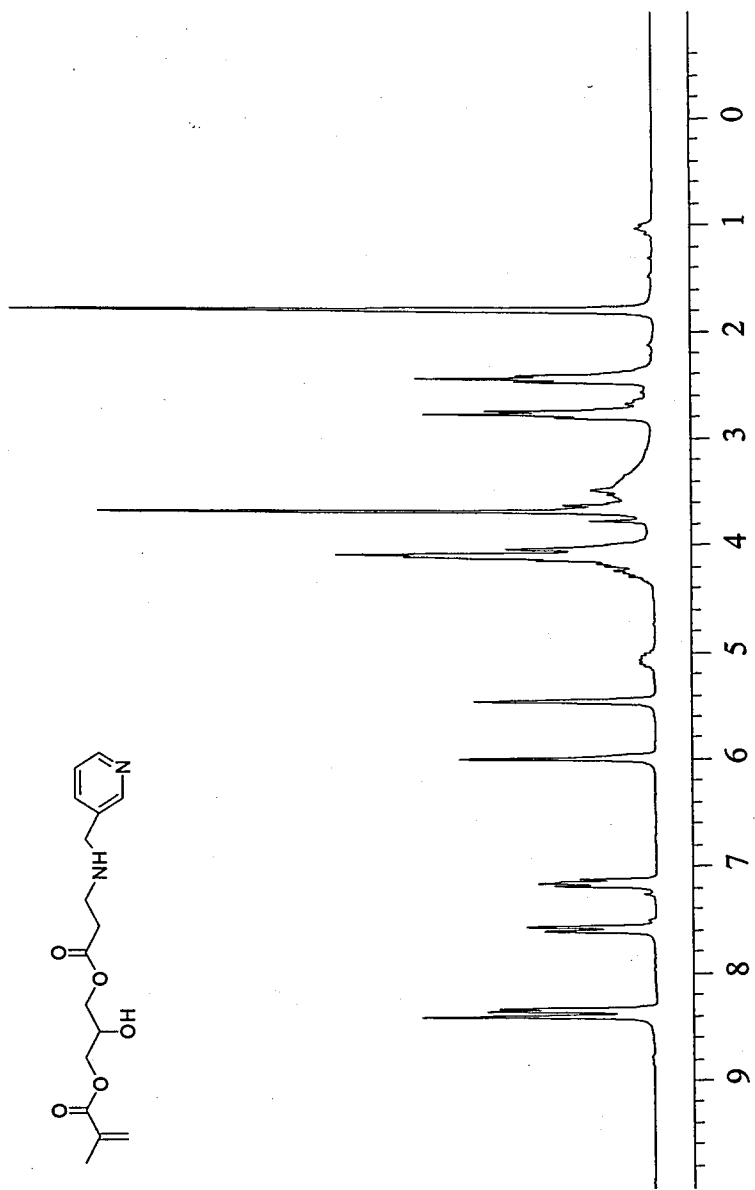


Figure 4.17. ¹H-NMR spectrum of AHM-PYR monomer

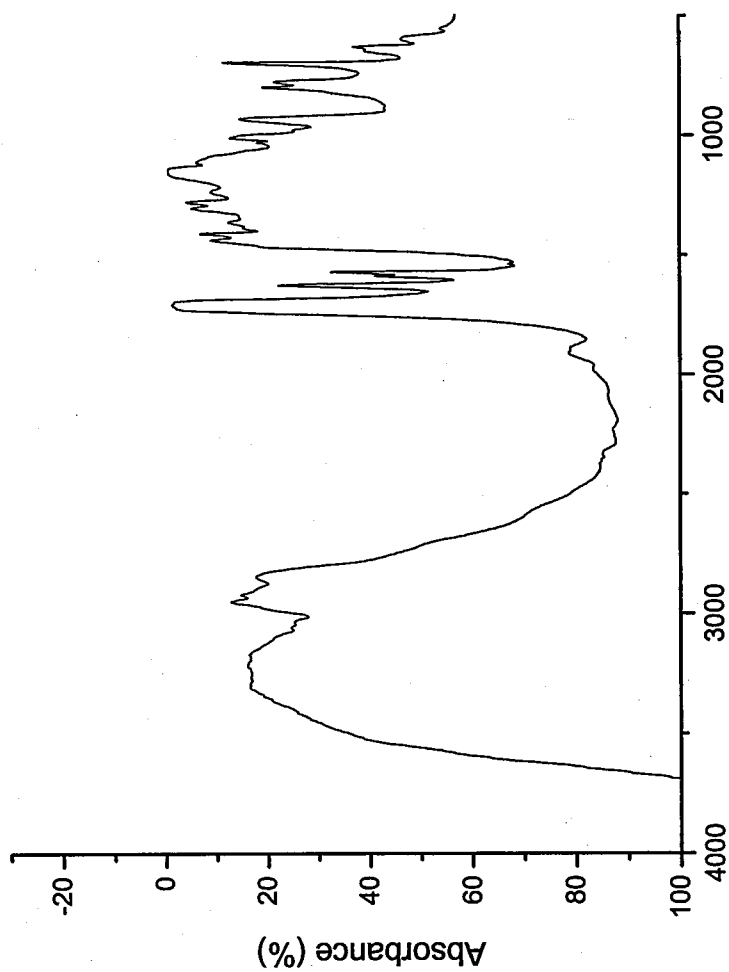
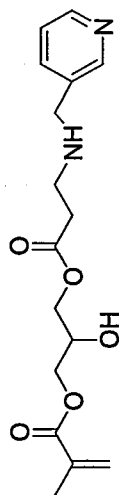


Figure 4.18. IR spectrum of AHM-PYR monomer

4.1.2. Synthesis of Acrylamide and Methacrylamide Derivatives

4.1.2.1. Synthesis of Acrylamide-3,3-iminobis(N,N-dimethylpropylamine) (ACRY-IDPA). A new acrylamide monomer was synthesized by the reaction of acryloyl chloride with 3,3-iminobis(N,N-dimethylpropylamine) in dry acetonitrile (Figure 4.19). The crude product was purified with column chromatography using methylene chloride and methanol (95:5) as eluent. The pure product was obtained as a yellow, viscous liquid in an 30 per cent yield. This monomer was soluble in water, hexane ether and chloroform.

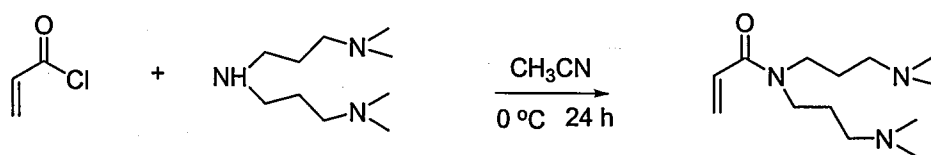


Figure 4.19. Synthesis of ACRY-IDPA

The ^{13}C -NMR spectrum shows (Figure 4.20) characteristic peaks for the methyl carbons attached to nitrogen atoms at 45.3 ppm, methylene carbons attached to N atom 56.9 and 44.7 ppm, double bond carbons at 127.6 and 127.7 ppm and carbonyl carbon at 166.1 ppm.

The IR spectrum of the derivative (Figure 4.21.) shows C-N stretchings at 1250 cm^{-1} , C=C peak at 1619 cm^{-1} , the carbonyl at 1785 cm^{-1} and C-H vibrations at $2952\text{--}2762\text{ cm}^{-1}$ which confirms formation of the product.

4.1.2.2. Synthesis of Methacrylamide-[3-(Aminomethyl) pyridine] (METH-PYR). A new methacrylamide monomer with pyridine moiety was synthesized by the reaction of methacryloyl chloride with 3-(Aminomethyl) pyridine using TEA as catalyst in methylene chloride (Figure 4.22). The crude product was purified with column chromatography using methylene chloride:methanol (95:5) as eluent. The pure product was obtained as a colorless liquid.

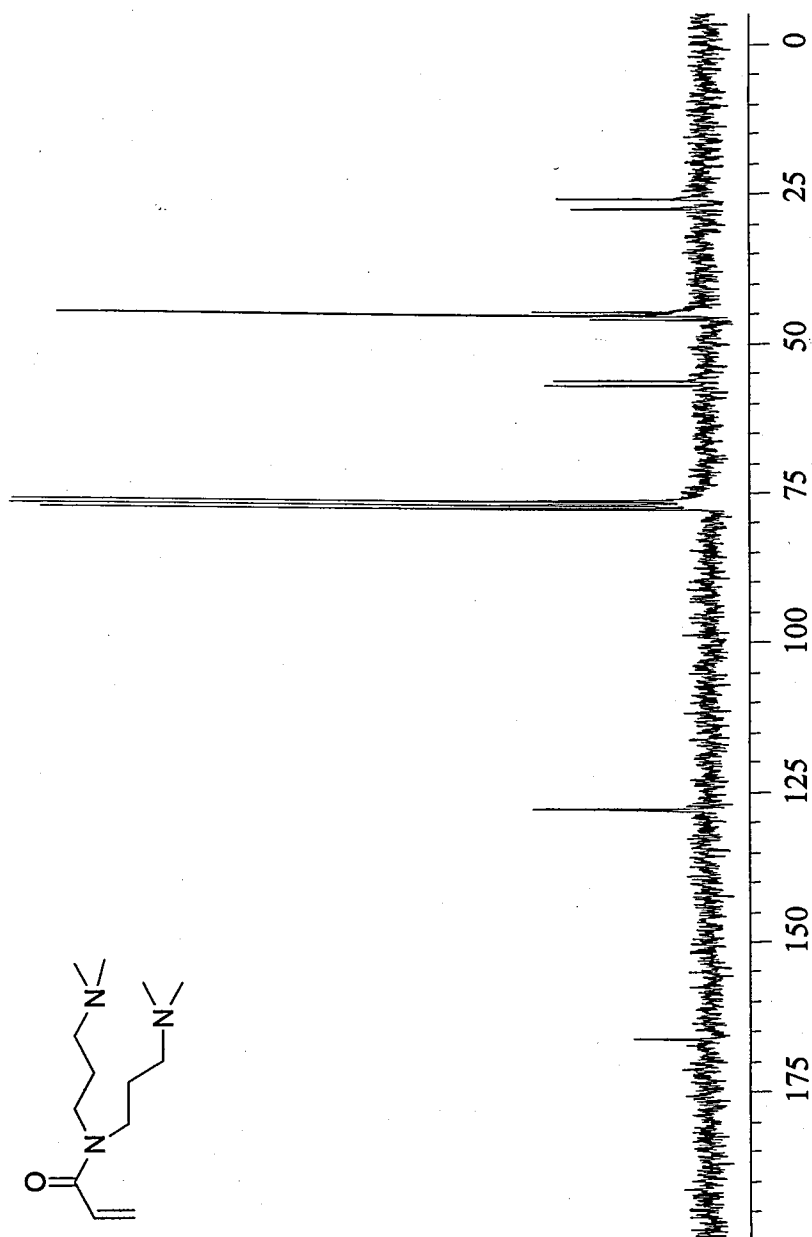


Figure 4.20. ^{13}C -NMR spectrum of ACRY-IDPA monomer

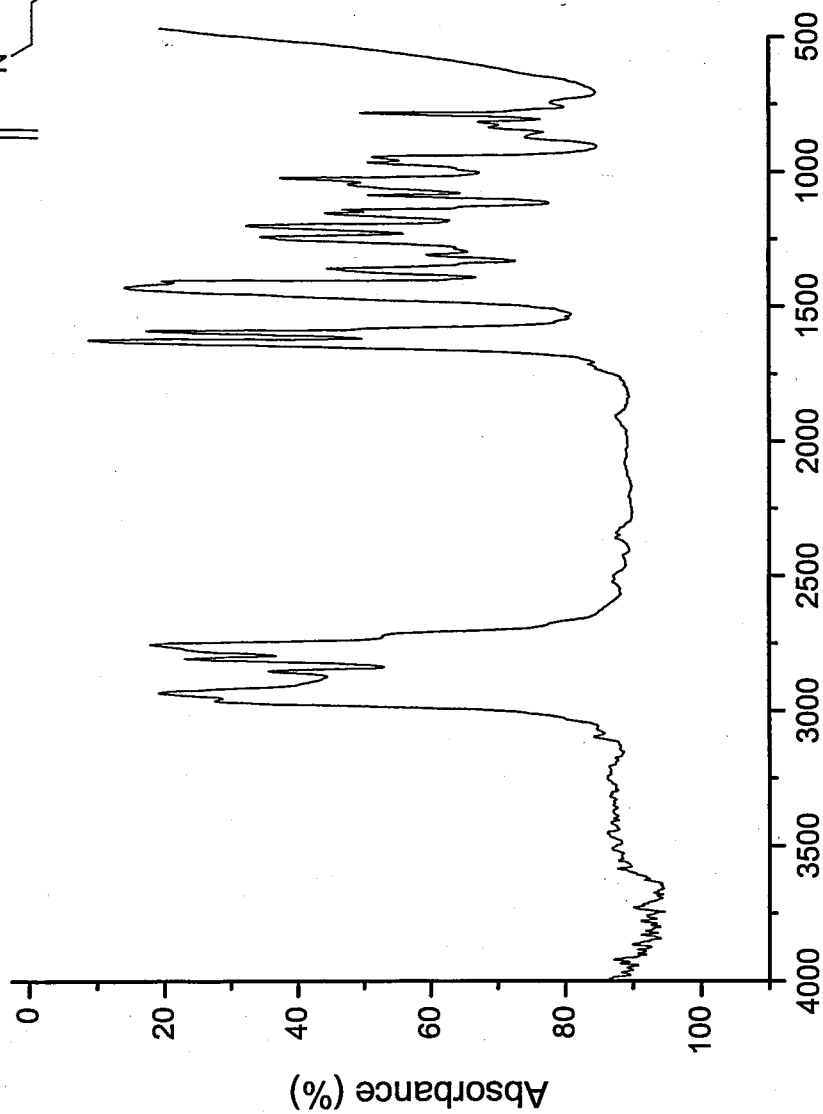
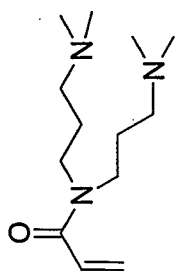


Figure 4.21. IR spectrum of ACRY-IDPA monomer

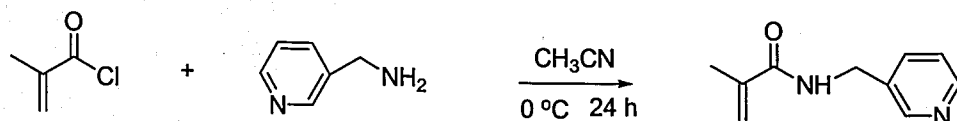


Figure 4.22. Synthesis of METH-PYR

The ^{13}C -NMR spectrum shows (Figure 4.23), methyl group attached to double bond at 18.2 ppm, methylene attached to NH at 40.4 ppm, double bond carbon peaks at 139.2 and 123.2 ppm, carbonyl carbon peak at 168.5 ppm and carbons on the pyridine ring at 119.7, 134.2, 135.2, 147.7 and 148.3 ppm.

^1H NMR (Figure 4.24) spectrum shows methyl protons attached to double bond at 1.7 ppm, methylene protons attached to NH at 4.2 ppm, the two sharp singlet peaks due to double bond at 5.5 and 5.1 ppm and the protons on the pyridine ring at 7, 7.4, 7.7 and 8.2 ppm.

4.1.3. Quaternization of AHM Derivatives

New methacrylate monomers containing pendant quaternary ammonium groups were synthesized from the hydroxylated amine and tertiary-amine functionalized acrylamide/methacrylamide monomers.

AHM-TMEDA monomer was quaternized with excess bromohexane in dry acetonitrile at 60 $^{\circ}\text{C}$ for 3 days (Figure 4.25). After evaporation of the solvent, the product was purified by dissolving in methanol and precipitation into diethylether to give an oily liquid in an 54 per cent yield. The quaternized monomer was soluble in water, methylenechloride, methanol, chloroform and acetone but insoluble in ether and hexane.

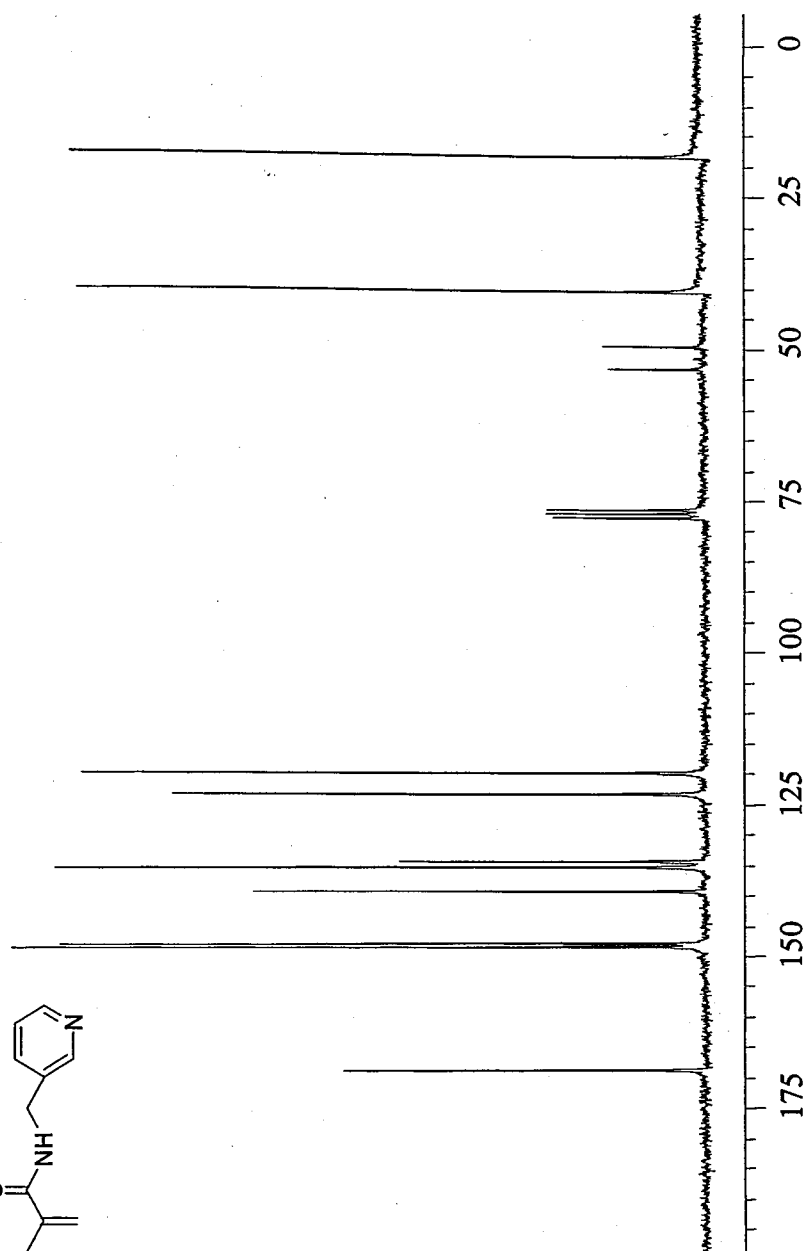
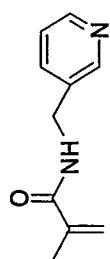


Figure 4.23. ^{13}C -NMR spectrum of METH-PYR monomer

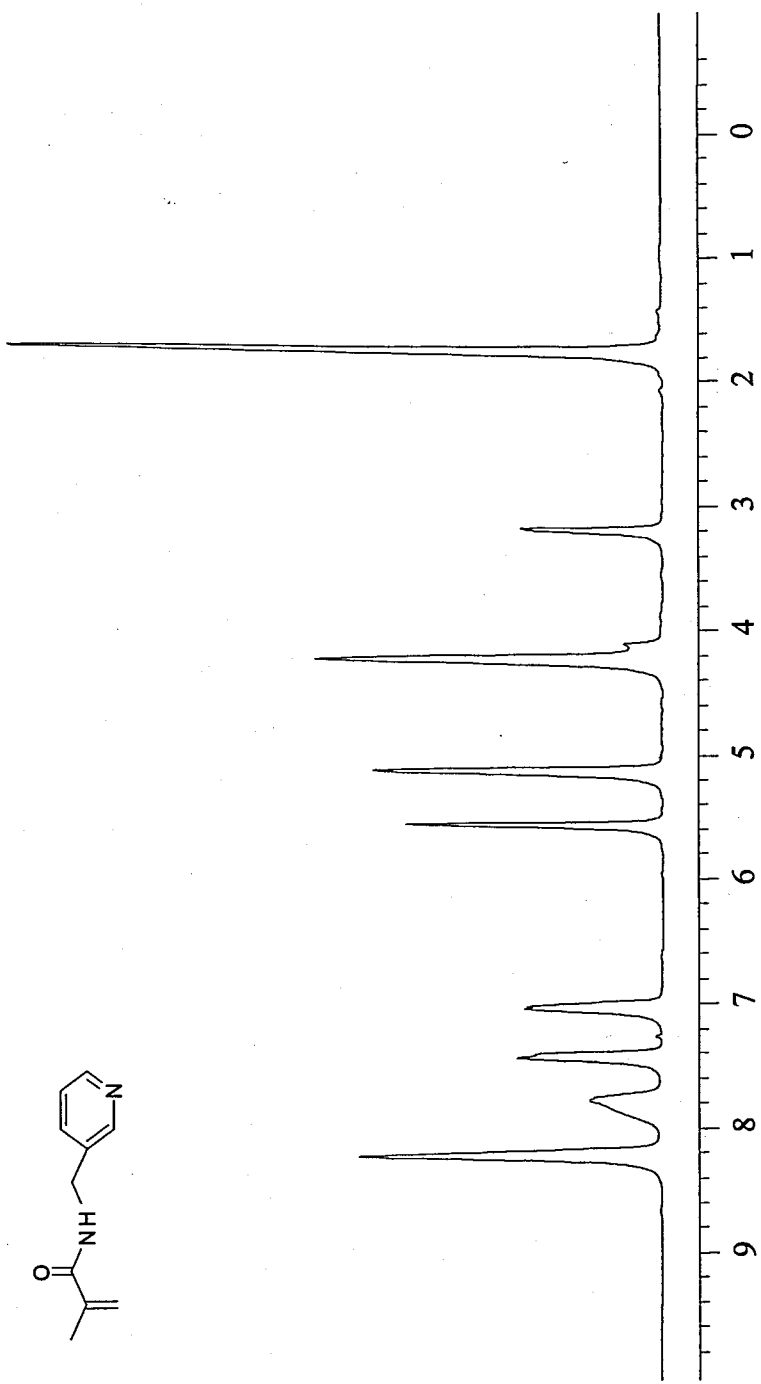


Figure 4.24. ¹H-NMR spectrum of METH-PYR monomer

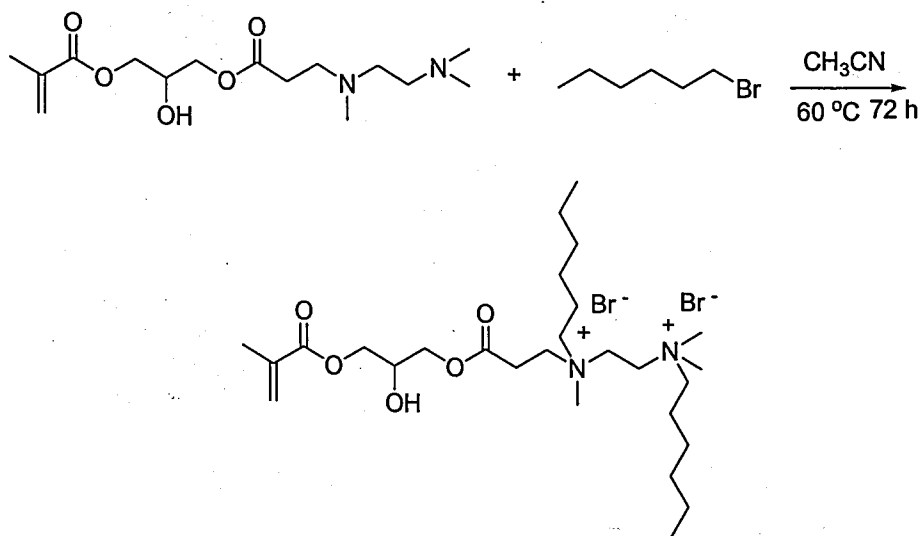


Figure 4.25. Synthesis of AHM-TMEDA QAC.

^{13}C -NMR spectrum of this monomer (Figure 4.26) shows methyl carbon attached to double bond at 18.2 ppm, other methylene carbon peaks due to alkyl group at 22.6, 25.7, 31.1 and 41.3 ppm, the methyl groups attached to nitrogen atom at 51.4 ppm, methylene carbons attached to nitrogen atom at 51.8 and 53.3 and 60.1 ppm, methylenes of ester groups 65.0 and 66.8 ppm and double carbon peaks at 126.1 and 135.7 ppm. The two carbonyl peaks also appeared at 165.1 and 172.1 ppm in the spectrum of the quaternized AHM-TMEDA monomer.

^1H NMR (Figure 4.27) spectrum shows methyl protons attached to double bond at 1.87 ppm, other methylene protons due to alkyl group at 1.3, 1.7, 1.8, 2.3, 2.5 and 2.9 ppm, methylene protons attached to quaternized nitrogen atom at 3.3 ppm, methylenes of ester groups at around 4.1 ppm and the two sharp singlet peaks due to double bond protons at 6.0 and 5.5 ppm.

The IR spectrum of the derivative (Figure 4.28) shows C-O vibrations 1125 cm^{-1} , C-N stretchings at 1250 cm^{-1} , C=C stretching peak at 1650 cm^{-1} , the ester carbonyl at 1750 cm^{-1} , C-H vibrations at 2995 cm^{-1} which confirms formation of the product. The broad peak at 3350 is also due to OH and NH stretching.

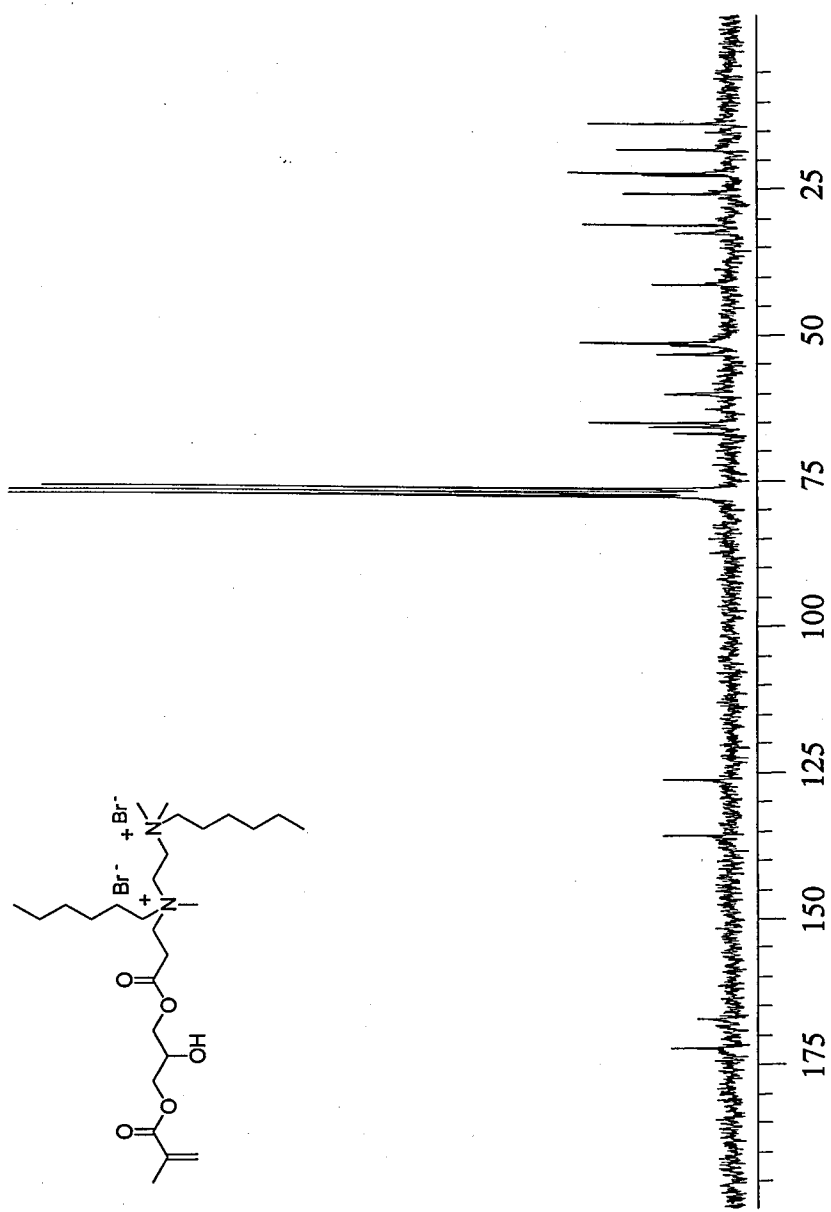


Figure 4.26. ^{13}C -NMR spectrum of AHM-TMEDA QAC

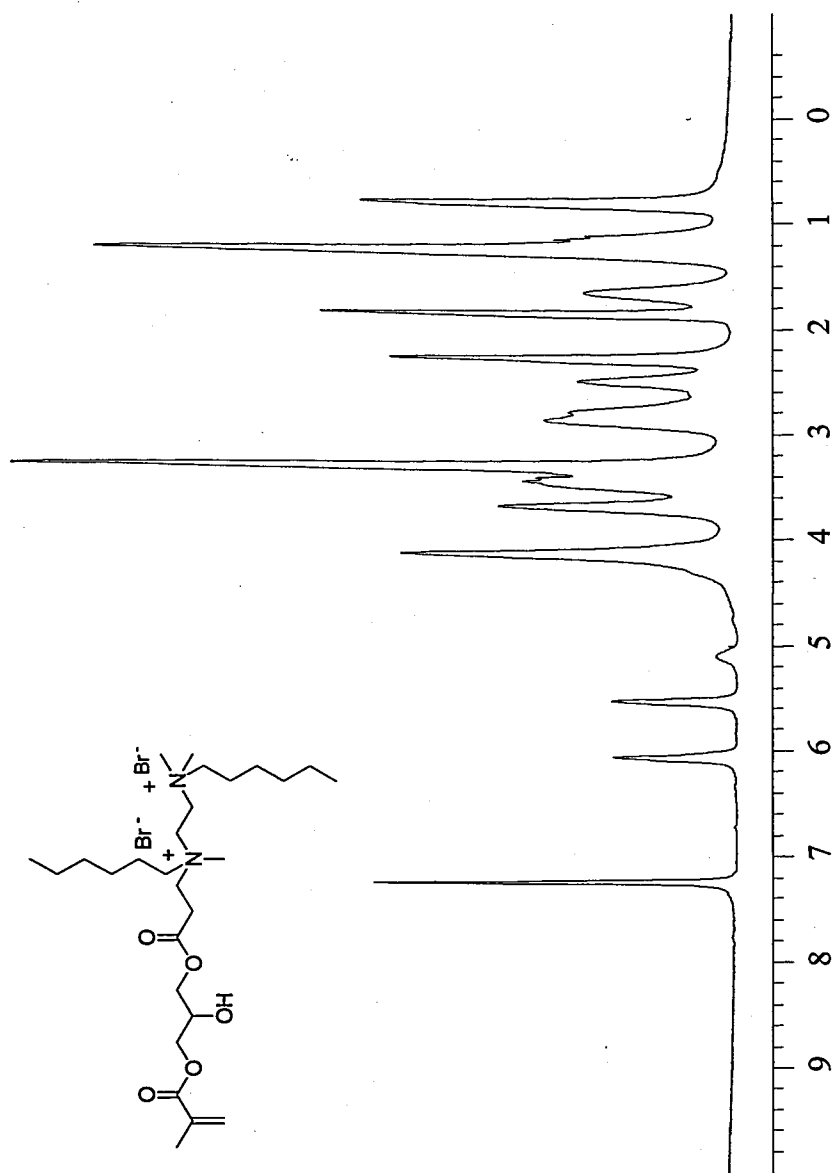


Figure 4.27. ¹H-NMR spectrum of AHM-TMEDA QAC

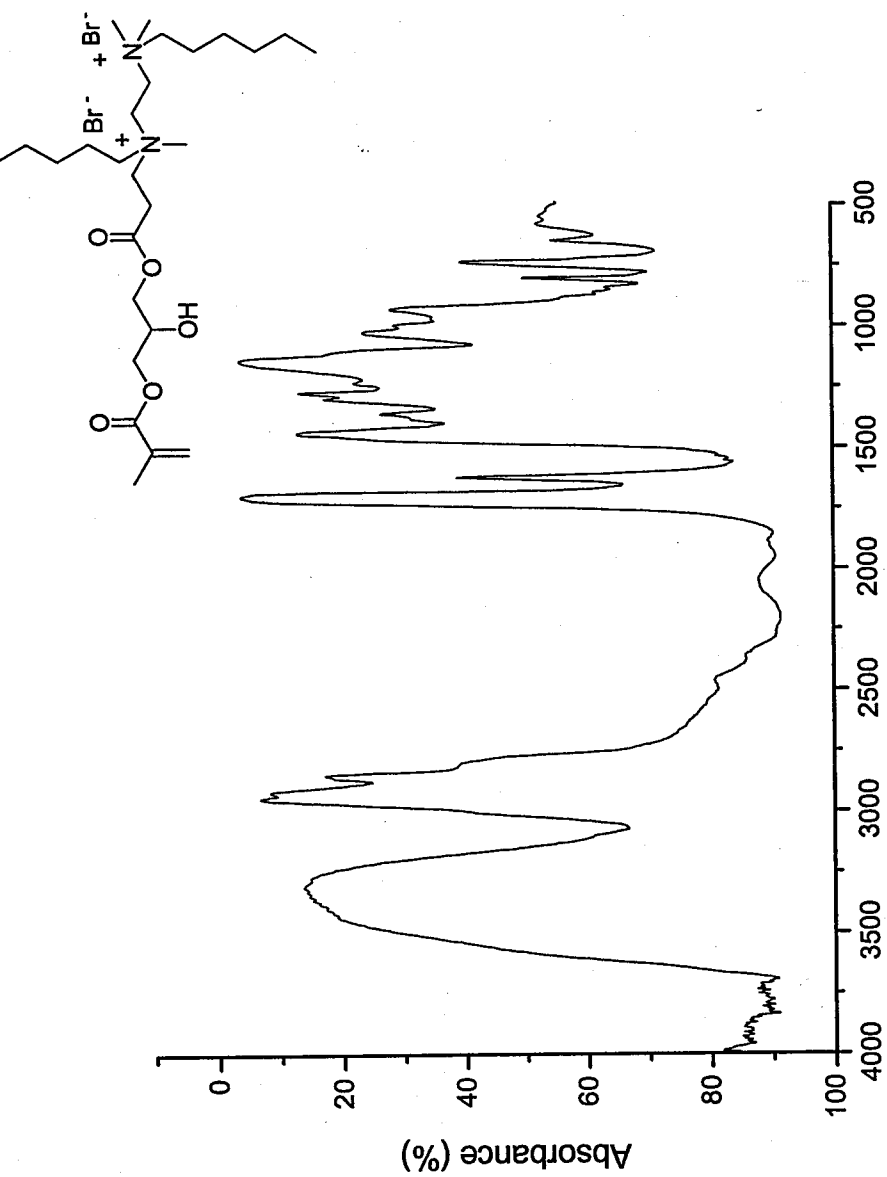


Figure 4.28. IR spectrum of AHM-TMEDA QAC

AHM-PYR monomer was quaternized with excess bromohexane in dry acetonitrile at 60 °C for 24 hours (Figure 4.29). After evaporation of the solvent, the product was purified by dissolving in methanol and precipitation into diethylether to give a dark yellow liquid. The quaternized monomer was soluble in water, chloroform and methanol but insoluble in ether.

When ^{13}C -NMR spectrum of the starting materials and the synthesized monomer are compared (Figure 4.30) the changes are obvious. Methyl carbon attached to double bond at 17.8 ppm, methylene attached to carbonyl group at 26.4 ppm, other methylene carbon peaks due to alkyl group at 13.4, 21.8, 25.2, 26.4, 30.5 and 31.1 ppm, methylene carbons attached to nitrogen atoms at 57.1, 54.2, 53.4, 48.7, 47.4 and 43.3 ppm and methylenes of ester groups at 66.5, 64.6 and 61.5 ppm were observed. The double carbon peaks and two carbonyl peaks are appeared at 125.7, 135.2 and 166.6, 172.0 ppm, respectively.

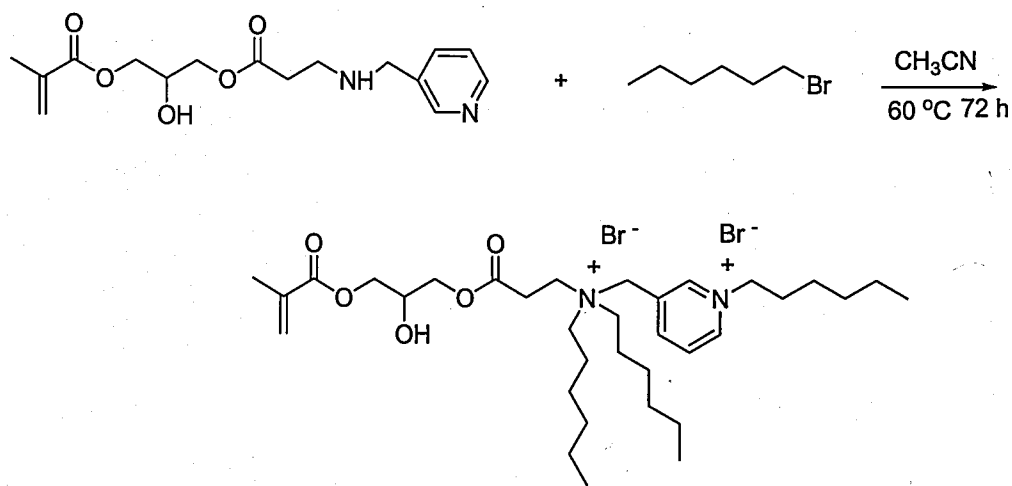


Figure 4.29. Synthesis of the AHM-PYR QAC

^1H NMR (Figure 4.31) spectrum shows methyl proton attached to double bond at 1.9 ppm, methylene attached to carbonyl at 2.3 ppm, other methylenes attached to quaternized nitrogen atom at 3.6 ppm, methylenes of ester groups at 4.2 ppm. The peaks

at 5.0 ppm and 5.5 ppm correspond to vinyl protons. The proton peaks of pyridine ring also appeared at 7.6, 7.9, 8.7 and 9.1 ppm.

The IR spectrum of the derivative (Figure 4.32) shows C-O vibrations at 1175 cm^{-1} , C-N stretchings at 1250 cm^{-1} , C=C stretching peak at 1625 cm^{-1} , the ester carbonyl at 1725 cm^{-1} , aliphatic C-H vibrations at $2910\text{--}2850\text{ cm}^{-1}$ which confirm formation of the product. The broad peak at 3250 is also due to OH and NH stretching.

4.1.4. Quaternization of ACRY-IDPA

The quaternized ACRY-IDPA monomer was obtained by the reaction of ACRY-IDPA with bromohexane in dry acetonitrile at $55\text{ }^{\circ}\text{C}$ for 24 hours (Figure 4.33). After evaporation of the solvent, the product was purified by dissolving in methanol and precipitation into diethylether to give a white oily liquid. The quaternized monomer was soluble in water, chloroform and methanol but insoluble in ether.

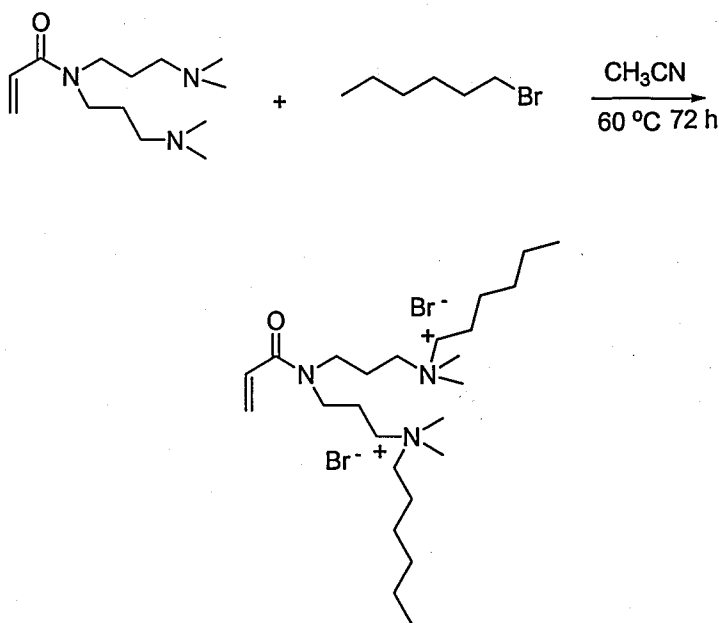


Figure 4.33. Synthesis of ACRY-IDPA QAC

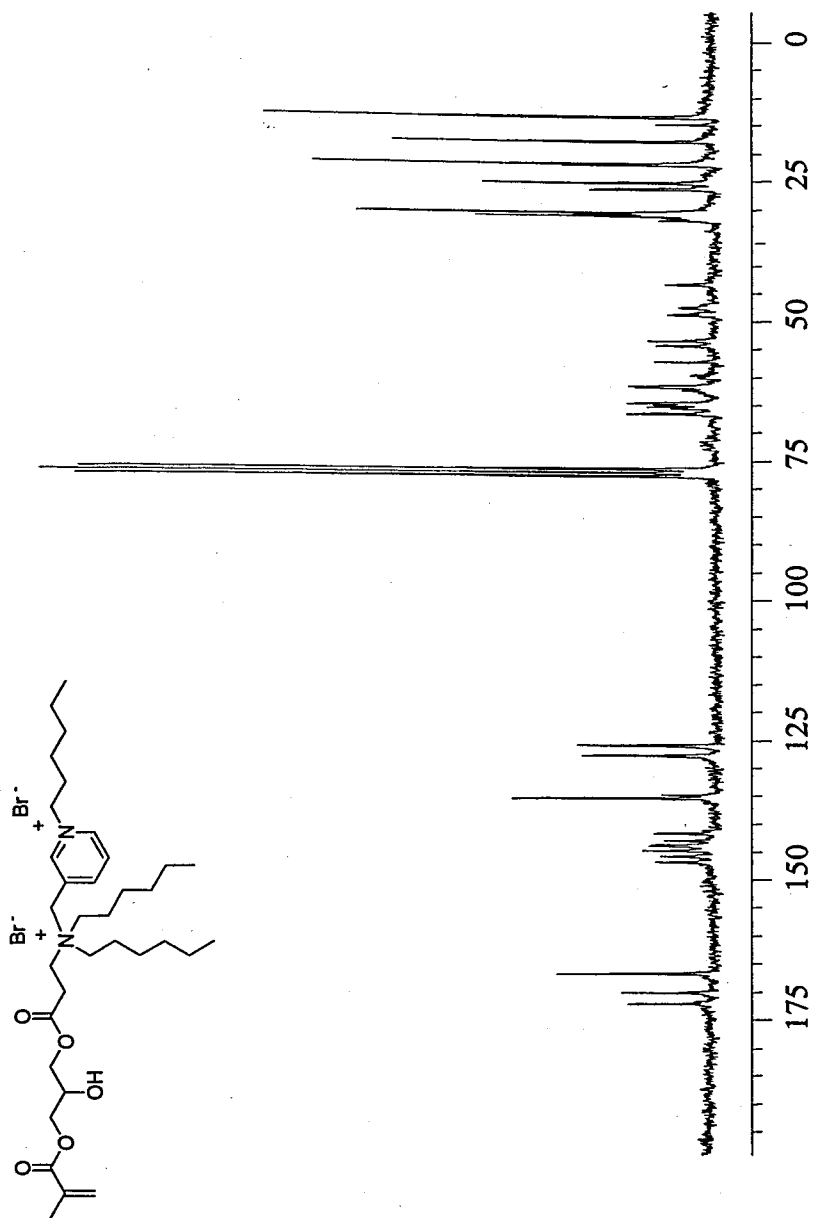


Figure 4.30. ¹³C-NMR spectrum of AHM-PYR QAC

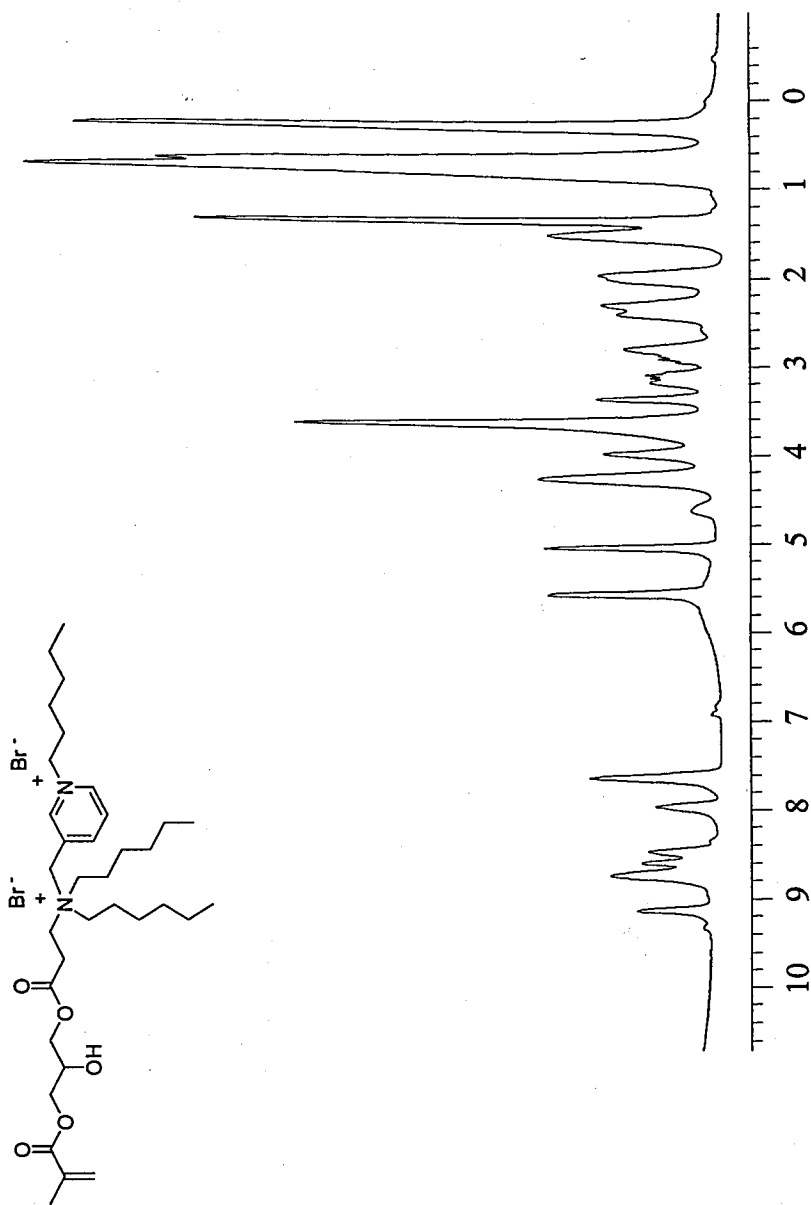


Figure 4.31. ¹H-NMR spectrum of AHM-PYR QAC

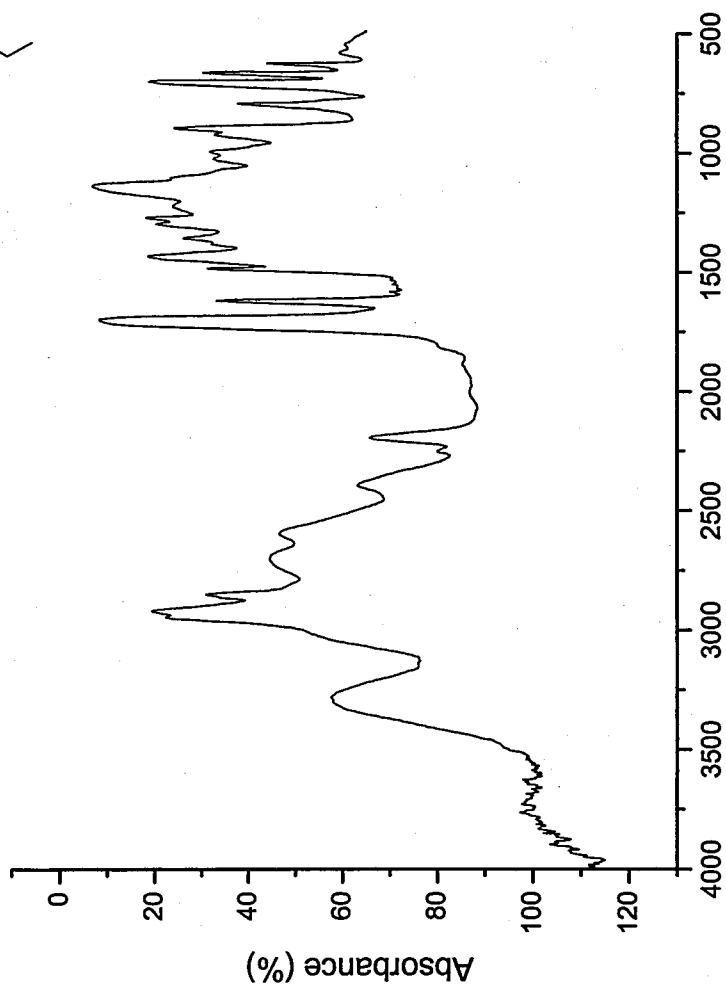
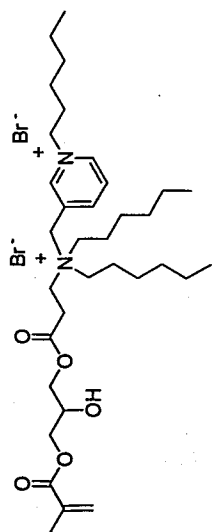


Figure 4.32. IR spectrum of AHM-PYR QAC

The reaction was monitored using ^{13}C NMR and ^1H NMR spectroscopy. The ^{13}C -NMR spectrum shows (Figure 4.34) methylene carbon peaks of alkyl group at 30.7, 25.4, 22.9, 22.2, 21.9 and 13.5 ppm, methyl carbons attached to quaternized nitrogen atoms at 50.6 ppm, methylene carbons attached to nitrogen atom at 44.3 ppm, methylene carbons attached to quaternized nitrogen atom at 64.6 and 61.5 ppm, double bond carbon peaks at 128.5 and 127.5 ppm and a carbonyl carbon peak at 166.3 ppm.

^1H NMR (Figure 4.35) spectrum shows methylene protons peaks of alkyl group appeared at 1.7, 1.3 and 0.8 ppm, methyl protons attached to quaternized nitrogen atoms at 2.3 ppm, methylenes attached to quaternized nitrogen atom at 3.4 ppm and vinyl protons at 5.8, 6.3 and 6.8 ppm.

The IR spectrum of the derivative (Figure 4.36) shows C-O vibrations at 1075 cm^{-1} , C-N stretchings at 1250 cm^{-1} , C=C stretching peak at 1625 cm^{-1} the ester carbonyl at 1675 cm^{-1} and C-H vibrations at $2928\text{--}2856\text{ cm}^{-1}$ which confirms formation of the product. The broad peak at 3428 cm^{-1} is due to OH and NH stretchings.

4.1.5. Quaternization of METH-PYR

Three new methacrylamide monomers with quaternary ammonium groups were synthesized from the reaction of METH-PYR with bromohexane (METH-PYR/1 QAC), bromooctane (METH-PYR/2 QAC) and bromohexadecane (METH-PYR/3 QAC). The quaternized monomers were soluble in water, chloroform and methanol but insoluble in ether.

The reactions were monitored using ^{13}C NMR and ^1H NMR spectroscopy (Figure 4.37). The ^{13}C -NMR spectrum of bromohexane (METH-PYR/1 QAC) derivative (Figure 4.38) showed characteristic peaks for methyl group attached to double bond at 18.7 ppm, methylene attached to NH at 40.1 ppm, carbons on the pyridine ring at 121.6, 138.4, 141.7, 144.5 and 145.4 ppm, double bond carbons at 142.3 and 127.6 ppm and a carbonyl carbon at 168.7 ppm. Six new peaks due to alkyl group also appeared at 62.1, 31.5, 30.8, 25.6, 22.2 and 13.7 ppm.

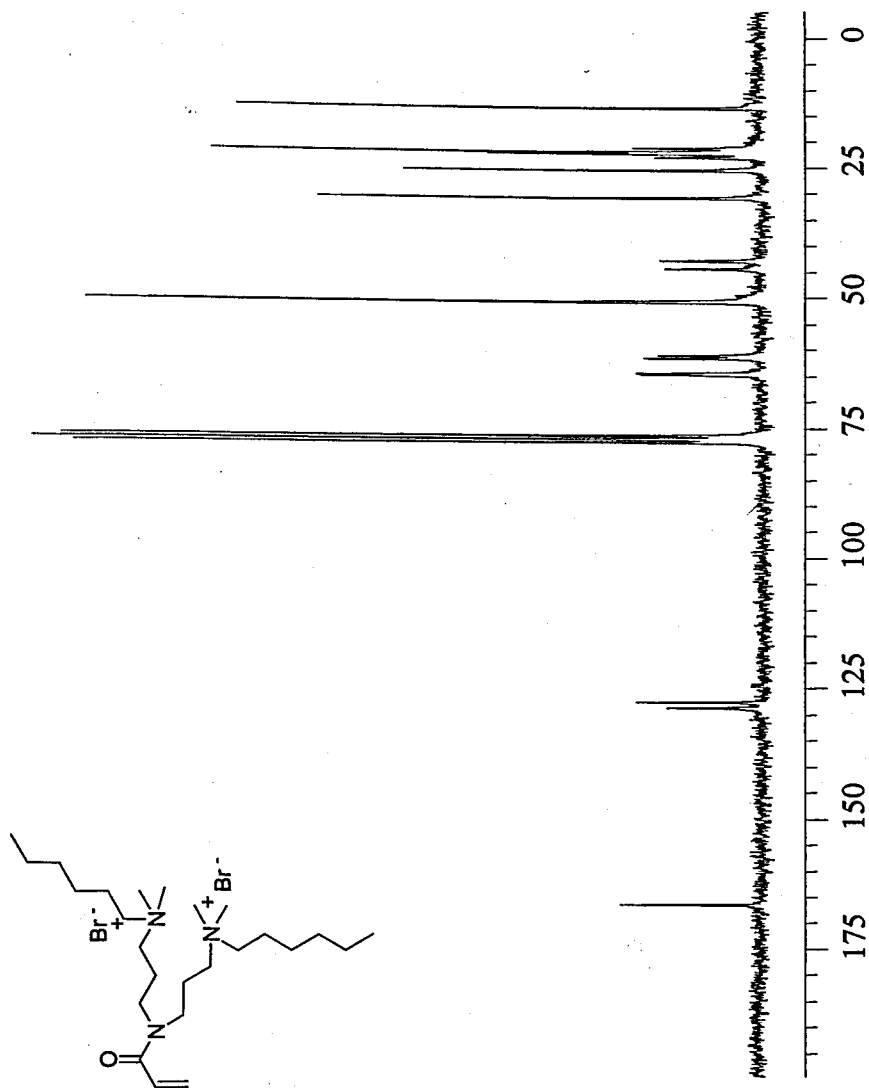


Figure 4.34. ¹³C-NMR spectrum of ACRY-IDPA QAC

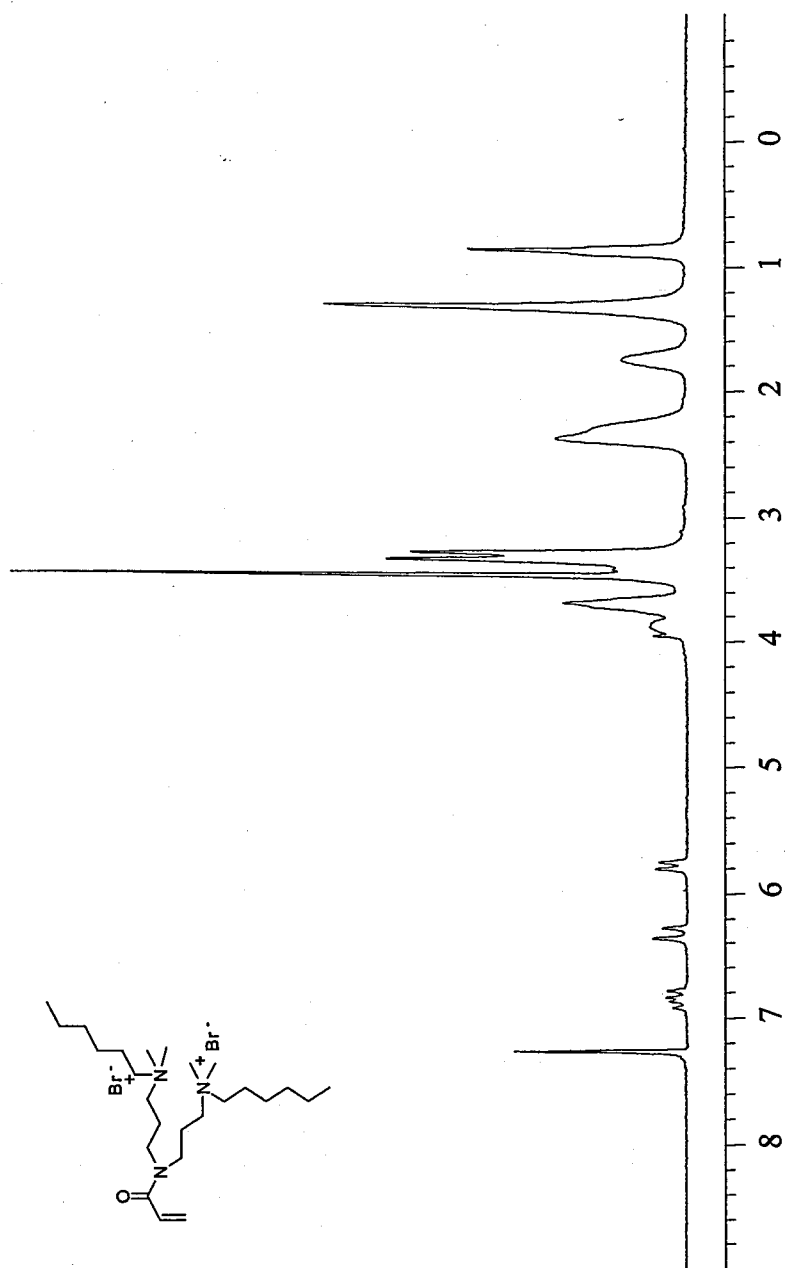


Figure 4.35. ^1H -NMR spectrum of ACRY-IDPA QAC

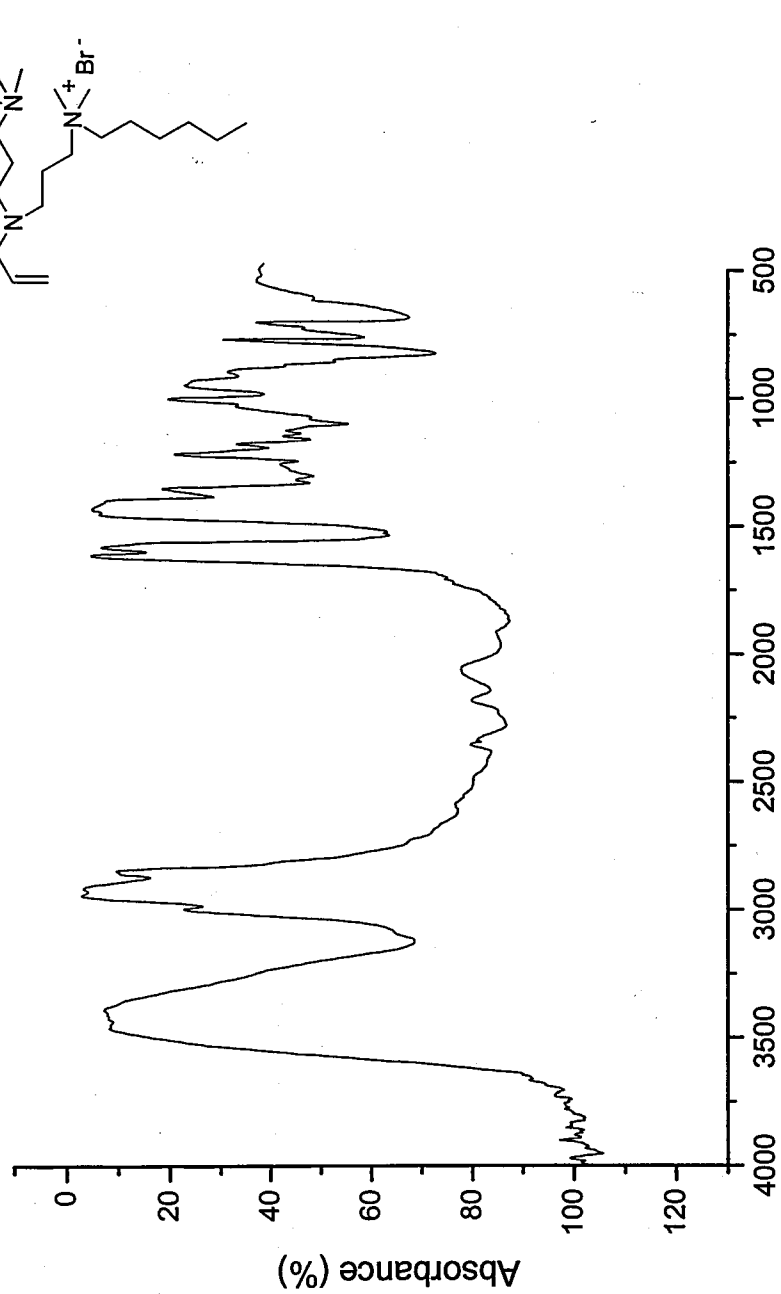


Figure 4.36. IR spectrum of ACRY-IDPA QAC

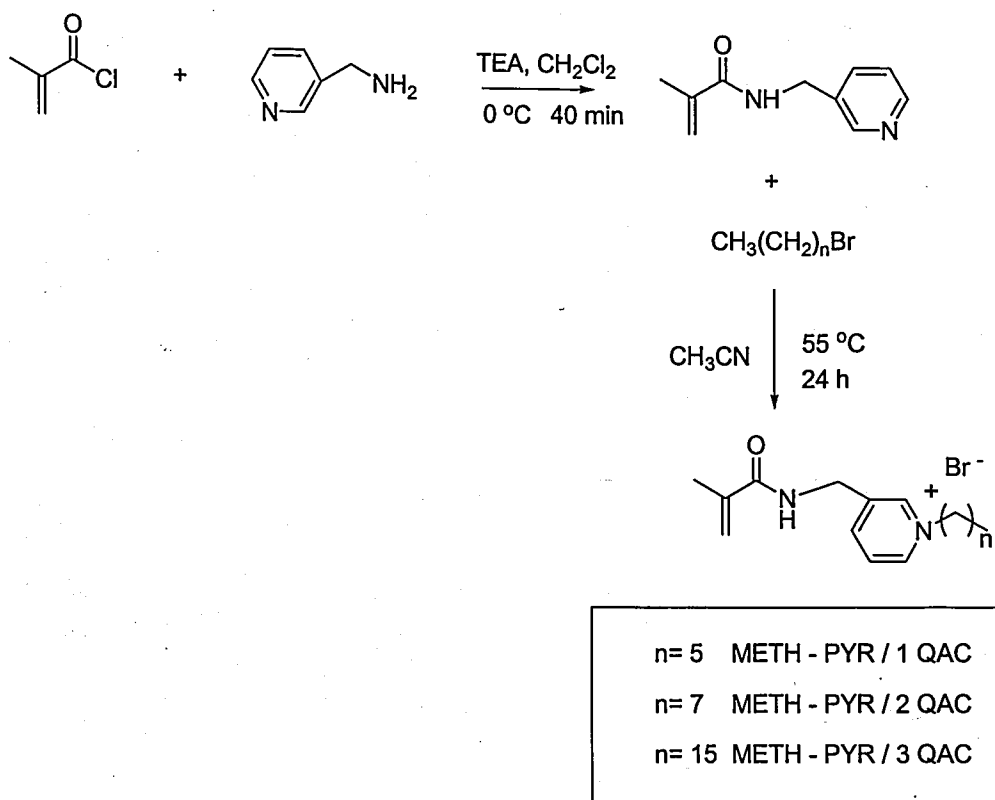


Figure 4.37. Synthesis of methacrylamide derivatives

The ^{13}C -NMR spectra of bromooctane (METH-PYR/2 QAC) and bromohexadecane (METH-PYR/3 QAC) derivatives (Figure 4.41, 4.44) showed similar peaks to that of bromohexane (METH-PYR/1 QAC) derivative. New peaks due to octyl and hexadecyl groups appeared between 14.1 and 62.3 ppm.

^1H NMR (Figure 4.39) spectrum of bromohexane derivative (METH-PYR/1 QAC) is characterized by methyl hydrogens attached to double bond at 1.3 ppm, methylenes due to alkyl group at 1.9 ppm, methylene attached to carbonyl group at 4.7 ppm, double bond hydrogens at 5.3 and 6.0 ppm and pyridine hydrogens at 7.9, 8.7, 9.1 and 9.4 ppm.

^1H NMR (Figure 4.42, 4.45) spectra of the bromooctane (METH-PYR/2 QAC) and bromohexadecane (METH-PYR/3 QAC) derivatives showed similar peaks to that of the bromohexane derivative.

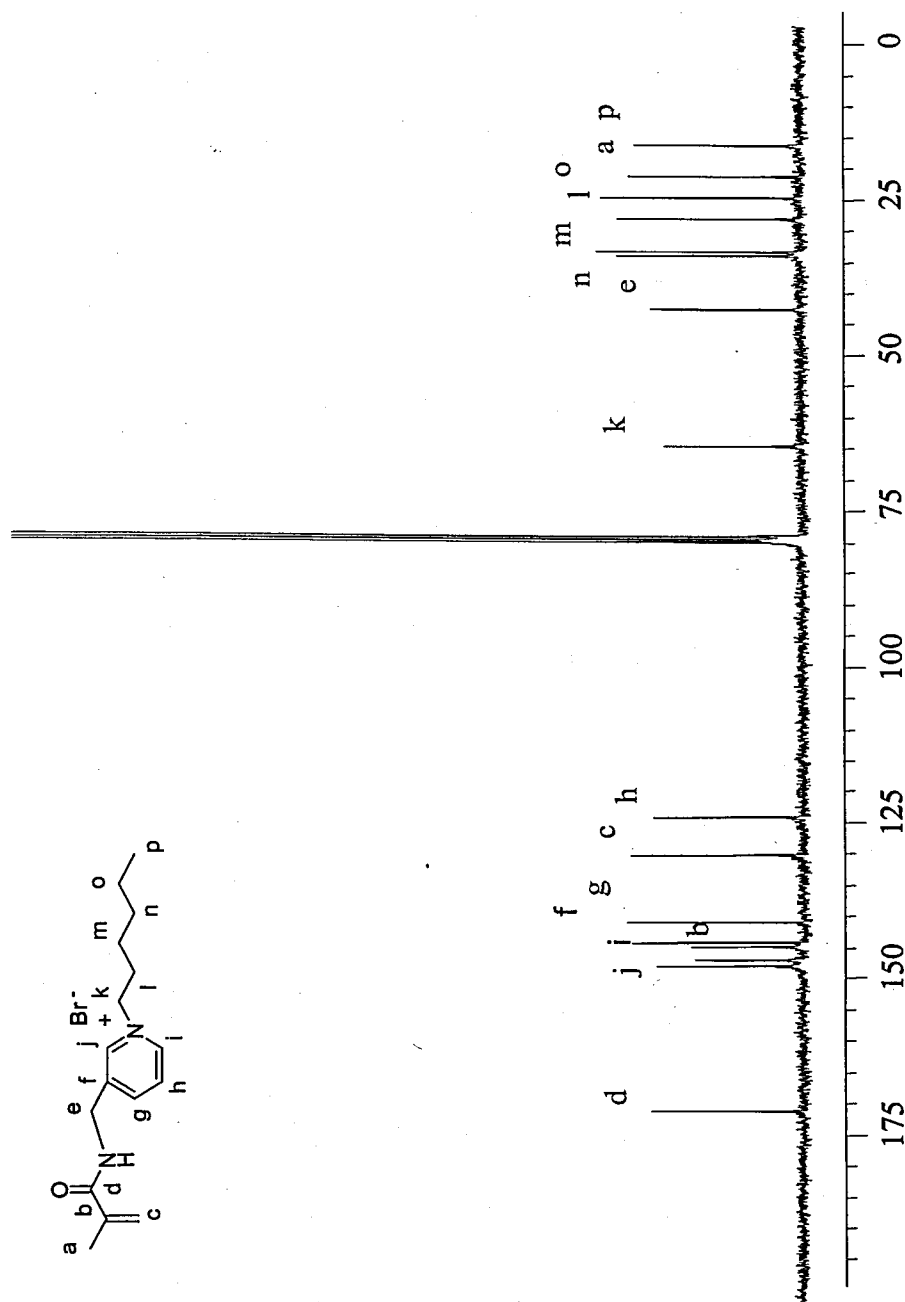


Figure 4.38. ¹³C-NMR spectrum of METH-PYR/1 QAC

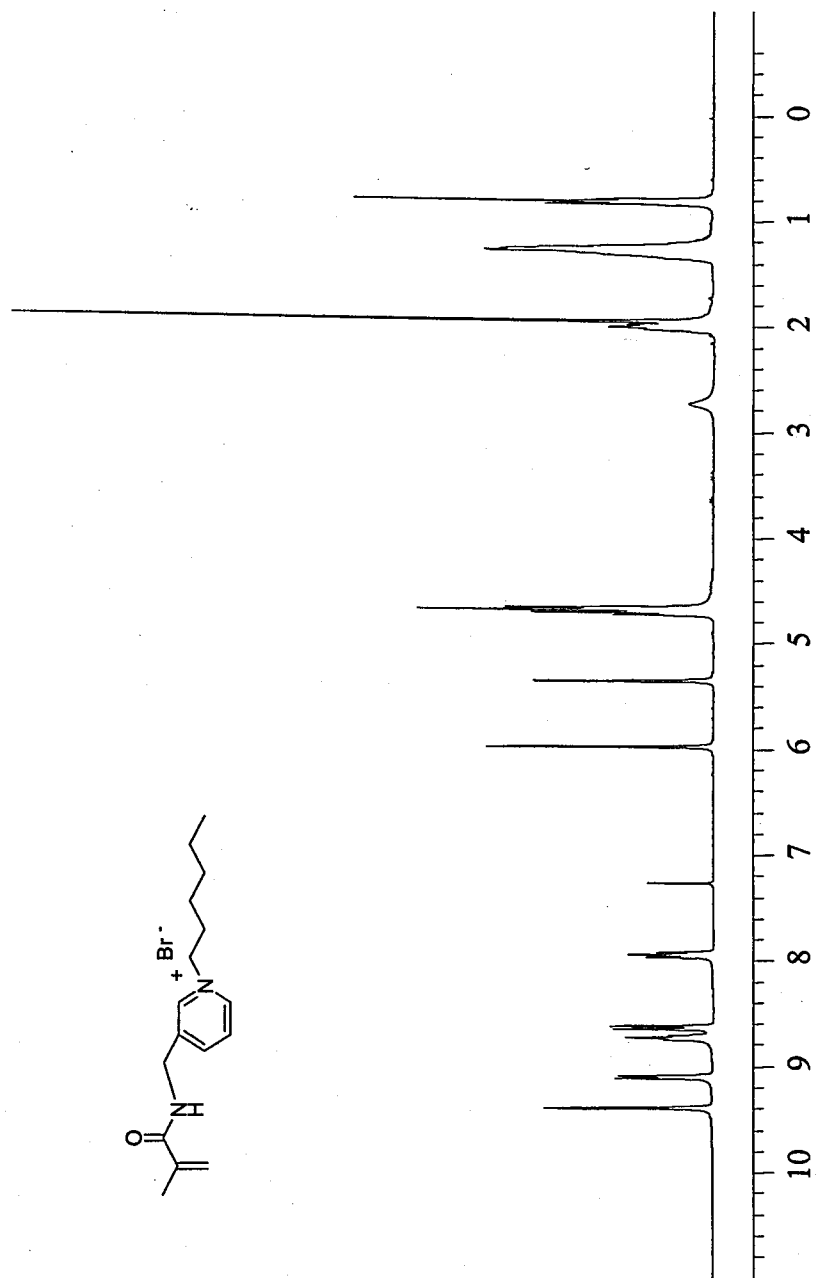


Figure 4.39. ¹H-NMR spectrum of METH-PYR/1 QAC

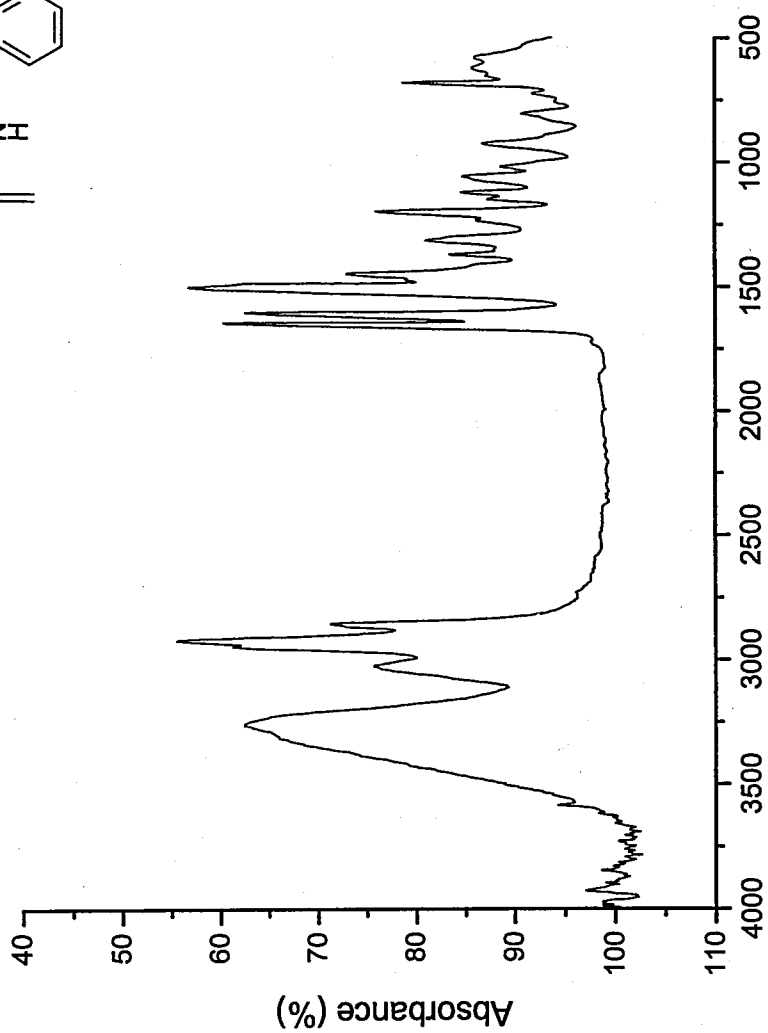
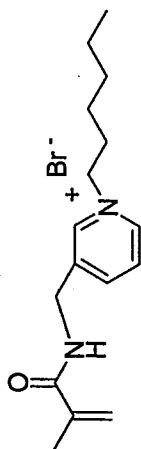


Figure 4.40. IR spectrum of METH-PYR/1 QAC

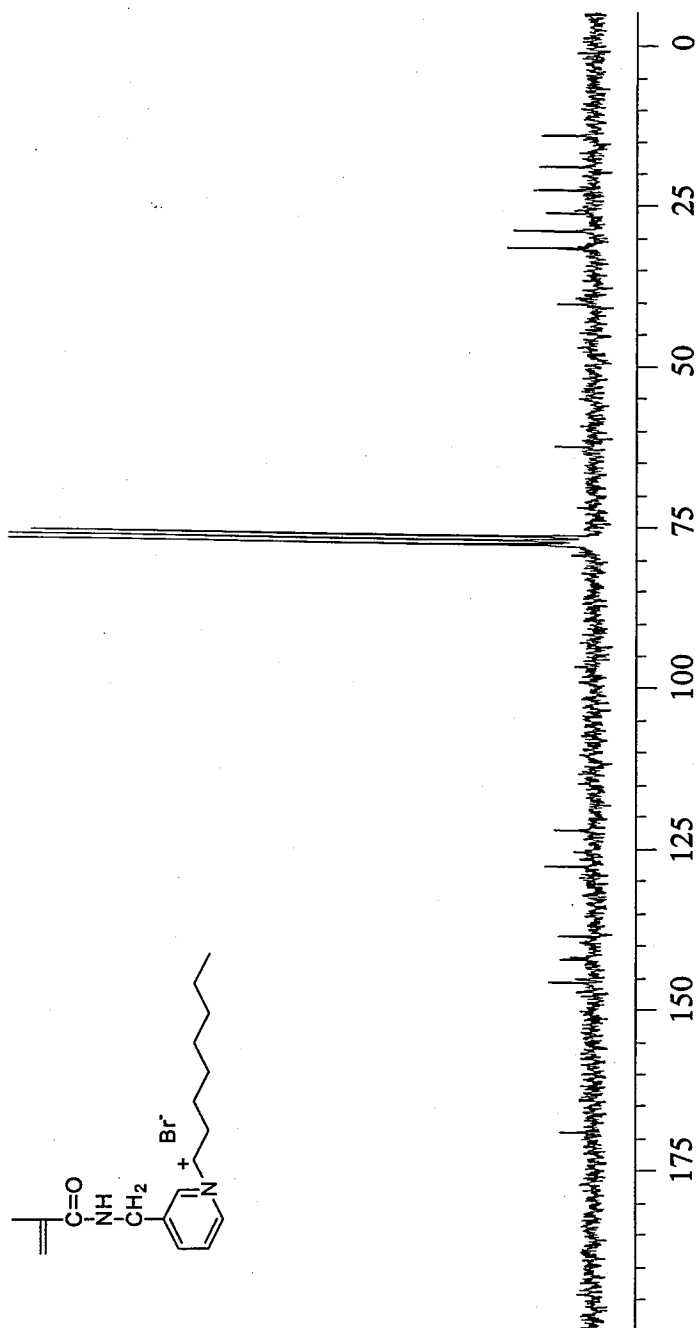


Figure 4.41. ^{13}C -NMR spectrum of METH-PYR/2 QAC

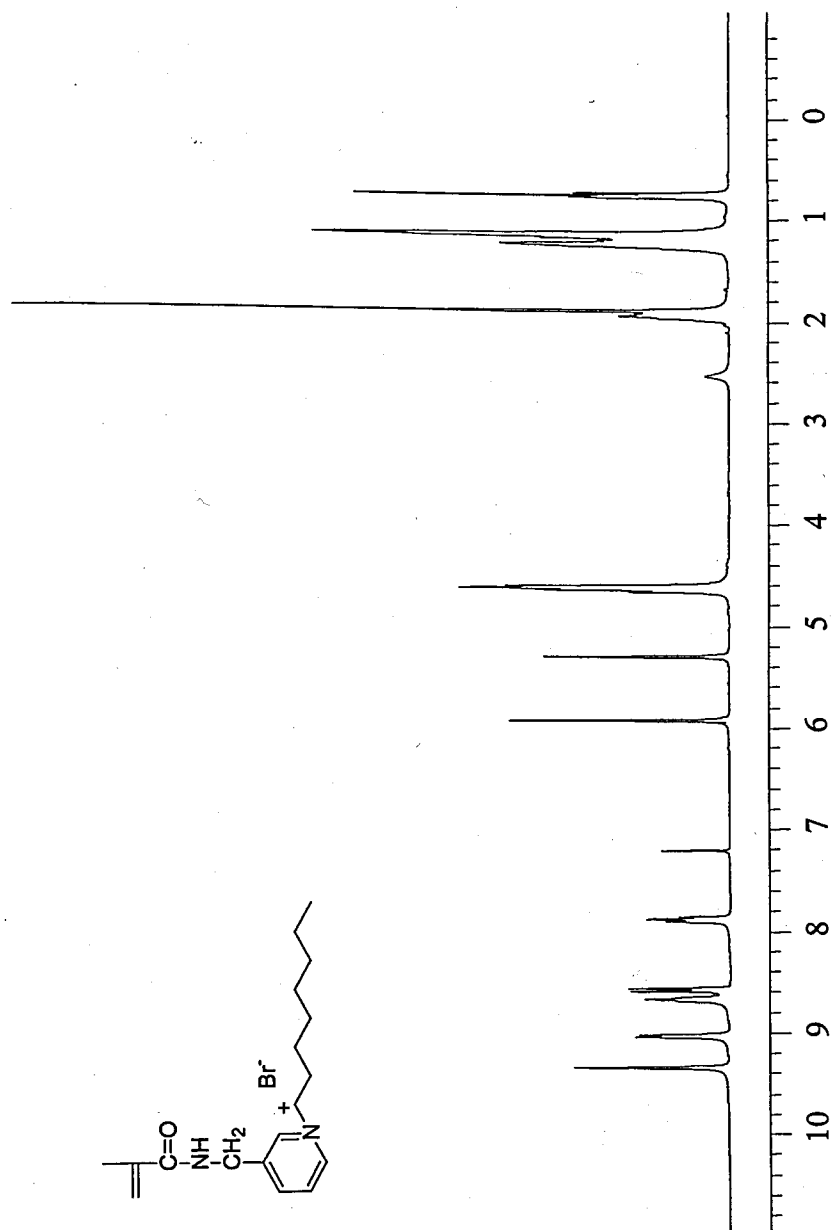


Figure 4.42. ¹H-NMR spectrum of METH-PYR/2 QAC

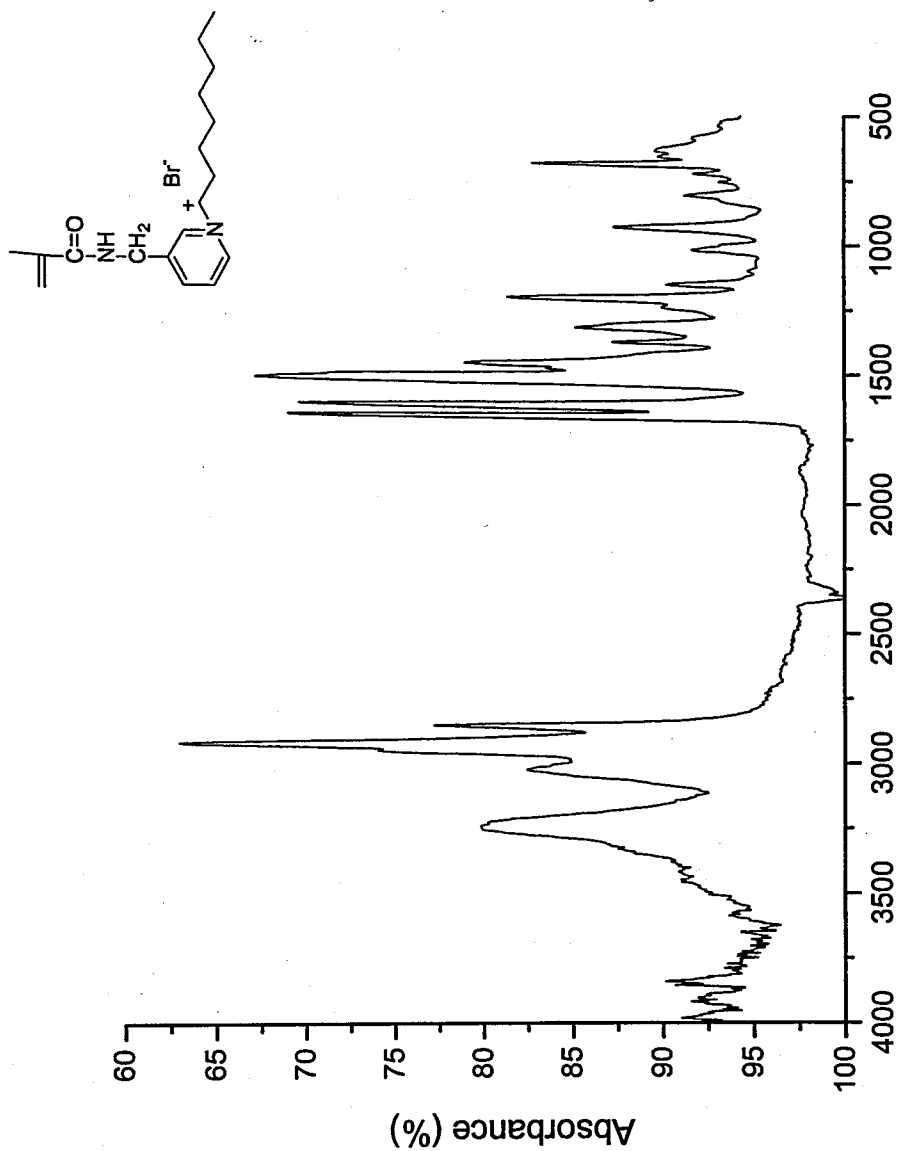


Figure 4.43. IR spectrum of METH-PYR/2 QAC

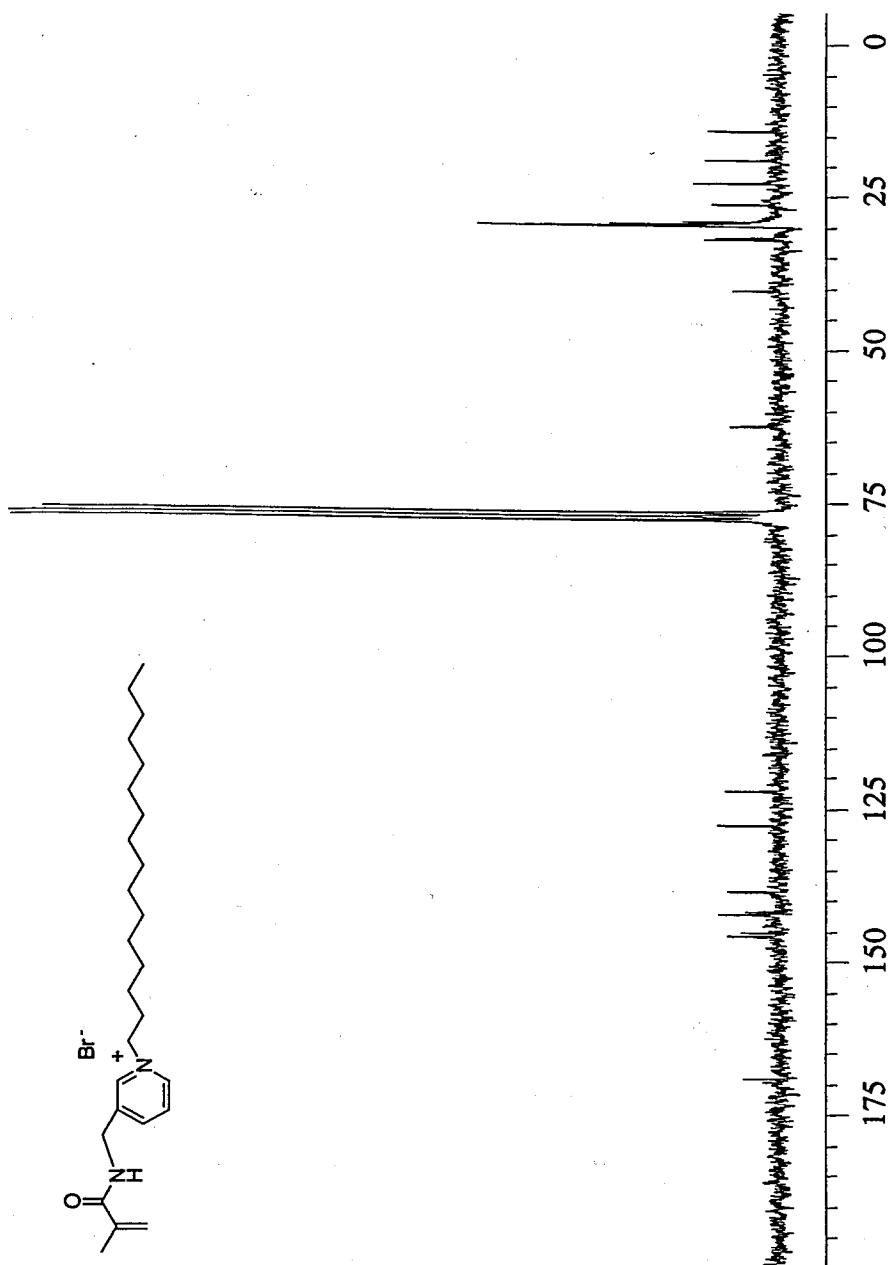


Figure 4.44. ¹³C-NMR spectrum of METH-PYR/3 QAC

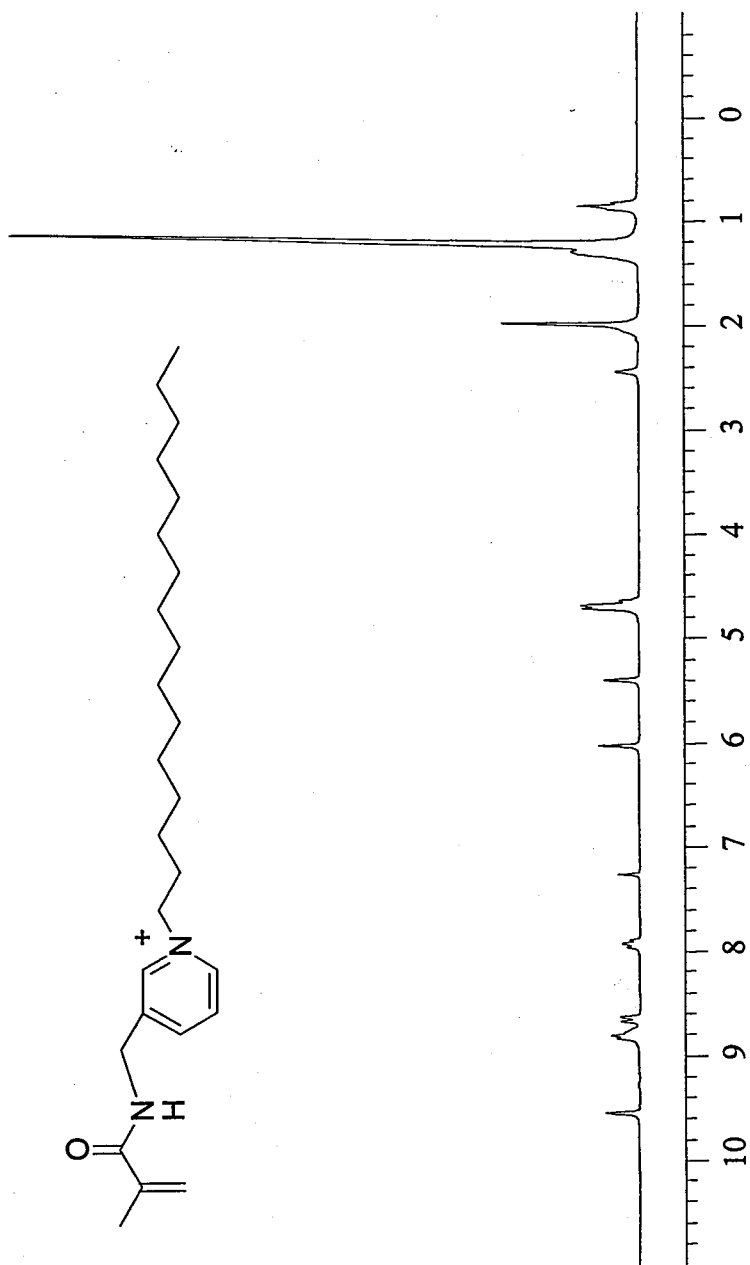


Figure 4.45. ^1H -NMR spectrum of METH-PYR/3 QAC

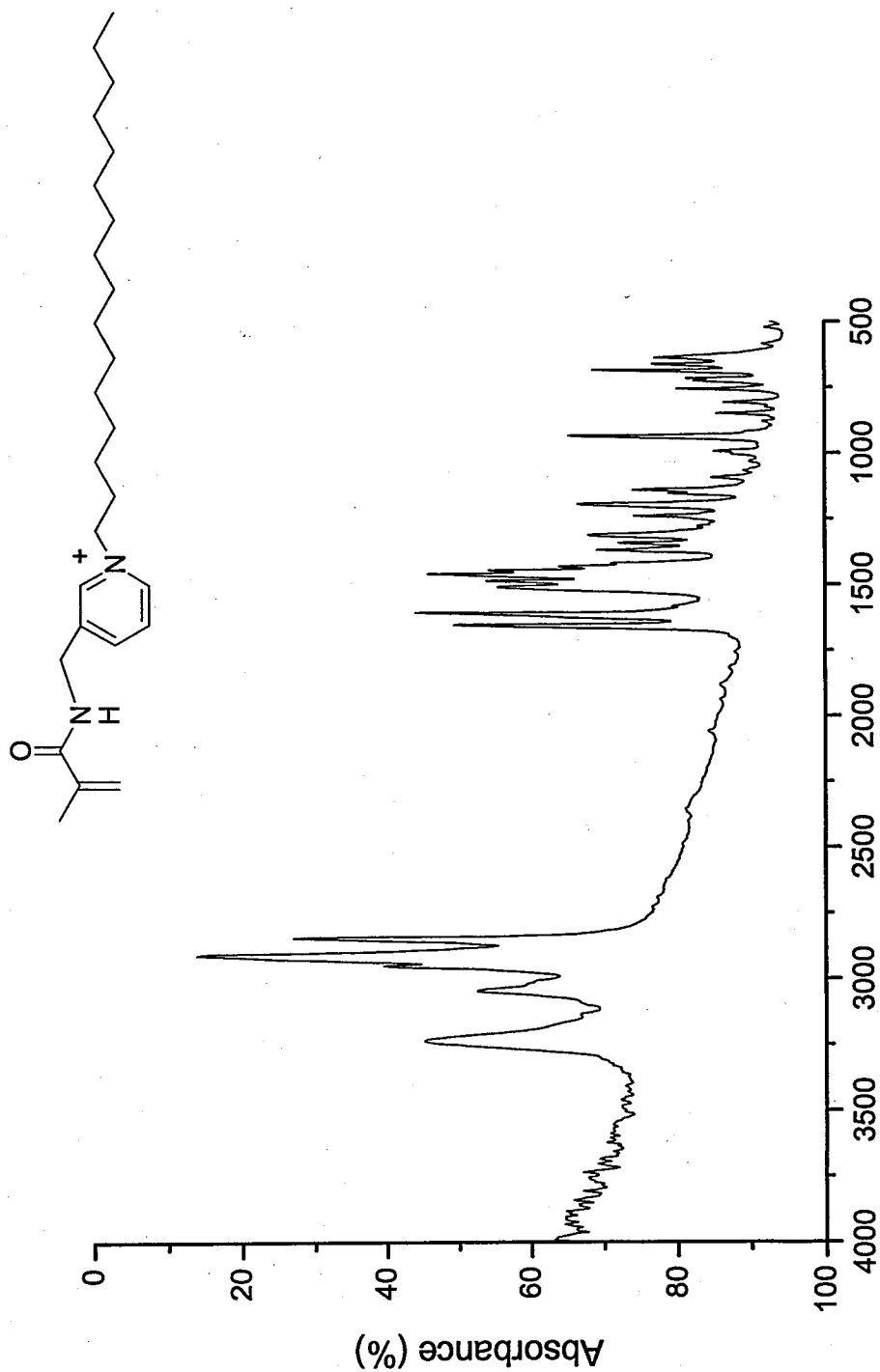


Figure 4.46. IR spectrum of METH-PYR/3 QAC

The IR spectrum of the derivatives (Figure 4.40, 4.43, 4.46) show C=C stretchings peak at $1613\text{--}1625\text{ cm}^{-1}$, C-N stretchings at 1225 cm^{-1} , carbonyl peak at 1675 cm^{-1} , C-H vibrations at 3021 and 2862 cm^{-1} which confirm formation of the products. The broad peaks at $3270\text{--}3285$ are also due to OH and NH stretchings.

4.1.6. Synthesis of Polymers

4.1.6.1 Photopolymerization of Amine Monomers. The reactivities of the synthesized monomers were investigated using photo-DSC. Photopolymerization of amine monomers were carried out on a TA Instruments Photo-DSC using 2,2-Dimethoxy-2-phenyl acetophenone (Irgacure 651) as an initiator.

4.1.6.2. Photopolymerization of Quaternary Ammonium Monomers. Photopolymerization of the AHM-DMAPA, AHM-TMEDA, AHM-IDPA and AHM-PYR monomers were photopolymerized under identical conditions of temperature ($30\text{ }^{\circ}\text{C}$), initiator concentration (2.0 mol per cent), and UV light intensity (1 mW/cm^2). Figure 4.47 shows the rates versus time plots of the monomers. Monomers AHM-DMAPA, AHM-TMEDA and AHM-PYR showed higher rates of polymerizations than AHM-IDPA. Maximum rates of polymerizations for AHM-DMAPA, AHM-TMEDA, AHM-IDPA and AHM-PYR were found to be 0.038 , 0.038 , 0.027 , 0.037 s^{-1} , respectively. The reason for the lower activity of AHM-IDPA is unclear but steric effect may be important. Figure 4.48 shows the conversion of these monomers as a function of time. The AHM-DMAPA, AHM-TMEDA and AHM-PYR showed the same conversions of 65 per cent, while AHM-IDPA gave 89 per cent conversion. The higher degree of conversion for this monomer may be due to autoacceleration that was not seen for the other systems.

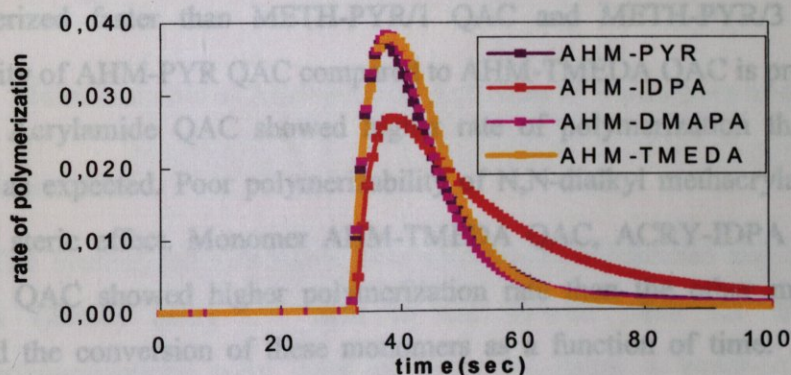


Figure 4.47. Rate versus time of AHM derivative monomers at $30\text{ }^{\circ}\text{C}$

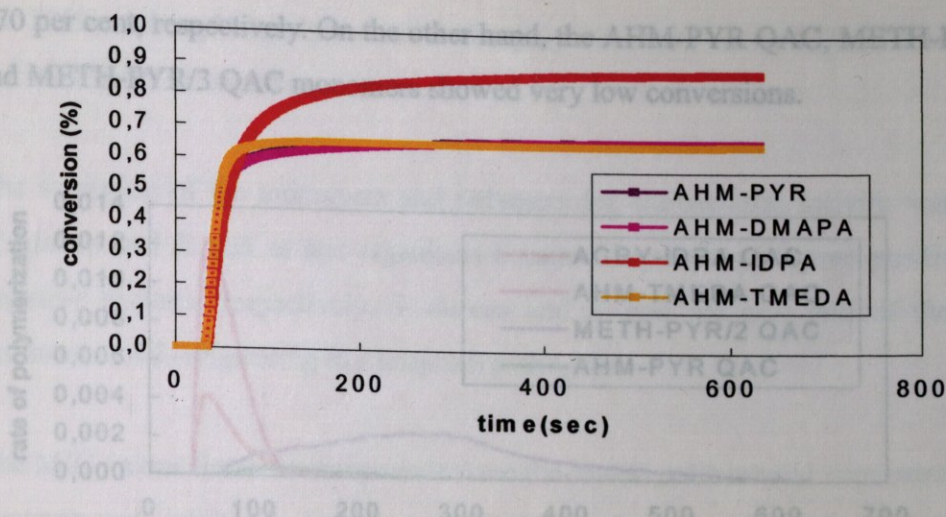


Figure 4.48. Conversion versus time of AHM derivative monomers at 30 °C

4.1.6.2. Photopolymerization of Quaternary Ammonium Monomers. Photopolymerization of the quaternary ammonium salts were carried out on a TA Instruments Photo-DSC using 2-hydroxy-1-[4-hydroxyethoxyphenyl]-2-methyl-1-propane (Irgacure 2959), as a water-soluble photoinitiator.

Quaternary ammonium monomers were photopolymerized under identical conditions of temperature (30 °C), initiator concentration (2 mol per cent), and UV light intensity (1mW/cm²). Figure 4.49 shows the rates versus time plots of the monomers. Maximum rates of polymerizations for AHM-TMEDA QAC, ACRY-IDPA QAC, METH-PYR/2 QAC were 0.012, 0.004 and 0.002 s⁻¹, respectively. On the other hand, the rates of AHM-PYR QAC, METH-PYR/1 QAC, and METH-PYR/3 QAC were found to be very low and not shown in the Figure 4.49. Although METH-PYR QACs have similar chemical structures (only the length of alkyl chains are different), METH-PYR/2 QAC polymerized faster than METH-PYR/1 QAC and METH-PYR/3 QAC. The lower reactivity of AHM-PYR QAC compared to AHM-TMEDA QAC is probably due to steric effect. Acrylamide QAC showed higher rate of polymerization than methacrylamide QACs as expected. Poor polymerizability of N,N-dialkyl methacrylamide monomers is due to steric effect. Monomer AHM-TMEDA QAC, ACRY-IDPA QAC and METH-PYR/2 QAC showed higher polymerization rate than the other monomers. Fig 4.50 showed the conversion of these monomers as a function of time. The conversions of AHM-TMEDA QAC, ACRY-IDPA QAC and METH-PYR/2 QAC were found to be 55,

18 and 70 per cent, respectively. On the other hand, the AHM-PYR QAC, METH-PYR/1 QAC and METH-PYR/3 QAC monomers showed very low conversions.

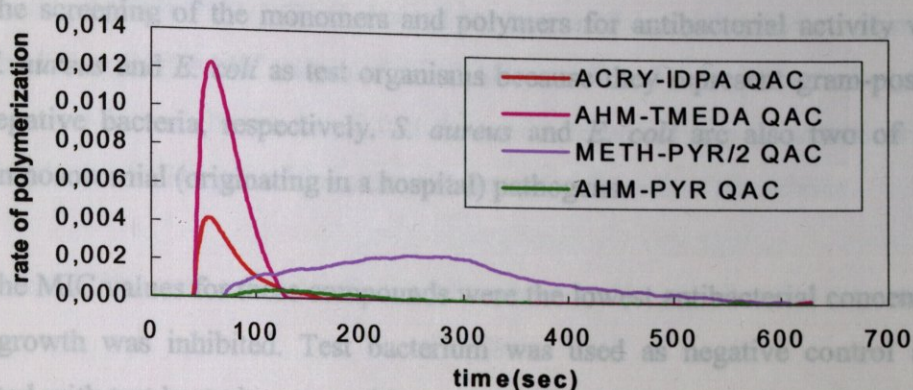


Figure 4.49. Rate versus time of Quaternary ammonium monomers

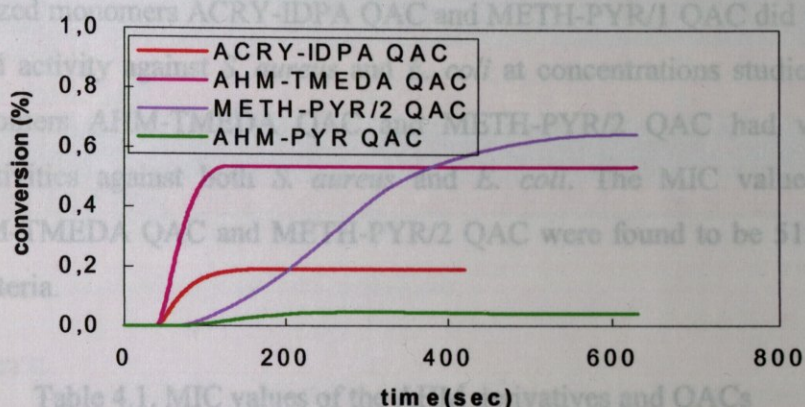


Figure 4.50. Conversion versus time of Quaternary ammonium monomers

Monomers	MIC	
	<i>E.coli</i>	<i>S.aureus</i>
AHM-TMEDA	>512	>512
AHM-IDPA	>512	>512

4.1.7. Measurements of Antibacterial Activities of Monomers and Polymers

Monomers:

ACRY-IDPA QAC	>512	>512
METH-PYR/1 QAC	>512	>512

The synthesized monomers were also homopolymerized and copolymerized with HEMA (20:80) using UV light in the 96-well plate for antibacterial testing. Photopolymerizations were done in water by using a water-soluble photoinitiator

PYR/2 QAC. It has a moderate activity against *E. coli* but good activity against *S. aureus*.

(Irgacure 2959). After photopolymerization the polymers were washed three times with methanol to remove unreacted monomers.

The screening of the monomers and polymers for antibacterial activity was done using *S. aureus* and *E. coli* as test organisms because they represent gram-positive and gram-negative bacteria, respectively. *S. aureus* and *E. coli* are also two of the most common nosocomial (originating in a hospital) pathogens.

The MIC values for these compounds were the lowest antibacterial concentration at which growth was inhibited. Test bacterium was used as negative control and TSB inoculated with test bacterium as positive control. The MIC was the lowest concentration with no visible growth.

The amine monomers AHM-DMAPA, AHM-TMEDA, AHM-IDPA, AHM-PYR and the quaternized monomers ACRY-IDPA QAC and METH-PYR/1 QAC did not show any antibacterial activity against *S. aureus* and *E. coli* at concentrations studied (Table 4.1). The monomers AHM-TMEDA QAC and METH-PYR/2 QAC had very low antibacterial activities against both *S. aureus* and *E. coli*. The MIC values of the monomers AHM-TMEDA QAC and METH-PYR/2 QAC were found to be 512 $\mu\text{g/mL}$ against both bacteria.

Table 4.1. MIC values of the AHM derivatives and QACs

Monomers	MIC	
	E.coli	S.aureus
AHM-DMAPA	>512	>512
AHM-TMEDA	>512	>512
AHM-IDPA	>512	>512
AHM-PYR	>512	>512
AHM-TMEDA QAC	512	512
AHM-PYR QAC	64	32
ACRY-IDPA QAC	>512	>512
METH-PYR/1 QAC	>512	>512
METH-PYR/2 QAC	512	512
METH-PYR/3 QAC	16	16

AHM-PYR QAC showed better activity than AHM-TMEDA QAC and METH-PYR/2 QAC. It has a moderate activity against *E. coli* but good activity against *S. aureus*.

The MIC value of this salt was found to be 64 $\mu\text{g/mL}$ against *E. coli* but it was found to be 32 $\mu\text{g/mL}$ against *S. aureus*. no good antibacterial activities. The visible growth of the homopolymers in the 96-well plate were observed thus they were indicated as negative.

Finally, METH-PYR/3 QAC showed the best antibacterial activity against both *S. aureus* and *E. coli*. The MIC values of this QAC were found to be 16 $\mu\text{g/mL}$ against both *S. aureus*. and *E. coli*. It was found that the antibacterial activity increased as the alkyl chain length attached to one of the nitrogens increased from 6 to 16 carbons.

METH-PYR/3 QAC only showed good antibacterial activity against *S. aureus* but not good Table 4.2. The antibacterial activities of the homopolymers of amine monomers and

QACs

Copolymers:

Homopolymers	Antibacterial activity	
Monomer	S.aureus	E.coli
AHM-DMAPA	-	-
AHM-TMEDA	-	-
AHM-IDPA	-	-
AHM-PYR	-	-
AHM-TMEDA QAC	-	-
AHM-PYR QAC	+	+
ACRY-IDPA QAC	+	+
METH-PYR/1 QAC	-	-
METH-PYR/2 QAC	-	-
METH-PYR/3 QAC	+	-

method. Therefore, the antibacterial activities of each copolymers were also determined using the same procedure with that of homopolymers.

Homopolymers:

It was observed that all monomers turned into crosslinked polymers after photopolymerization. The amine and quaternary ammonium compounds have methyl groups attached to N. These methyl hydrogens can be easily abstracted to give new methylene radicals and result in crosslinked polymer formation. Therefore, the MIC values of these homopolymers could not be determined by using the broth dilution method. The antibacterial activities of each homopolymers were determined by observing the growth. If any visible growth in the 96-well plate was not observed it meant that the QAC had antibacterial activity. Thus, it was indicated as positive. If some visible growth was observed in the 96-well plate, it was indicated as negative.

The homopolymers of amine monomers and AHM-TMEDA QAC, METH-PYR/1 QAC, METH-PYR/2 QAC had no good antibacterial activities. The visible growth of the homopolymers in the 96-well plate were observed thus they were indicated as negative.

The homopolymers of AHM-PYR QAC and ACRY-IDPA QAC showed no visible growth in the cells. Thus, it is possible to say that both of the homopolymers had good antibacterial activities against both *S. aureus*. and *E. coli*. However, the homopolymer of METH-PYR/3 QAC only showed good antibacterial activity against *S. aureus* but not good antibacterial activity against *E. coli*.

Copolymers:

The minimum inhibitory concentration (MIC) values of the copolymers of amine monomers and QACs with HEMA (20:80) were determined by using the broth dilution method as the lowest antibacterial concentration at which growth was inhibited.

Because the copolymerization of all of the monomers gave crosslinked polymers MIC values of these copolymers could not be determined by using the broth dilution method. Therefore, the antibacterial activities of each copolymers were also determined using the same procedure with that of homopolymers.

Table 4.3. The antibacterial activities of the copolymers of AHM derivatives and QACs

Copolymers		Antibacterial activity	
Monomer	Hema (%)	S.aureus	E.coli
AHM-DMAPA	80	-	-
AHM-TMEDA	80	-	-
AHM-IDPA	80	-	-
AHM-PYR	80	-	-
AHM-TMEDA QAC	80	-	-
AHM-PYR QAC	80	+	+
ACRY-IDPA QAC	80	+	+
METH-PYR/1 QAC	80	-	-
METH-PYR/2 QAC	80	-	-
METH-PYR/3 QAC	80	-	-

The copolymers of amine monomers (AHM derivatives) and AHM-TMEDA QAC, METH-PYR/1 QAC, METH-PYR/2 QAC, METH-PYR/3 QAC had no good antibacterial activities. The visible growth of the homopolymers in the 96-well plate were observed thus they were indicated as negative.

Only the copolymers of the quaternized AHM-PYR QAC and ACRY-IDPA QAC with HEMA showed no visible growth in the cells. Thus, it is possible to say that both of these copolymers of AHM-PYR QAC and ACRY-IDPA QAC had good antibacterial activities against both *S. aureus*. and *E. coli*.

4.2. Synthesis and Photopolymerizations of New Crosslinkers

One series of ester derivatives with increasing size of spacer between double bonds was synthesized from the reactions of TBHMA with succinyl chloride, adipoyl chloride and dodecanedioyl dichloride (Figure 4.51). The t-butyl ester group is well known for acid-catalyzed elimination yielding the carboxylic acid and isobutylene. We have used this reaction to deprotect the monomers containing t-butyl group to obtain monomers with diacid functionality. Two new ether derivatives of TBHMA were synthesized (Figure 4.52) from the reactions of TBBr with triethyleneglycol and Bisphenol A. T-butyl ester groups were deprotected to obtain diacid monomers.

The reactivities of the monomers were investigated using Photo-DSC. The polymerization rates and conversions were determined for each of the monomers. The effect of monomer structure on the polymerization reactivity were determined. The diacid monomers may have potential for adhesion to metal and dentin. They can be used for dental composites and coatings.

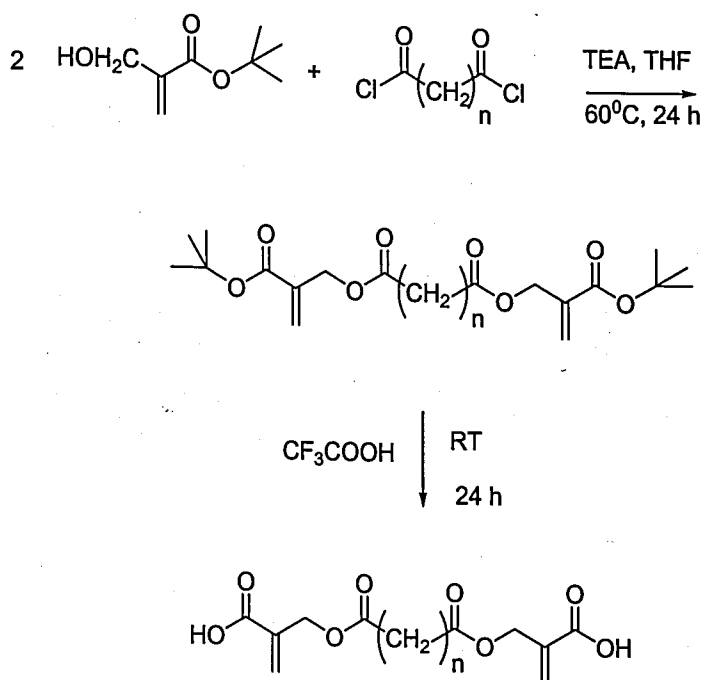


Figure 4.51. General synthetic scheme for ester-linked diacid monomers

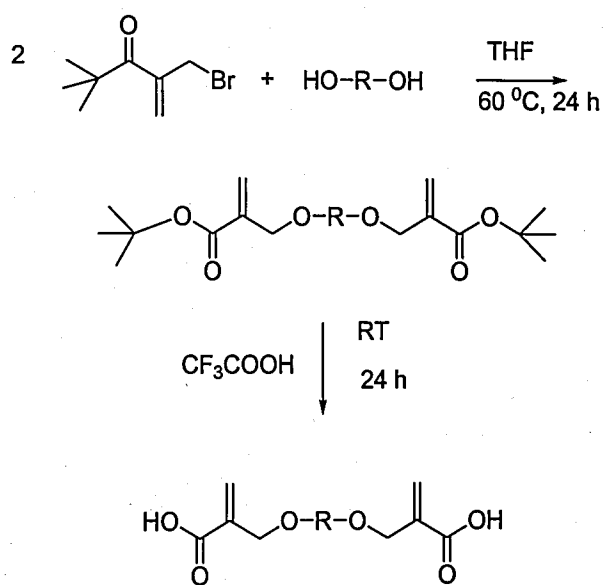


Figure 4.52. General synthetic scheme for ether-linked diacid monomers

4.2.1. Synthesis of Tert-Butyl α -Hydroxymethyl Acrylate (TBHMA) and Tert-Butyl α -Bromomethyl Acrylate (TBBr)

TBHMA was synthesized from the reaction of t-butyl acrylate and paraformaldehyde in the presence of 1,4-Diazobicyclo [2.2.2] octan (DABCO) as catalyst (Figure 4.53) using literature procedures.

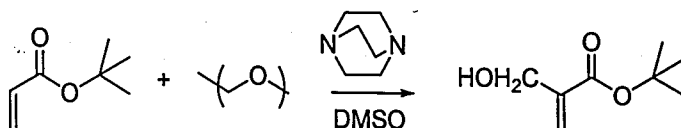


Figure 4.53. Synthesis of TBHMA

^{13}C -NMR spectrum of TBHMA (Figure 4.54) is characterized by methylene carbon at 60.8 ppm, tert-butyl carbons at 80.48 and 27.5 ppm, the double bond carbons at 123.23 and 140.85 ppm and the carbonyl carbon peak at 165.06 ppm.

^1H -NMR spectrum of TBHMA shows t-butyl protons at 1.4 ppm, methylene protons at 3.9 ppm, a hydroxyl proton at 4.13 ppm and double bond protons at 5.61 ppm and 5.95 ppm.

IR spectrum shows peaks at 1639, 1709, 2978-2934 and 3419 cm^{-1} , which can be assigned to $\text{C}=\text{C}$, $\text{C}=\text{O}$, $\text{C}-\text{H}$ and $\text{O}-\text{H}$.

Reaction of TBHMA (Figure 4.55) with PBr_3 in ether gave TBBr as a colorless liquid in 80-90 per cent yield.

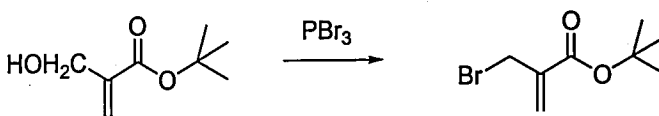


Figure 4.55. Synthesis of TBBr

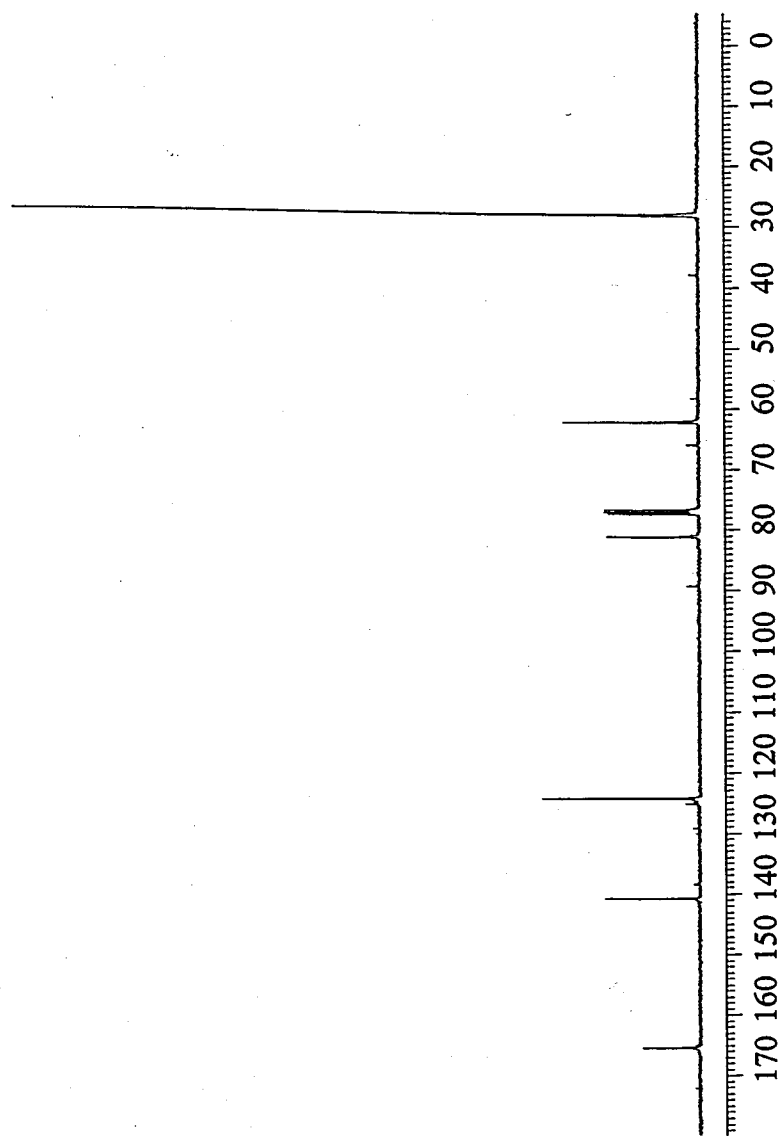


Figure 4.54. ^{13}C -NMR spectrum of TBHMA

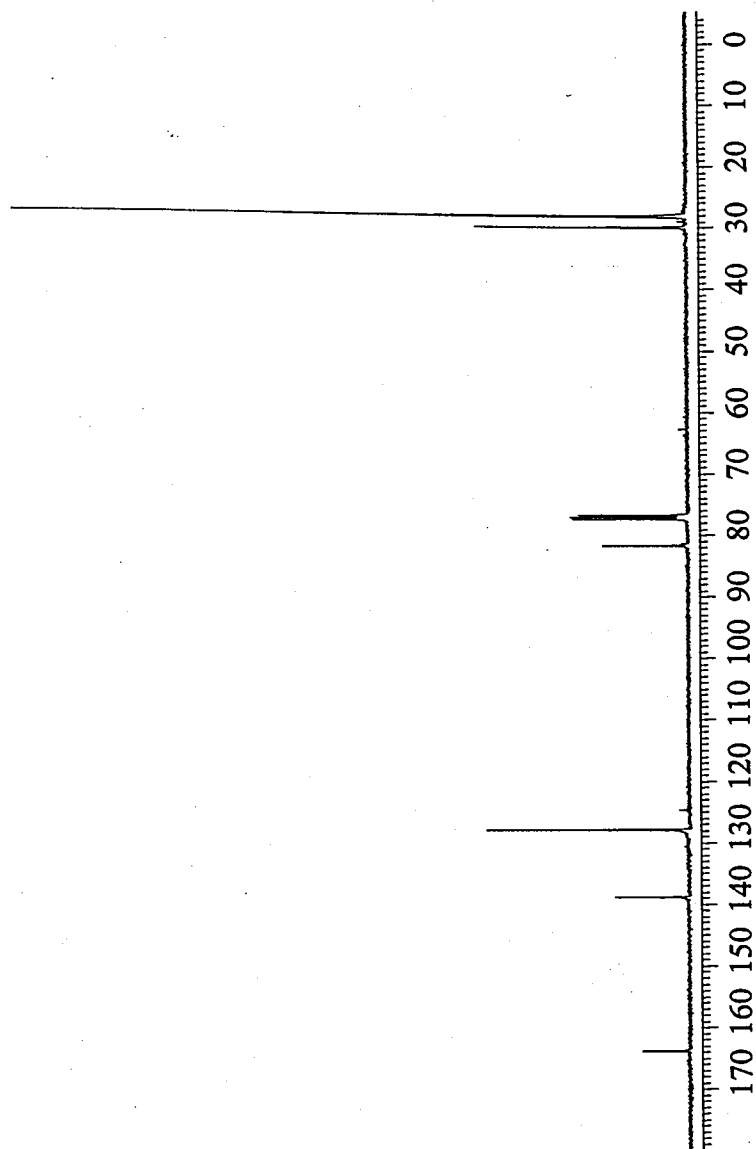


Figure 4.56. ^{13}C -NMR spectrum of TBBBr

^{13}C -NMR spectrum of TBBr (Figure 4.56) shows the disappearance of $\text{CH}_2\text{-OH}$ peak of TBHMA at 60.87 ppm and appearance of new peak at 29.68 ppm due to $\text{CH}_2\text{-Br}$.

^1H -NMR spectrum of TBBr shows a singlet at 0.7 ppm for tert-butyl ester protons, a singlet at 3.9 ppm due to CH_2Br protons, two doublets for double bond protons at 5.0 and 5.3 ppm.

IR spectrum shows no hydroxyl absorption peak at 3411 cm^{-1} .

4.2.2. Synthesis of TBHMA-Ester Diacid and Ether Diacid Derivatives

4.2.2.1. Synthesis of TBHMA-Succinyl ester-diacid Derivative. TBHMA-Succinyl ester derivative was synthesized (Figure 4.57) from the reaction of TBHMA with succinyl chloride using DMAP as catalyst in THF at 60°C . The crude product yield was 91 per cent. This intermediate monomer was hydrolyzed with trifluoro acetic acid under N_2 and purified by recrystallization from methanol to give a white solid with a melting point of $169\text{-}170^\circ\text{C}$ in 15.6 per cent yield.

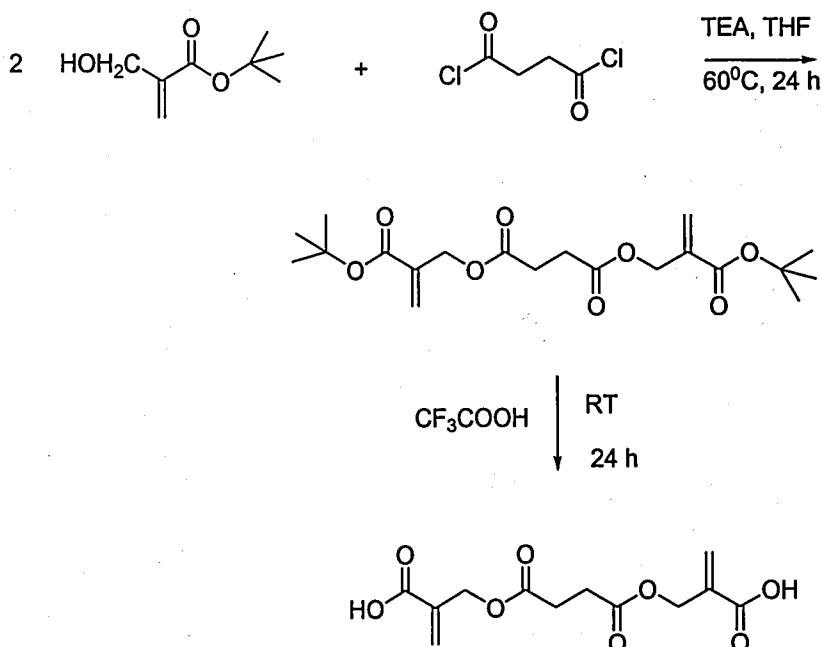


Figure 4.57. Synthesis of TBHMA-Succinyl ester diacid derivative

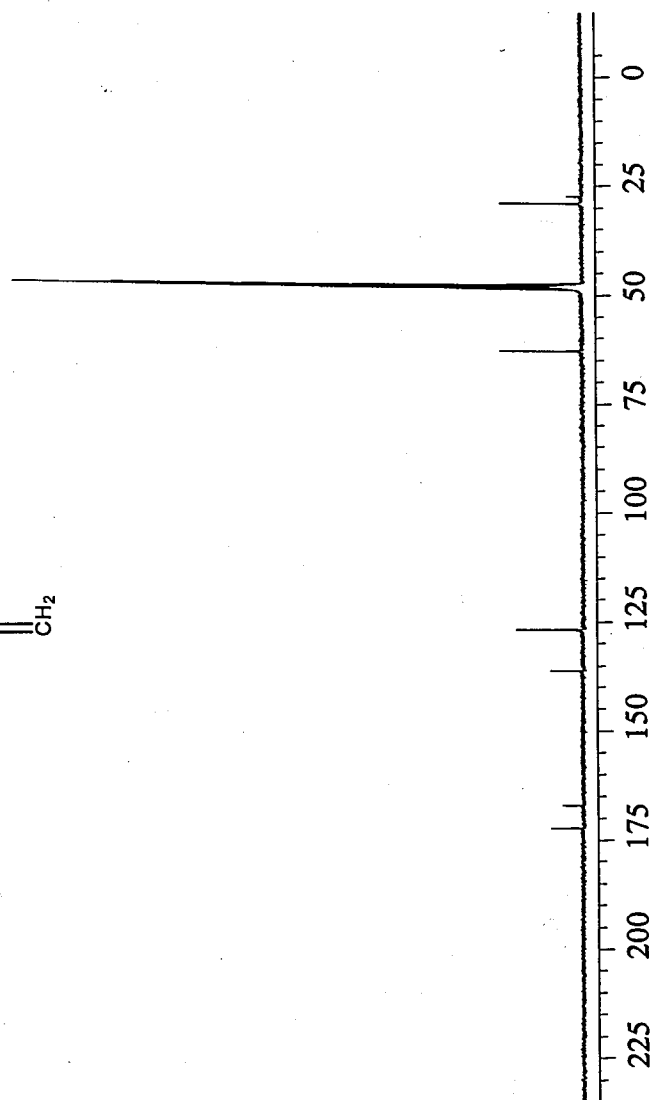
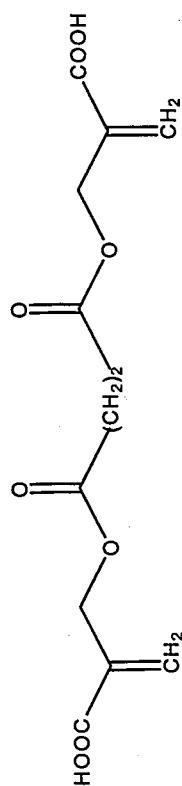


Figure 4.58. ^{13}C -NMR spectrum of TBHMA-Succinyl ester diacid derivative

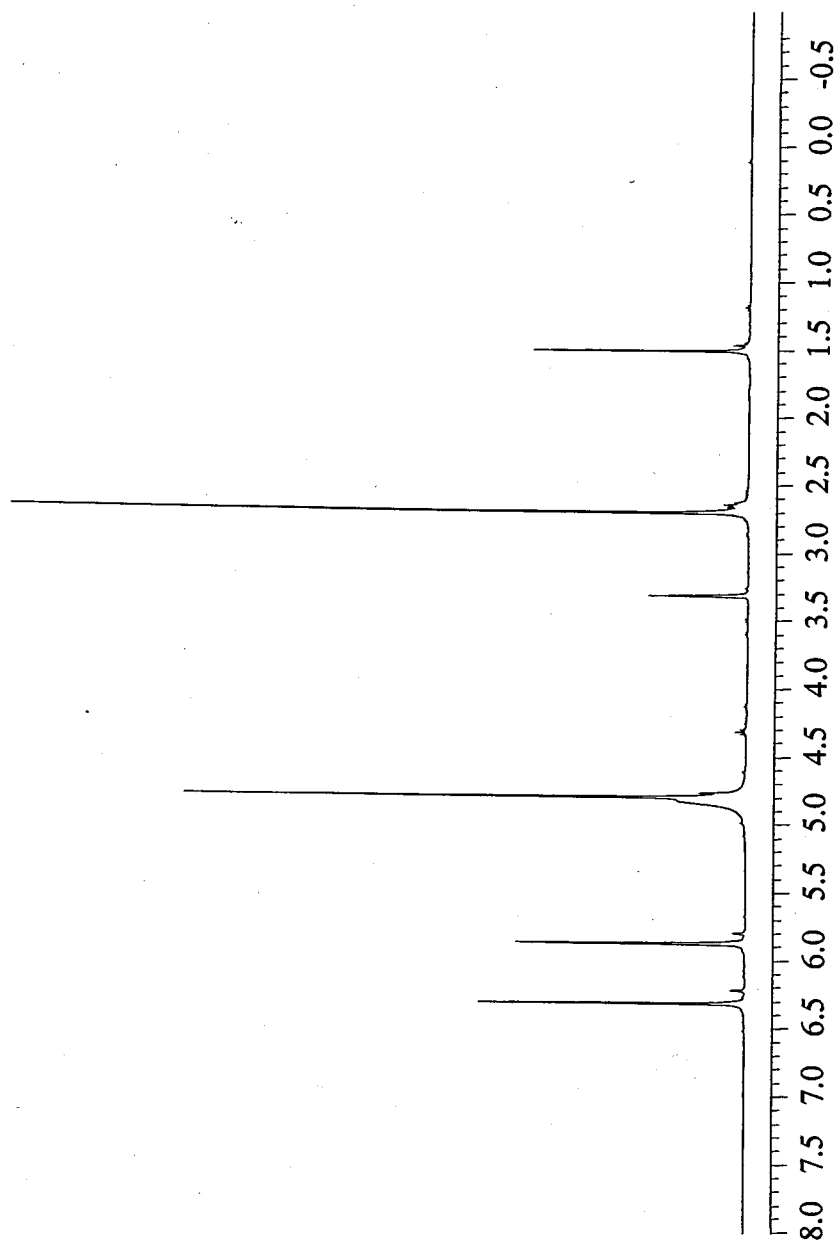


Figure 4.59. ^1H -NMR spectrum of TBHMA-Succinyl ester diacid derivative

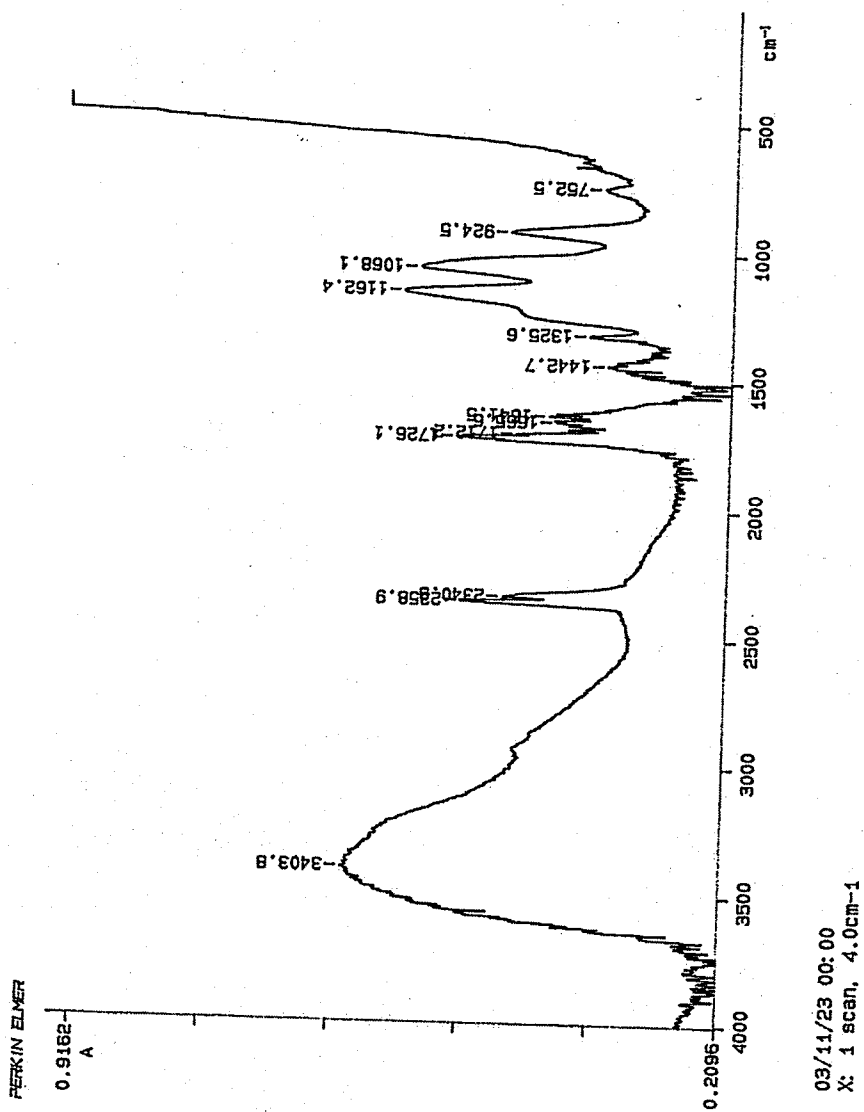


Figure 4.60. IR spectrum of TBHMA-Succinyl acid derivative

The TBHMA-Succinyl ester-diacid derivative was soluble in methanol, DMSO but insoluble in chloroform, methylenechloride, diethylether and hexane. This monomer was also partially soluble in water.

^{13}C -NMR spectrum of TBHMA-Succinyl ester-diacid derivative (Figure 4.58) showed characteristic peaks for methylene carbons of the succinyl group at 29.7 ppm, double bond carbons at 127.4 and 136.9 ppm, two different carbonyls due to ester and carboxylic acid at 167.8 and 172.9 ppm.

^1H -NMR spectrum of TBHMA-Succinyl ester-diacid derivative (Figure 4.59) showed methylene protons of the succinyl group at 2.7 ppm, ester methylenes at 4.8 ppm and double bond protons at 5.9 and 6.2 ppm.

The FT-IR spectrum of this monomer (Figure 4.60) showed the double bond peak at 1641 cm^{-1} plus two different carbonyl peaks due to ester and carboxylic acid groups at 1726 and 1665 cm^{-1} . The appearance of hydroxyl group at 3403 cm^{-1} confirmed the formation of the product.

4.2.2.2. Synthesis of TBHMA-Adipoyl ester-diacid Derivative. TBHMA-Adipoyl ester derivative was synthesized by reacting TBHMA with adipoyl chloride in THF in the presence of DMAP (Figure 4.61) at 60°C for 24 hours. This intermediate monomer was subjected to hydrolysis with CF_3COOH and purified by recrystallization from methanol to give a white solid with a melting point of $143\text{--}145^\circ\text{C}$ in 9 per cent yield.

The TBHMA-Adipoyl ester-diacid derivative was soluble in chloroform, methanol, DMSO and methylenechloride but insoluble in water, diethylether and hexane.

^{13}C -NMR spectrum of TBHMA-Adipoyl ester-diacid derivative (Figure 4.62) showed characteristic peaks for methylene carbons of the adipoyl group at 25.4 ppm, methylenes of ester groups and two methylene groups attached to carbonyls at 63.6 and 34.5 ppm, double bond carbons at 127.7 and 137.3 ppm plus two different carbonyls due to ester and carboxylic acid at 168.1 and 174.1 ppm.

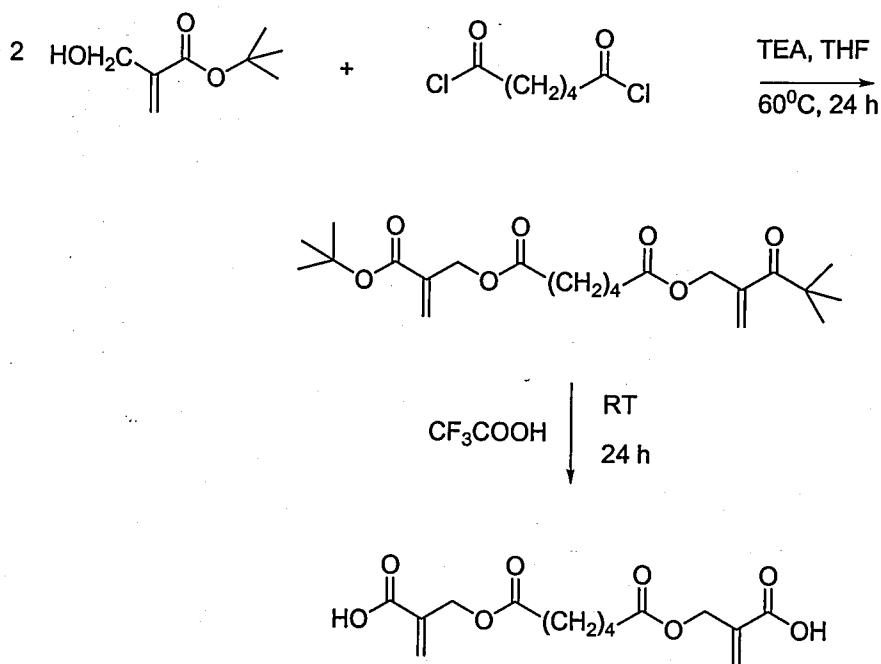


Figure 4.60. Synthesis of TBHMA-Adipoyl ester diacid derivative

^1H -NMR spectrum of TBHMA-Adipoyl ester derivative (Figure 4.63) showed methylene protons of the adipoyl group at 2.3 ppm, ester methylenes at 4.6 ppm and double bond protons at 5.7 and 6.2 ppm.

The FT-IR spectrum of this monomer (Figure 4.64) showed the double bond peak at 1630 cm^{-1} and carbonyl peaks due to ester and carboxylic acid groups at 1728 and 1670 cm^{-1} . The appearance of hydroxyl group at 3420 cm^{-1} confirmed the formation of the product.

4.2.2.3. Synthesis of TBHMA-Dodecanedioyl ester-acid Derivative. Reaction of TBHMA with dodecanedioyl dichloride in the presence of DMAP gave a diester intermediate which was hydrolyzed with CF_3COOH to obtain a diacid monomer (Figure 4.65).

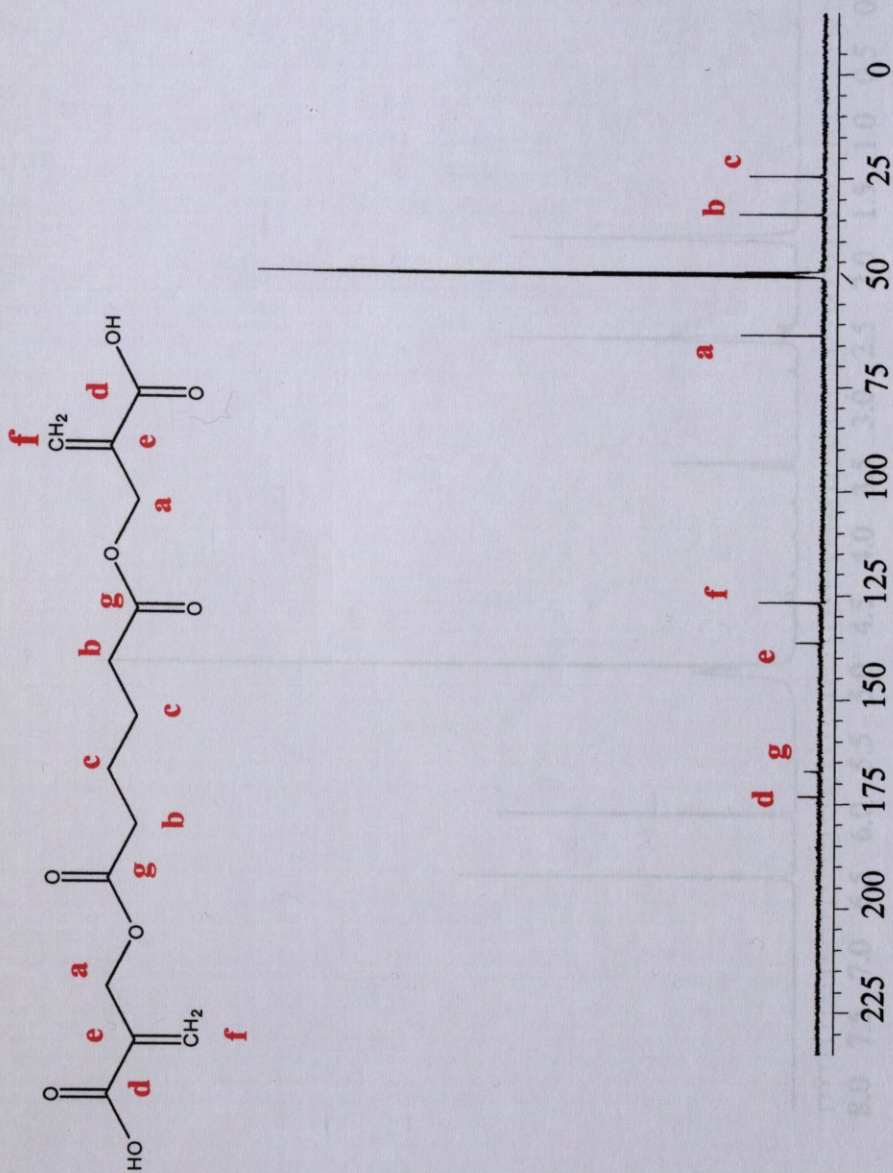


Figure 4.62. ^{13}C -NMR spectrum of TBHMA-Adipoyl ester diacid derivative

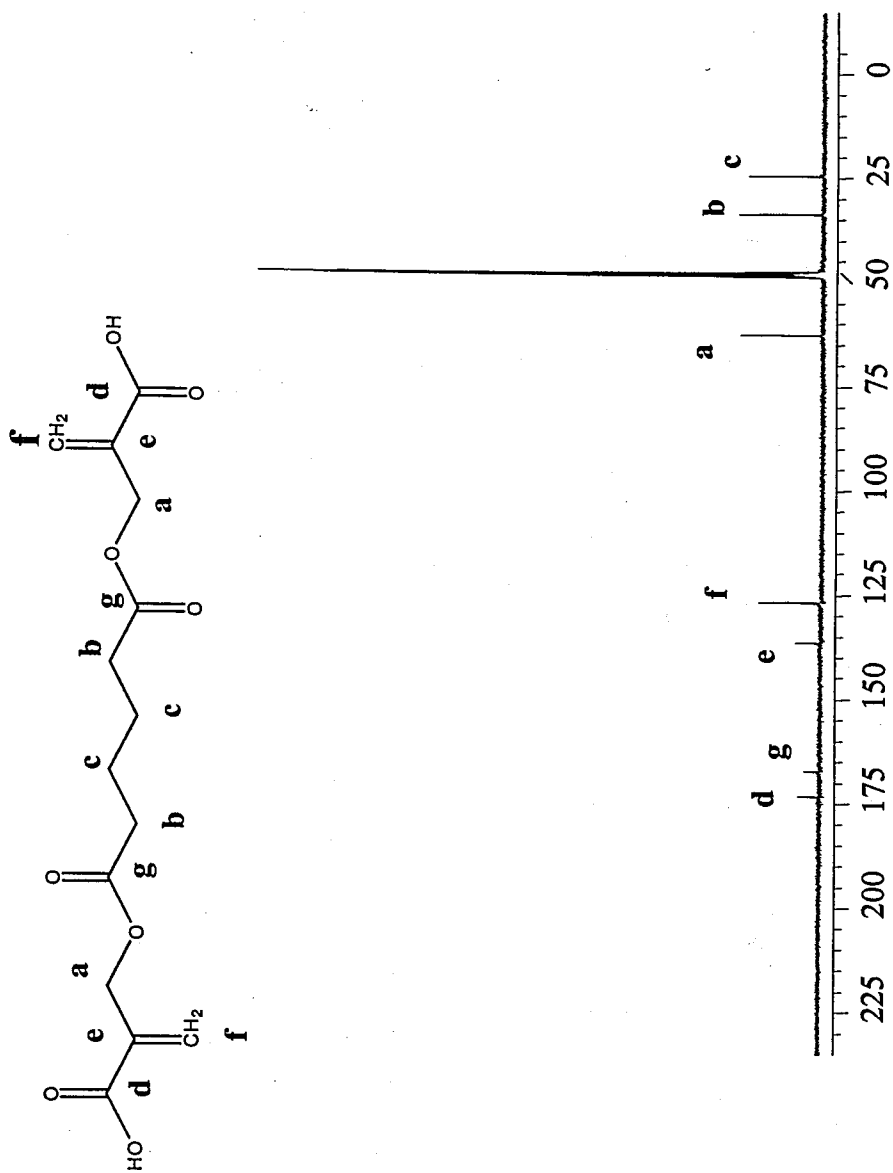


Figure 4.62. ^{13}C -NMR spectrum of TBHMA-Adipoyl ester diacid derivative

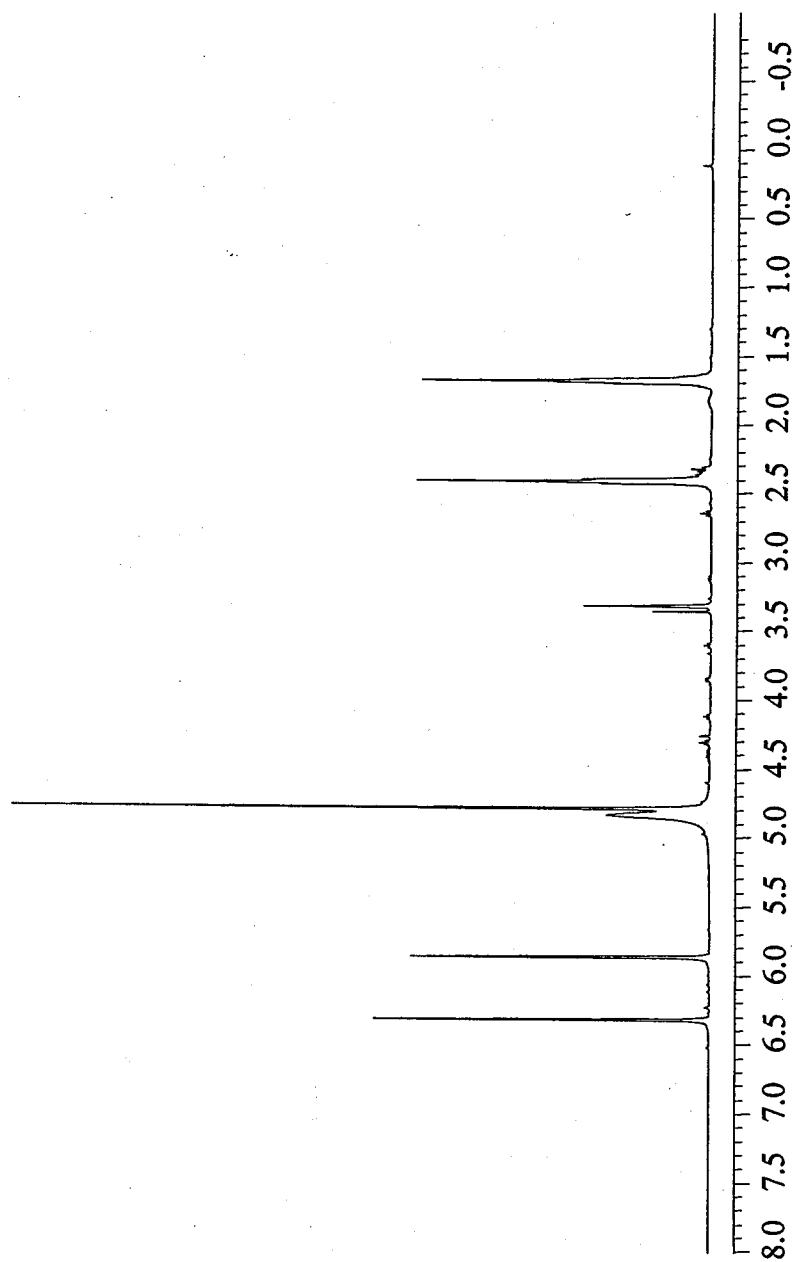


Figure 4.63. ^1H -NMR spectrum of TBHMA-Adipoyl ester diacid derivative

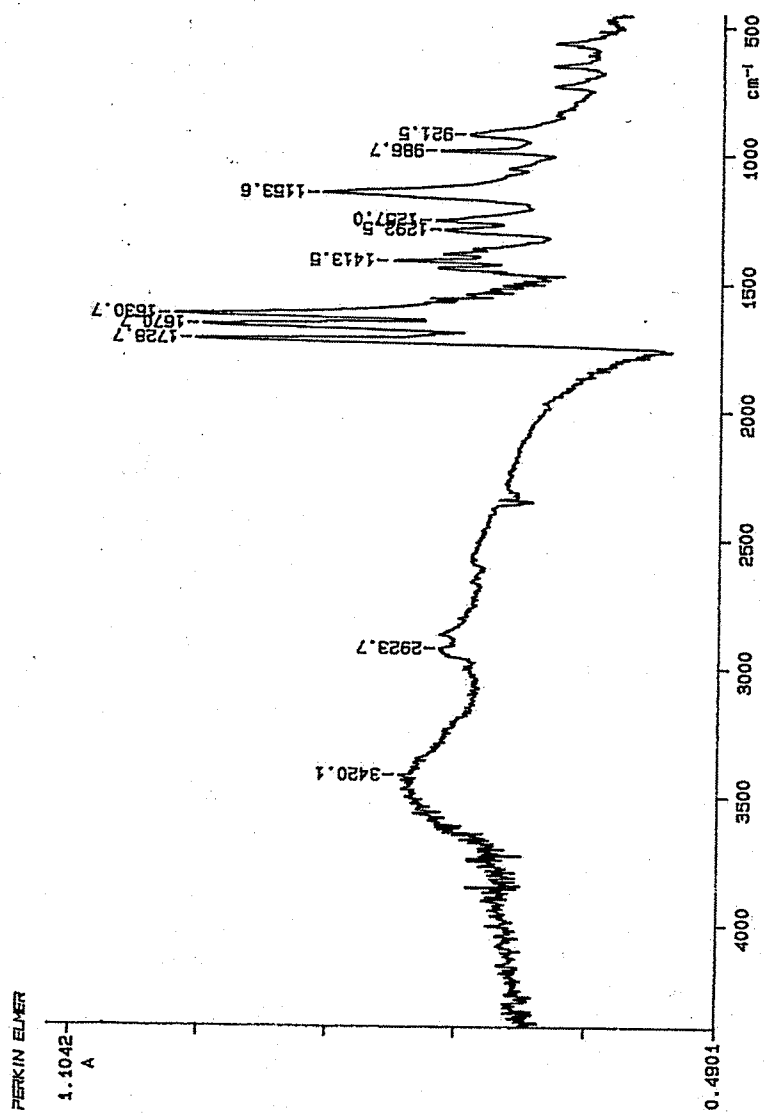


Figure 4.64. IR spectrum of TBHMA-Adipoyl ester diacid derivative

The TBHMA-Dodecanedioyl ester-diacid derivative was soluble in chloroform, methanol, DMSO and methylenechloride but insoluble in water, diethylether and hexane.

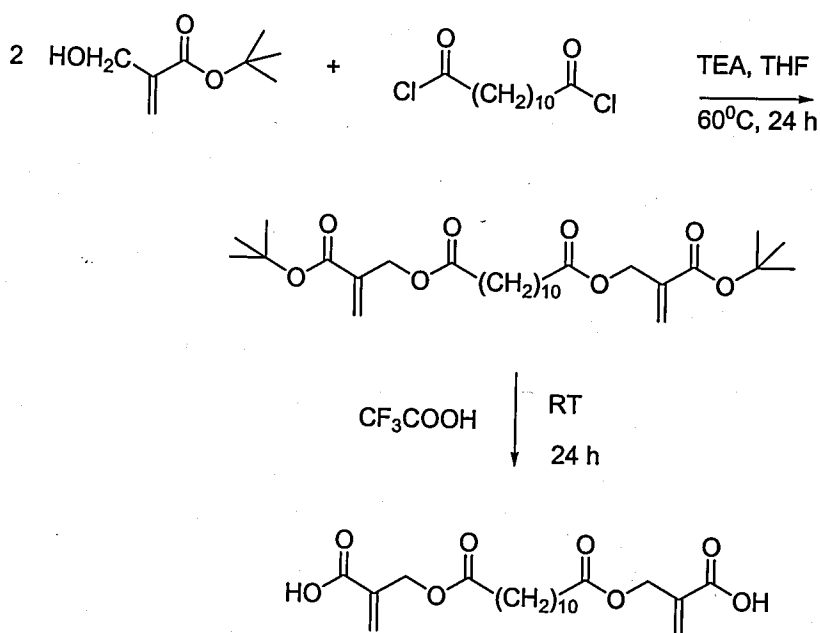


Figure 4.64. Synthesis of TBHMA-Dodecanedioyl ester diacid derivative

The reaction was monitored using ^{13}C NMR and ^1H NMR spectroscopy. The ^{13}C NMR spectrum showed disappearance of t-butyl carbons at 27.5 ppm after the reaction. The spectrum shows (Figure 4.66) methylenes at 23.7 and 27.6 ppm, two methylene groups attached to carbonyls at 61.1 and 32.6 ppm, double bond carbon peaks at 135.2 and 125.5 ppm, methylenes of ester groups and two different carbonyls due to ester and carboxylic acid at 165.2 and 171.3 ppm.

¹H NMR (Figure 4.67) spectrum showed methylene protons of the dodecanedioyl group at 1.3 ppm. Methylene protons attached to carbonyl groups also appeared at 2.3 ppm, ester methylenes at 4.7 ppm and double bond protons at 5.8 and 6.2 ppm.

The FT-IR spectrum of the derivative (Figure 4.68) showed C-O vibrations at 1166 cm^{-1} , C=C stretching peak at 1635 cm^{-1} , and the ester carbonyl at 1725 cm^{-1} .

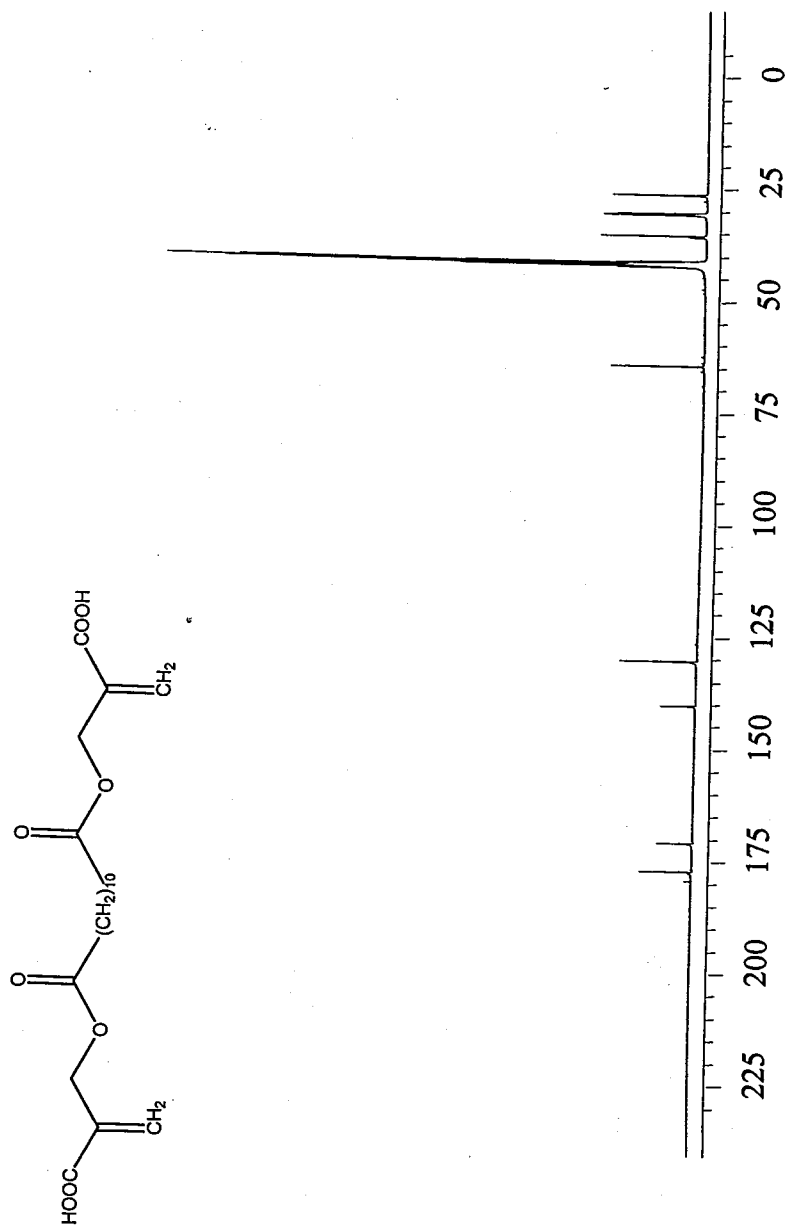


Figure 4.66. ^{13}C -NMR spectrum of TBHMA-Dodecanedioyl ester diacid derivative

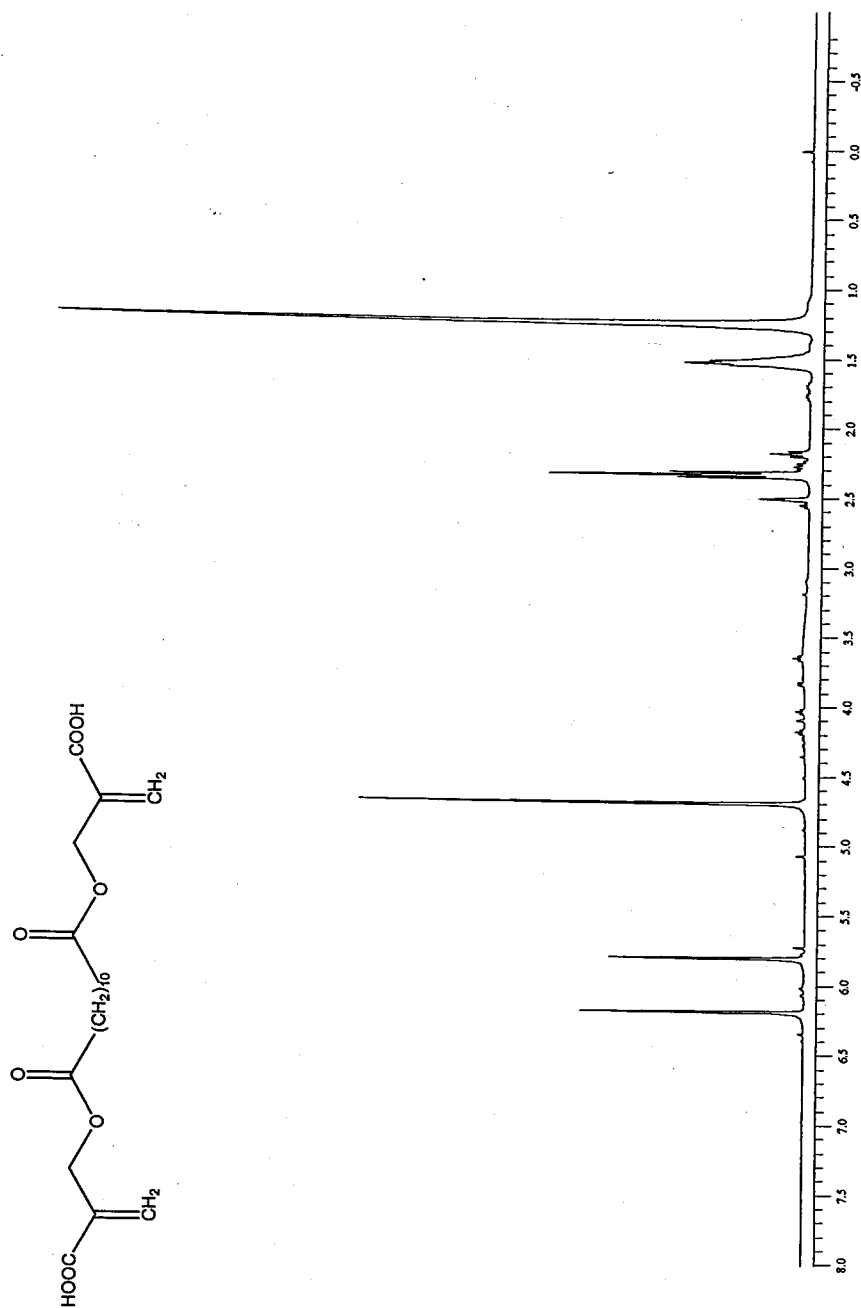


Figure 4.67. $^1\text{H-NMR}$ spectrum of TBHMA-Dodecanedioyl ester diacid derivative

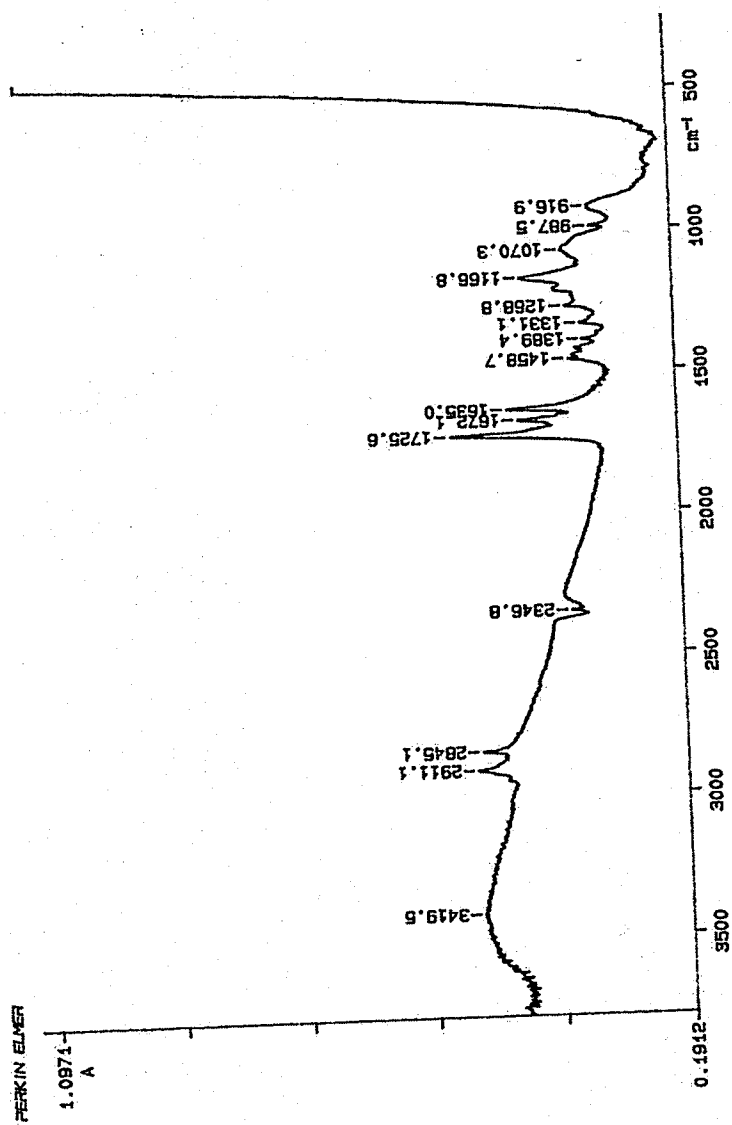


Figure 4.68. IR spectrum of TBHMA-Dodecanediol ester diacid derivative

4.2.2.4. Synthesis of TBBBr-Bisphenol A diacid Derivative. A new ether-linked diacid monomer was (Figure 4.69) synthesized in two steps. The first step involved reaction of TBBBr and Bisphenol A in the presence of TEA as catalyst to give a ether-diester intermediate. In the second step the intermediate was hydrolyzed with CF_3COOH . The ether-diacid monomer was obtained in 57 per cent yield as a white solid with a melting point of 189.1°C .

The TBBBr-Bisphenol A diacid derivative was soluble in methanol and DMSO but insoluble in water chloroform, methylene chloride, and hexane. It is also partially soluble in diethylether.

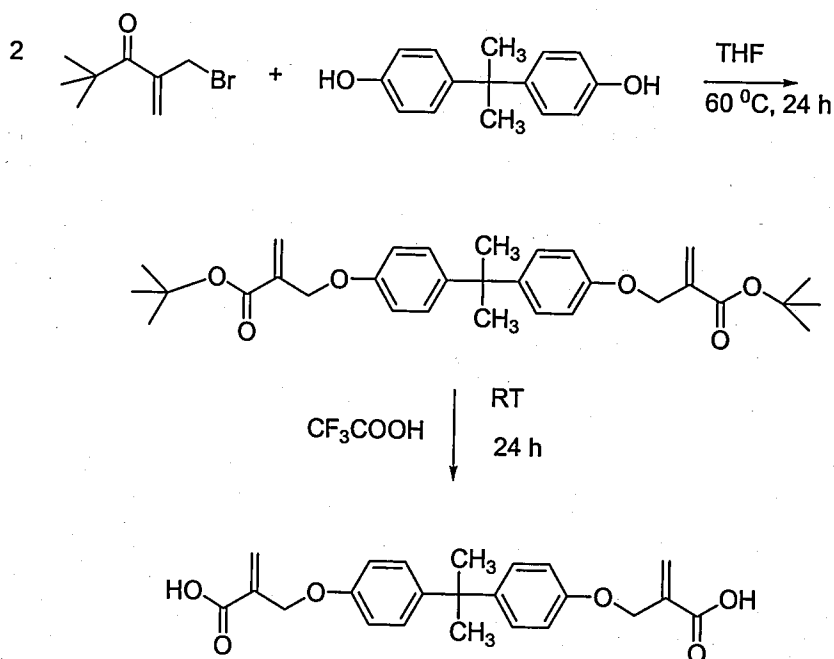


Figure 4.69. Synthesis of TBBBr-Bisphenol A diacid derivative

In the ^{13}C -NMR spectrum the peaks correspond to t-butyl groups disappeared at 27.5 ppm. The two methyls of bisphenol groups appeared at 41.3 ppm (Figure 4.70). The carbon peaks of ether groups at 65.9 ppm and pyridine carbons at 113.9, 127.3, and 136.8 ppm. Carbonyl and double bond carbons at 166.3 and 126.0, 142.7 ppm were observed.

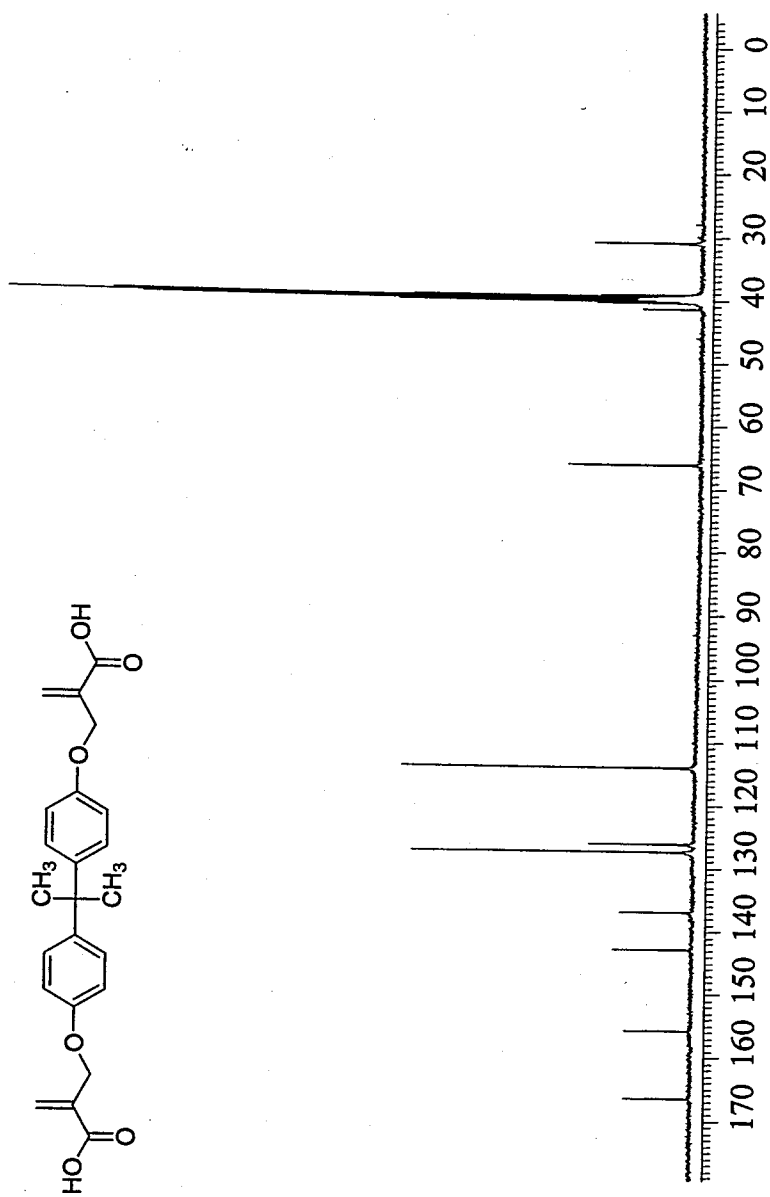


Figure 4.70. ^{13}C -NMR spectrum of TBBP-Bisphenol A diacid derivative

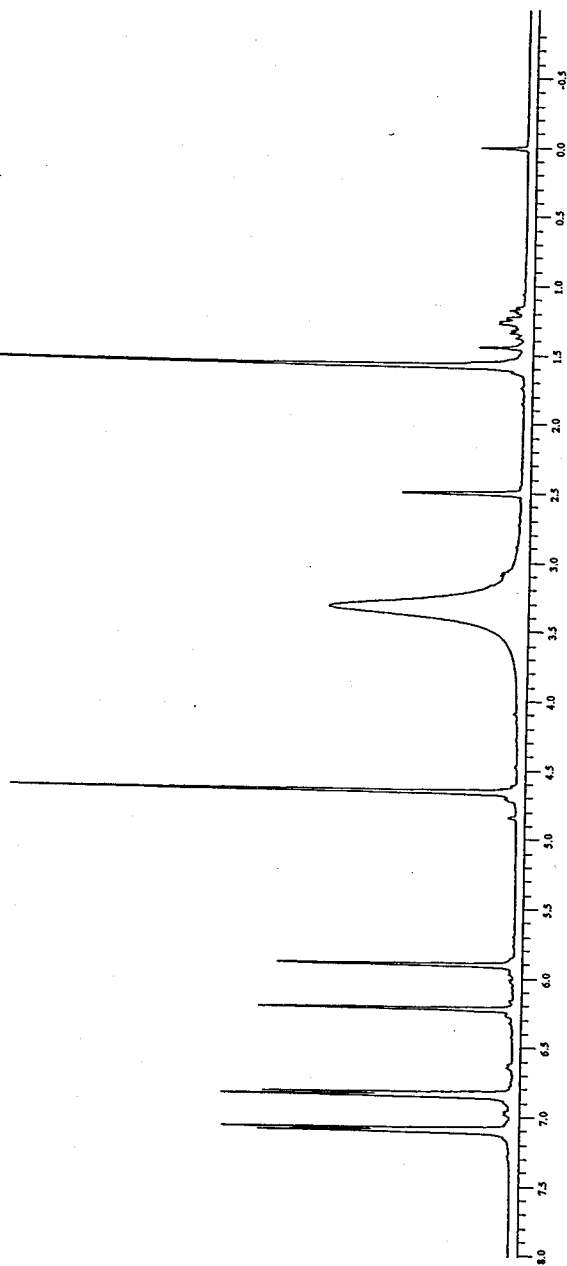
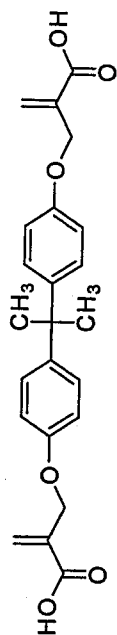


Figure 4.71. ¹H-NMR spectrum of TBBP-Bisphenol A diacid derivative

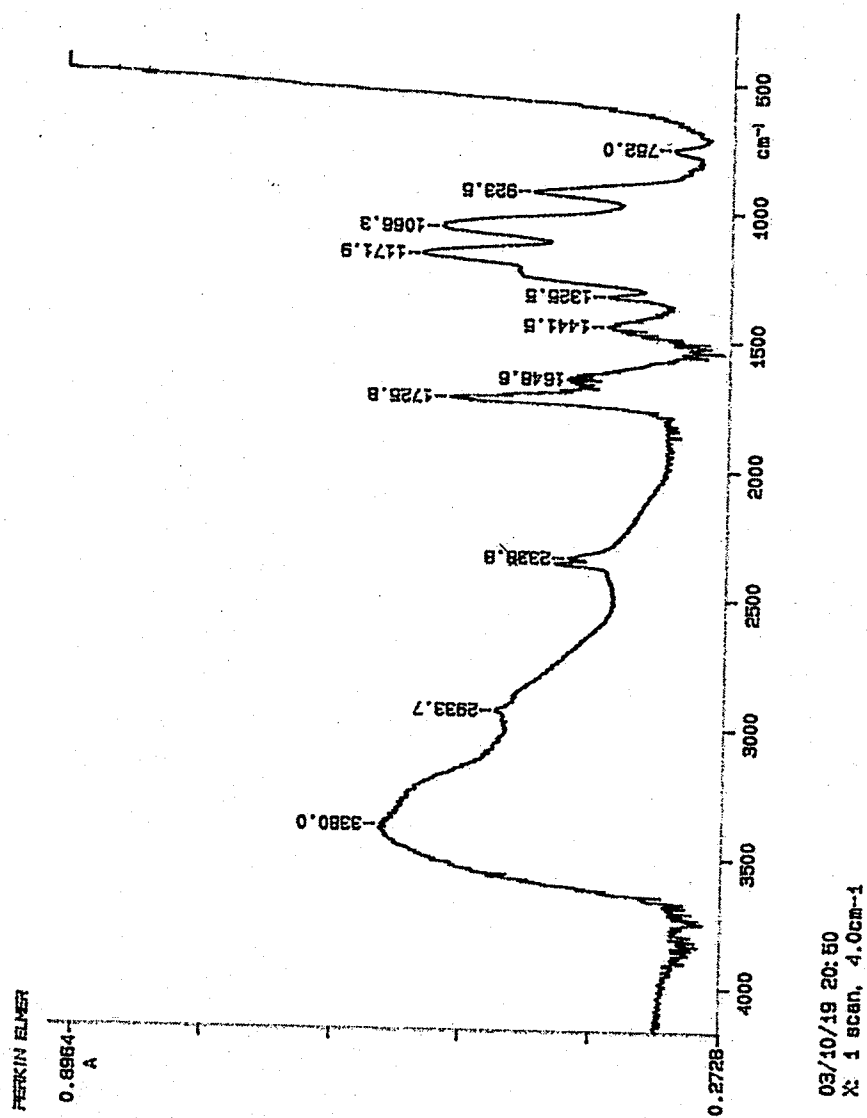


Figure 4.72. IR spectrum of TBBBr-Bisphenol A diacid derivative

^1H NMR (Figure 4.71) spectrum showed two methyl protons appeared at 1.6 ppm, ether methylenes at 4.6 ppm, double bond protons at 5.9 and 6.2 ppm and pyridine protons of the bisphenol group at 6.8 and 7.1 ppm.

The IR spectrum of the derivative (Figure 4.72) showed C-O vibrations at 1171 cm^{-1} , C=C stretching peak at 1648 cm^{-1} , the ester carbonyl at 1725 cm^{-1} , and C-H vibrations at 2933 cm^{-1} . The broad peak around 3380 cm^{-1} was due to OH stretching which confirmed the formation of the product.

4.2.2.5. Synthesis of TBBr-Triethyleneglycol diacid Derivative. Another ether-diacid derivative was synthesized by reacting TBBr with triethyleneglycol in THF in the presence of TEA (Figure 4.73) at 60°C for 24 hours under nitrogen followed by hydrolysis with CF_3COOH at room temperature for 24 h.

The ether-diacid monomer was soluble in water, chloroform, methanol, DMSO and methylenechloride but insoluble in hexane. It is also partially soluble in diethylether.

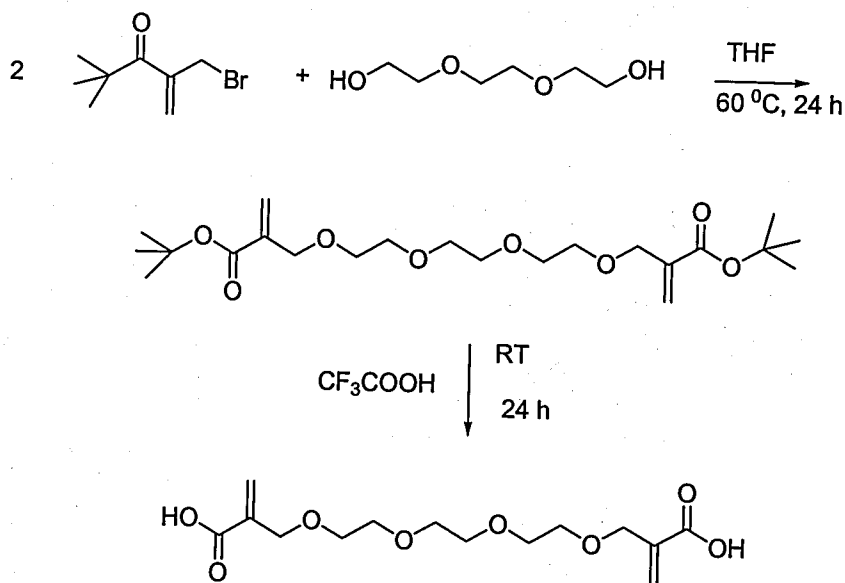


Figure 4.73. Synthesis of TBBr-Triethyleneglycol diacid derivative

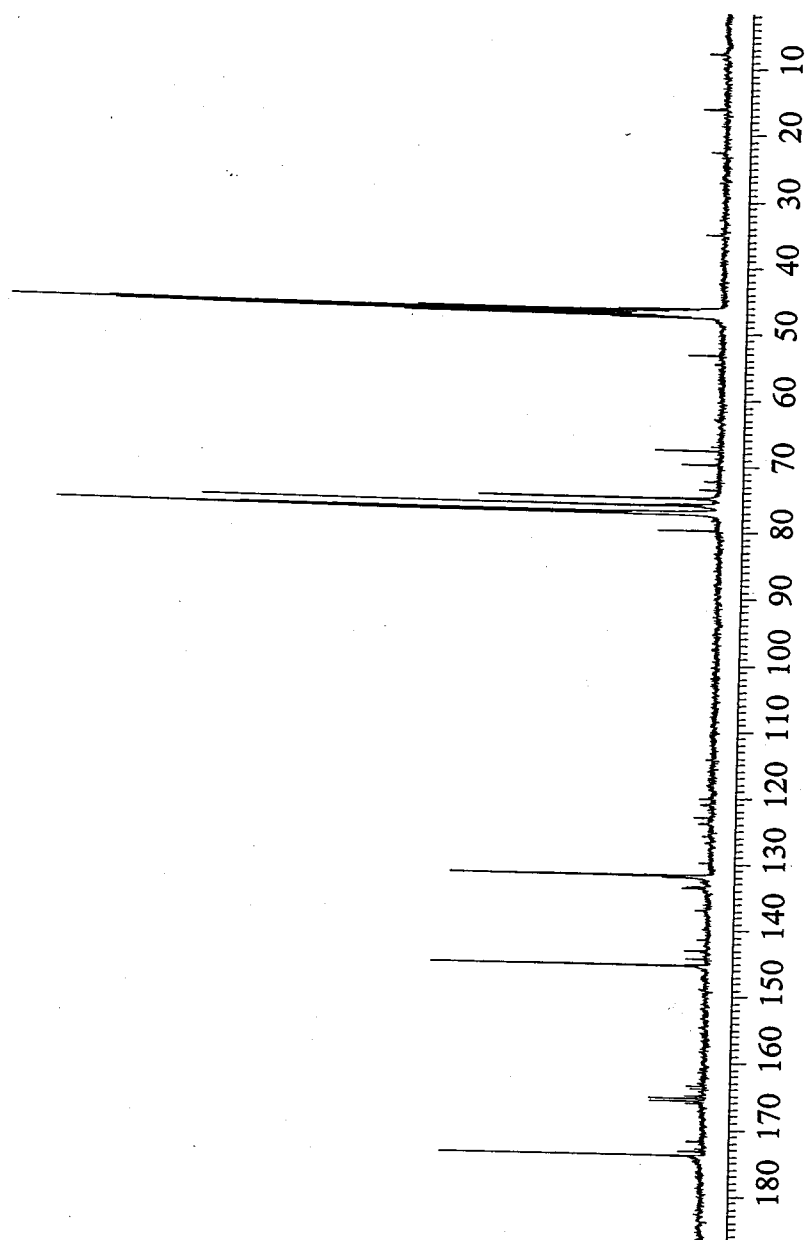


Figure 4.74. ^{13}C -NMR spectrum of TBBT-Triethyleneglycol diacid derivative

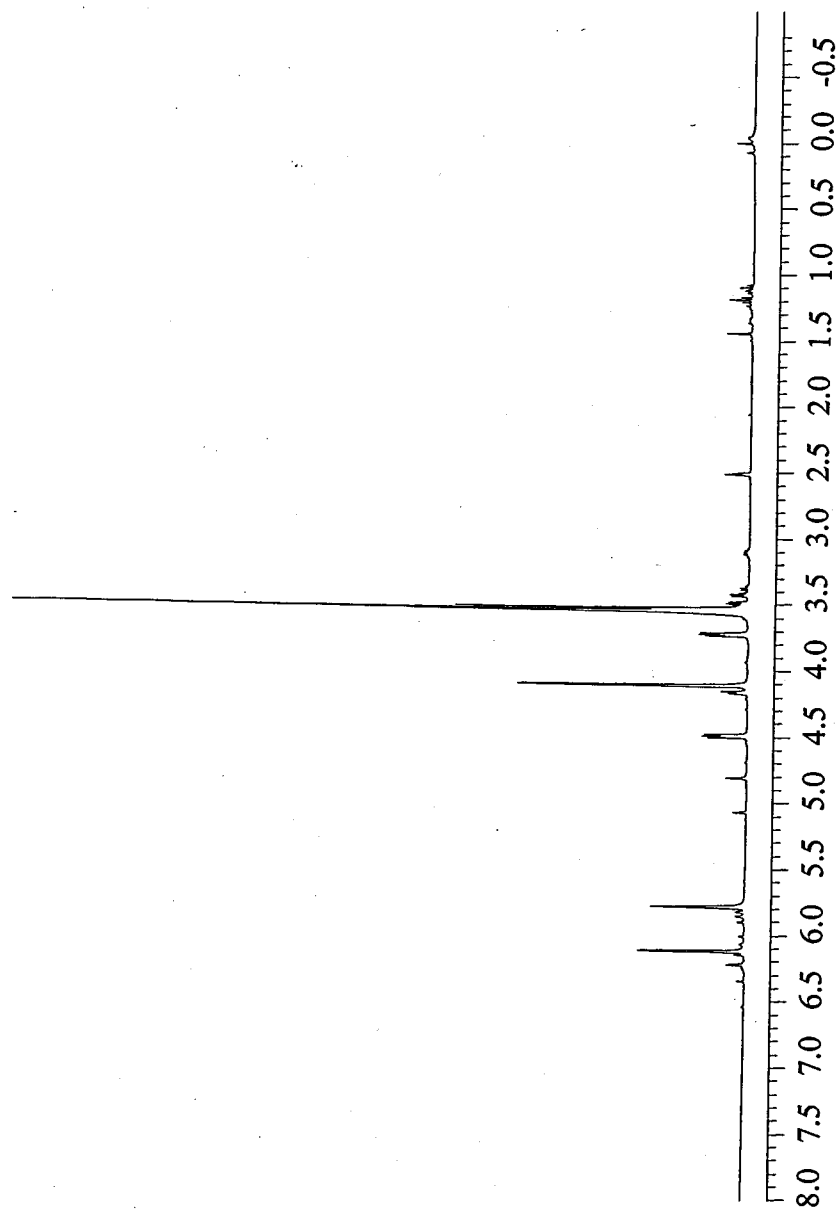


Figure 4.75. ^1H -NMR spectrum of TBBT-Triethyleneglycol diacid derivative

The ^{13}C NMR spectrum showed disappearance of t-butyl carbons at 27.5 ppm after the reaction. The spectrum shows (Figure 4.74) methylenes of ether group at 68 and 72 ppm, double bond carbon peaks at 138.5 and 125.0 ppm and one carbonyl peak due to carboxylic acid at 166.0 ppm.

^1H NMR (Figure 4.75) spectrum showed methylenes of triethyleneglycol group at 3.5 ppm, CH_2O groups attached to double bonds at 4.1 ppm and double bond protons at 5.8 and 6.1 ppm.

4.2.3. Photopolymerizations

Photopolymerizations of the monomers were followed by Photo-DSC. All the photopolymerizations were performed under identical conditions of initiator concentration (2.0 mol per cent) and UV light intensity ($1\text{mW}/\text{cm}^2$) but at different temperatures (at 40°C and 60°C). The exotherms were recorded during copolymerizations of ester and ether diacid monomers with HEMA (0.5:99.5) at 40°C and 60°C (Figure 4.76, 4.77, 4.78, 4.79). The rates and conversions of these four diacid monomers were compared with bulk HEMA.

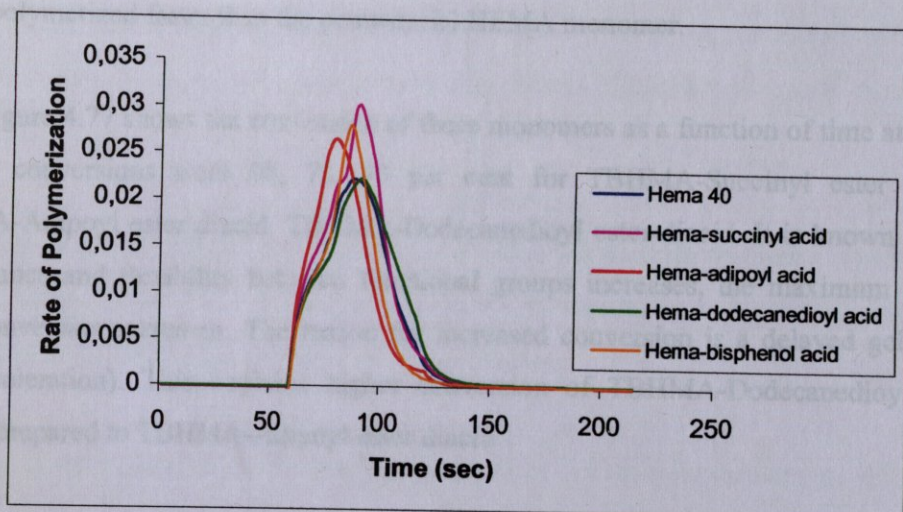


Figure 4.76. Rates versus time of HEMA with multifunctional crosslinkers at 40°C (0.5 mol per cent concentration)

The ^{13}C NMR spectrum showed disappearance of t-butyl carbons at 27.5 ppm after the reaction. The spectrum shows (Figure 4.74) methylenes of ether group at 68 and 72 ppm, double bond carbon peaks at 138.5 and 125.0 ppm and one carbonyl peak due to carboxylic acid at 166.0 ppm.

^1H NMR (Figure 4.75) spectrum showed methylenes of triethyleneglycol group at 3.5 ppm, CH_2O groups attached to double bonds at 4.1 ppm and double bond protons at 5.8 and 6.1 ppm.

4.2.3. Photopolymerizations

Photopolymerizations of the monomers were followed by Photo-DSC. All the photopolymerizations were performed under identical conditions of initiator concentration (2.0 mol per cent) and UV light intensity ($1\text{mW}/\text{cm}^2$) but at different temperatures (at 40°C and 60°C). The exotherms were recorded during copolymerizations of ester and ether diacid monomers with HEMA (0.5:99.5) at 40°C and 60°C (Figure 4.76, 4.77, 4.78, 4.79). The rates and conversions of these four diacid monomers were compared with bulk HEMA.

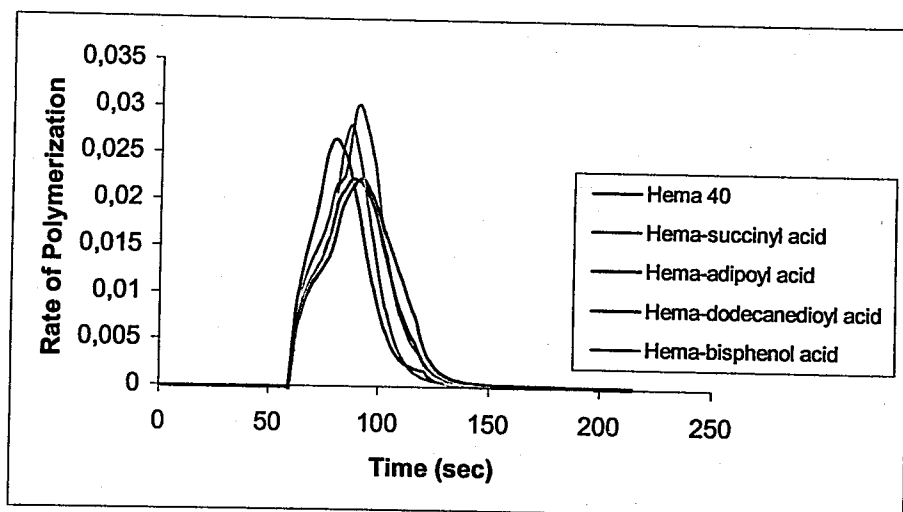


Figure 4.76. Rates versus time of HEMA with multifunctional crosslinkers at 40°C (0.5 mol per cent concentration)

Figure 4.76 shows the rates versus time plots for TBHMA-Succinyl ester diacid, TBHMA-Adipoyl ester diacid, TBHMA-Dodecanedioyl ester diacid and TBBBr-Bisphenol A ester diacid with HEMA (0.5:99.5) at 40 °C. The maximum rate of polymerizations for HEMA:TBHMA-Succinyl ester diacid, HEMA:TBHMA-Adipoyl ester diacid, HEMA:TBHMA-Dodecanedioyl ester diacid and HEMA were found to be 0.031, 0.026, 0.023 and 0.023 s⁻¹, respectively.

It is obvious that, as the monomer flexibility (size of spacer between double bonds) increased, the rate of polymerization decreases while the conversion increases. TBHMA-Succinyl ester diacid monomer has higher rates of polymerization than other dimethacrylate monomers. This is due to the shortest spacer between double bonds which brings the double bonds close to each other and enhances the rate of polymerization. Similar behavior was also reported for the photopolymerization of diethylene glycol dimethacrylate (DEGDMA), poly(ethylene glycol 200) dimethacrylate (PEG200DMA) and poly(ethyleneglycol 600) dimethacrylate (PEG600DMA). When the rates of polymerization of DEGDMA, PEG200DMA, PEG600DMA were compared with respect to the increasing number of ethylene glycol units in the monomer, the maximum rate of polymerization was found to decrease.

It was also observed that TBHMA-Succinyl ester diacid, TBHMA-Adipoyl ester diacid polymerized faster than the commercial HEMA monomer.

Figure 4.77 shows the conversion of these monomers as a function of time at 40 °C. Overall conversions were 98, 75, 90 per cent for TBHMA-Succinyl ester diacid, TBHMA-Adipoyl ester diacid, TBHMA-Dodecanedioyl ester diacid. It is known that as the distance and flexibility between functional groups increases, the maximum double bond conversion increases. The reason for increased conversion is a delayed gel effect (autoacceleration). This explains higher conversion of TBHMA-Dodecanedioyl ester diacid compared to TBHMA-Adipoyl ester diacid.

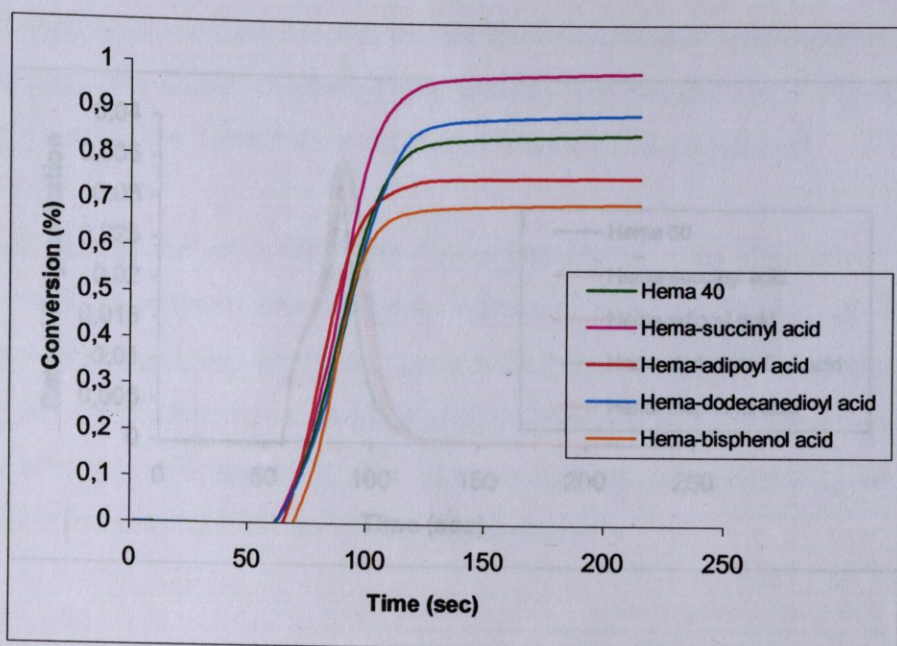


Figure 4.77. Conversions versus time of HEMA with multifunctional crosslinkers at 40 °C (0.5 mol per cent concentration)

It has also been observed that conversion increases for systems that are polymerized at faster rates. As the polymerization rate increases, the volume relaxation is unable to keep pace with conversion, leading to increased free volume formation. The free volume in excess of equilibrium causes higher mobility which results in increased conversion. This explains higher conversion reached during HEMA:TBHMA-Succinyl ester diacid polymerization.

The rate of polymerization of HEMA:TBBBr-Bisphenol A ether diacid was 0.028 s^{-1} , faster than HEMA. The TBBBr-Bisphenol A diacid monomer had the lowest conversion (70 per cent) due to the highest rigidity of this monomer.

Figure 4.78 shows the rates versus time plots for the monomers at 60 °C. All monomers showed similar rate of polymerizations. The maximum rate of polymerization for HEMA, TBHMA-Succinyl diacid, TBHMA-Adipoyl diacid, TBHMA-Dodecanedioyl diacid and TBBBr-Bisphenol A diacid were found to be 0.033, 0.032, 0.036, 0.034 and 0.031 s^{-1} , respectively. It was found that all monomers showed the higher rates of polymerization at 60 °C than the those of 40 °C.

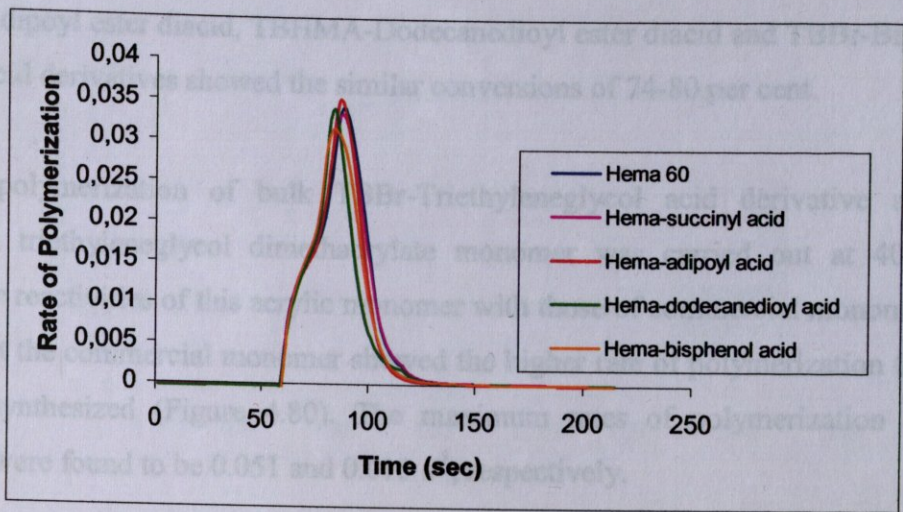


Figure 4.78. Rates versus time of HEMA with multifunctional crosslinkers at 60 °C (0.5 mol per cent concentration)

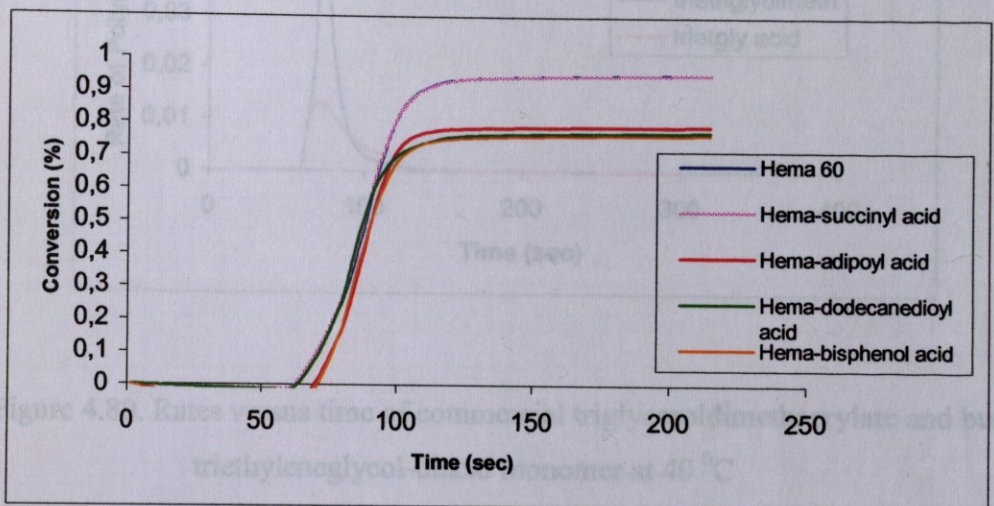


Figure 4.79. Conversions versus time of HEMA with multifunctional crosslinkers at 60 °C (0.5 mol per cent concentration)

Figure 4.79 shows the conversion of these monomers as a function of time. TBHMA-Succinyl ester diacid monomer and the commercial HEMA monomer had the same conversions of 95 per cent that was the highest conversion among other monomers.

same conversions of 95 per cent that was the highest conversion among other monomers. TBHMA-Adipoyl ester diacid, TBHMA-Dodecanedioyl ester diacid and TBBBr-Bisphenol A ether diacid derivatives showed the similar conversions of 74-80 per cent.

The polymerization of bulk TBBBr-Triethyleneglycol acid derivative and the commercial triethyleneglycol dimethacrylate monomer was carried out at 40 °C to compare the reactivities of this acrylic monomer with those of commercial monomer. It is obvious that the commercial monomer showed the higher rate of polymerization than the monomer synthesized (Figure 4.80). The maximum rates of polymerization of two monomers were found to be 0.051 and 0.015 s⁻¹, respectively.

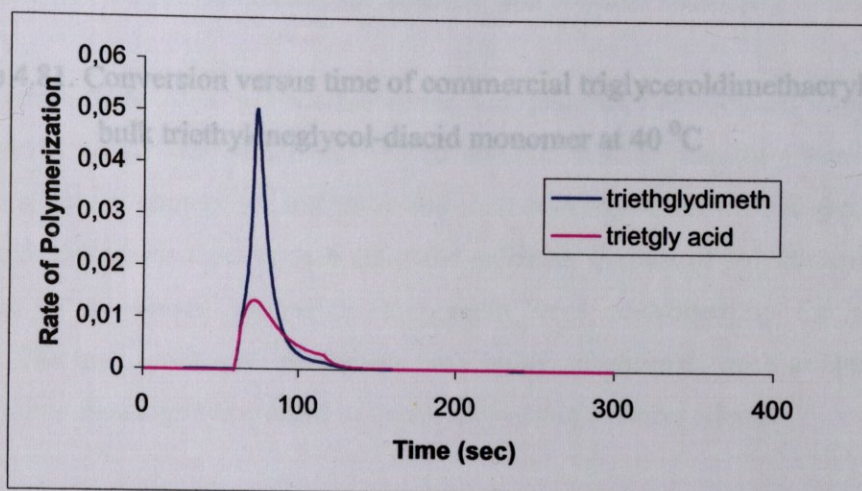


Figure 4.80. Rates versus time of commercial triglyceroldimethacrylate and bulk triethyleneglycol-diacid monomer at 40 °C

Figure 4.81 shows the conversion of these monomers as a function of time at 40 °C. The maximum conversions of the bulk TBBBr-Triethyleneglycol diacid derivative and the commercial triethyleneglycol dimethacrylate monomer were found to be 45 and 78 per cent, respectively. It was obvious that the conversion of the new monomer synthesized was lower than the commercial one.

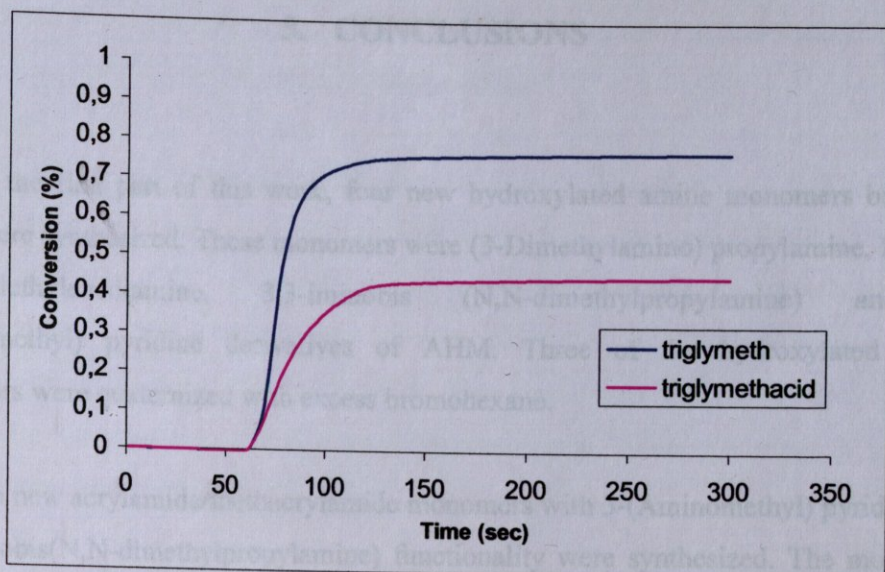


Figure 4.81. Conversion versus time of commercial triglyceroldimethacrylate and bulk triethyleneglycol-diacid monomer at 40 °C

5. CONCLUSIONS

In the first part of this work, four new hydroxylated amine monomers based on AHM were synthesized. These monomers were (3-Dimethylamino) propylamine, N,N,N'-trimethylethylenediamine, 3,3-iminobis (N,N-dimethylpropylamine) and 3-(Aminomethyl) pyridine derivatives of AHM. Three of the hydroxylated amine monomers were quaternized with excess bromohexane.

Two new acrylamide/methacrylamide monomers with 3-(Aminomethyl) pyridine and 3,3-iminobis(N,N-dimethylpropylamine) functionality were synthesized. The monomers were quaternized with bromohexane, bromooctane and bromohexadecane.

The reactivities of the synthesized amine and quaternary ammonium monomers in photopolymerizations were determined with photo-DSC. Amine monomers were found to be very reactive in photopolymerizations due to H-bonding effect of OH group which brings the double bonds close to each other and enhances the rate of polymerization. The reactivities of quaternary ammonium monomers were controlled by the monomer structure. The methacrylamide monomers with bulky substituents such as quaternized AHM-Pyridine monomer were found to be unreactive due to steric effects.

The antibacterial activities of the synthesized monomers and their homopolymers and copolymers with HEMA were investigated using gram positive and gram negative bacteria and MIC values were determined. Amine monomers, their homopolymers and copolymers did not show any antibacterial activities. Quaternized AHM-PYR monomer, its homopolymer and copolymer with HEMA showed antibacterial activity against both bacteria. It was found that the antibacterial activities of METH-PYR QACs increased as the alkyl chain length on N increased.

In the second part of this study, three new ester-linked diacid monomers were synthesized from the reaction of succinyl chloride, adipoyl chloride, and dodecanedioyl dichloride with TBHMA followed by hydrolysis with CF_3COOH . Two new ether-linked

acid monomers were synthesized from the reaction of bisphenol A and triethyleneglycol with TBBr followed by hydrolysis of t-butyl groups.

All monomers were photopolymerized using photo-DSC to understand the structure-reactivity relationship of the monomers. The ester-linked TBHMA-Succinyl diacid monomer at 40 °C had higher rates of polymerization than other diacid monomers and HEMA due to the shortest spacer between double bonds . TBHMA-Succinyl diacid monomer also gave the highest conversion. The ether-linked TBBr-Bisphenol A diacid monomer photopolymerized faster than the commercial HEMA, whereas it gave the lower degree of conversion than HEMA due to its rigid structure.

All monomers showed the similar rate of polymerizations at 60 °C and these values were higher than those of 40 °C as expected.

Ether-linked triethyleneglycol diacid monomer showed lower rate of polymerization and conversion than commercial triethyleneglycol dimethacrylate monomer.

REFERENCES

1. *Antibacterial agents* http://www.tutts.edu/med/apua/Q&A_antibacterials.html, 2004.
2. Kawabata, N and M. Nishiguchi, "Antibacterial Activity of Soluble Pyridinium-Type Polymers", *Applied and Enviromental Microbiology*, Vol. 54, No. 10, pp. 2532-2535, 1998
3. Dizman, B., O. M. Elasri and L. J. Mathias, "Synthesis and Antibacterial Activities of New Water-soluble Bis-quaternary Ammonium Methacrylate Polymers", accepted for publication in JAPS.
4. Gabrielska, J., J. Sarapuk, S. Przestalski and P. Wroclaw, *Tenside, Surfactants, Detergents*, Vol. 31, No. 5, pp. 296-298, 1994.
5. Dogmak G. *Klasse von Desinfektionmitteln Otsch. Med Wochenschr* Vol. 61, pp. 829-832, 1935.
6. Li, G.J., J. R. Shen and Y. L. Zhu, *J. Appl. Polym. Sci.*, Vol. 78, pp. 668-675, 2000.
7. Talaro, K. and A. Talaro, in *Foundations in Microbiology*, WCB Publishers, pp. 286-287, 1993.
8. Goodson, B. A., N. S. Ehrhardt, J. Nuss, K. Johnson, M. Giedlin, R. Yamamoto, W. H. Moos, A. Krebber, M. Ladner, M. B. Giacona, C. Vitt and J. Winter, *Antimicrob. Agents Chemother.*, Vol. 43, pp. 1429-1434, 1999.
9. Sauvet, G., S. Dupont, K. Kazmierski and J. Chojnowski, *J. Appl. Polym. Sci.* Vol. 75, pp. 1005-1012, 2000.
10. Borman, S., *Sci. Tech.*, Vol. 79, No. 22, pp. 13, 2001.

11. Abel, T., J. I. Cohen, R. Engel, M. Filshtinskaya, A. Melkonian and K. Melkonian, *Carbonhydr. Res.*, Vol. 37, No. 24, pp. 2495-2499, 2002.
12. Baumgarten, P. K., "Electrostatic Spinning of Acrylic Microfibers", *J. of Colloid and Interface Science*, Vol. 36, pp. 71-79, 1971.
13. Harkes, G., J. Dankert and J. Feijen, "Growth of uropathogenic Escherichia Coli strains at solid surfaces", *Journal of Biomaterial Science, Polymer Edition* 3, pp. 403-418, 1992.
14. Sun, G., International Patent No. WO 00/15897, 2000.
15. <http://www.brunel.ac.uk/depts/BI/project/microbio/cellstrc/bacwall/peptidog.htm>, 2004.
16. <http://www.cat.cc.md.us/courses/bio141/labmanua/lab6/lab6.html>, 2004.
17. Akelah, A. and A. Moet (Eds.), *Functionaized Polymers and their applications*, Chapman and Hall, London, 1990.
18. Moon, W., J. C. Kim, K. Chung, E. Park, M. Kim and J. Yoon, "Antimicrobial activity of a Monomer and Its Polymer Based on Quinolone", *J. of Appl. Polymer Sci.*, Vol. 90, pp. 1797-1801, 2003.
19. Hugo, W. B. and A. R. Longworth, *J. Pharm. Pharmacol*, Vol. 18, pp. 569, 1966.
20. Kanazawa, A., T. Ikeda and T. Endo, "Antibacterial Activity of Polymeric Sulfonium Salts", *J. Polym. Sci. Part A: Polym. Chem.* Vol. 31, pp. 2873-2876, 1993.
21. Tashiro, T., "Antibacterial and Bacterium Adsorbing Macromolecules", *Macromol. Mater. Eng.*, Vol. 286, No. 2, pp. 63-87, 2001.

22. Nurdin, N., G. Helary and G. Sauvet, "Biocidal polymers Active by Contact. II. Biological Evaluation of Polyurethane Coatings with Pendant Quaternary Ammonium Salts", *Journal of Applied Polymer Science*, Vol. 50, pp. 663-670, 1993.
23. Thölmann, D., B. Kossmann and F. Sosna, "Polymers with antimicrobial properties", http://www.piusinfo.de/dokumente/docdir/vince/praxis_info/pdf/Vincen tz-0603-Polymerswith.pdf, 2004.
24. Kanazawa, A., T. Ikeda and T. Endo, "Polymeric Phosphonium Salts as a Novel Class of Cationic Biocides. VII. Synthesis and Antibacterial activity of Polymeric Phosphonium Salts and Their Model Compounds Containing Long Alkyl Chains", *Journal of Applied Polymer Science* Vol. 53, pp. 1237-1244, 1994.
25. Franklin T. J. and G. A. Snow, *In biochemistry of Antimicrobial Action*, Chopman and Hall, London, pp. 58, 1981.
26. Bangham, A. D, *Annu. Res. Biochem.*, Vol. 41, pp. 753, 1972.
27. Ikeda, T., H. Hirayama, H. Yamaguchi, S. Tazuke and M. Watanabe, *Antimicrob. Agents Chemother*, Vol. 30, pp. 132, 1986.
28. Cohen, J. I., T. Abel, M. Filshtinskaya, K. Melkonian, D. Burkett and R. Engel, *Abstracts of Papers*, 223rd ACS National Meeting, Orlando, FL, United States, 2002, CARB-059.
29. Senuma, M., T. Tashiro, M. Iwakura and K. Kaeriyama, *J. Appl. Polym. Sci.*, Vol. 37, pp. 2873-2843, 1989.
30. Ikeda, T. And S. Tazuke, *Macromol. Rapid Commun.*, Vol.4, No. 7, pp. 459-461, 1983.

31. Tebbs, S. E. and T. S. J. Elliott, *J. Antimicrob. Chemother.*, Vol. 31, No. 2, pp. 261-271, 1993.
32. Kenawy, E., F. I. Abdel-Hay, A. E. R. El-Shanshoury and M. H. El-Newehy, "Biologically Active Polymers. V. Synthesis and Antimicrobial Activity of Modified Poly(glycidyl methacrylate-co-2-hydroxyethyl methacrylate) Derivatives with Quaternary Ammonium and Phosphonium Salts", *Journal of Polymer Science: Part A: Polymer Chemistry*, Vol. 40, pp. 2384-2393, 2002.
33. Woo, G. L. Y., M. L. Yang, H. Q. Yin, F. Jaffer, M. W. Mittelman and J. P. Santerre, *J. Biomed. Mater. Res.*, Vol. 59, pp. 35, 2002.
34. Gottenbos, B., H. C. Mei, F. Klatter, P. S. Nieuwenhuijs and H. J. Busscher, *Biomaterials*, Vol. 23, pp. 1417, 2002.
35. Sun, Y. And G. Sun, *J. Polym. Sci. Part A: Poly. Chem.* Vol. 39 pp. 3348, 2001.
36. Bajaj, P., *J. Appl. Polym. Sci.* Vol. 83, pp. 631, 2002.
37. Jarwis, W. R. and W. J. Martone, *J. Antimicrob. Chemother.*, Suppl A, pp. 19-24, 1992.
38. Borman, S., *Sci. Tech.*, Vol. 80, No. 22, pp. 36, 2002.
39. Decker, C., "Kinetic Study and New Applications of UV Radiation Curing", *Macromol. Rapid Commun.*, Vol. 23, No. 18, pp. 1067-1093, 2002.
40. Uminski, M. and L. M. Saija, *Surf. Coat. Int.* Vol. 6, pp. 244, 1995.
41. Decker, C., "Photoinitiated Crosslinking Polymerization", *Prog. Polym. Sci.* Vol. 21, pp. 593-650, 1996.

42. Decker, C. and K. Moussa, *J. Polym. Sci., Polym. Chem. Ed.* Vol. 28, pp. 3429, 1990.
43. Hageman, H. J., *Progr. Org. Coat.* Vol. 13, pp. 123, 1985.
44. Chandra R. and R. K. Soni, "Recent Developments in Thermally Curable and Photocurable Systems", *Prog. Polym. Sci.*, Vol. 19, pp. 137-169, 1994.
45. Dietliker, K., "Chemistry and Technology of UV and EB Formulation for Coatings, Inks and Paints. 3", pp. 59, SITA Technology, London, 1981.
46. Chang, C., A. Mar, A. Tiefenthaler and D. Wostratzky, "Photoinitiators: Mechanism and Applications" *Handbook of Coatings Additives* Vol. 2, 1992.
47. Green, C. E., B. P. Starck and S. A. Zahir, *J. Macro. Sci. Res. Macro. Chem.* C21, pp. 187, 1982.
48. Tryson, G. R. and A. R. Shultz, *J. Polym. Sci., Polym. Phys. Ed.* b17, pp. 2059, 1979.
49. Kloosterboer, J. G., *Adv. Polym. Sci.* Vol. 84, No. 1, 1988.
50. Simon, G., P. Allen, D. Bennett, D. Williams and E. Williams, *Macromolecules*, Vol. 22, pp. 3555, 1989.
51. Li, D., S. Zhu and A. E. Hamielec, *Polymer*, Vol. 34, pp. 1383, 1993.
52. Schulz, G. V. Z., *Phys. Chem. (Frankfurt am Main)*, Vol. 8, pp. 290, 1956.
53. Anseth, K. S., M. W. Cynthia and C. N. Bowman, "Kinetic Evidence of reaction Diffusion during the polymerization of Multi(meth)acrylate Monomers", *Macromolecules*, Vol. 27, pp. 650-655, 1994.

54. Avci, D., J. Nobles and L. J. Mathias, "Synthesis and Photopolymerization Kinetics of New Flexible Diacrylate and Dimethacrylate Based on C18 Diacid", *Polymer*, Vol. 44, pp. 963-968, 2003.
55. Anseth K. S. and C. N. Bowman, *Chem. Eng. Sci.*, Vol. 49, pp. 2207-2217, 1994.
56. Young, S. J., A. R. Kannurpatti and C. N. Bowman, "Effect of Comonomer Concentration and Functionality on Photopolymerization Rates, Mechanical Properties and Heterogeneity of The Polymer", *Macromol. Chem. Phys.*, Vol. 199, pp. 1043-1049, 1998.
57. Jansen, J. F. G. A., A. A. Dias, M. Dorschu and B. Coussens, "Fast Monomers: Factors Affecting The Inherent Reactivity of Acrylate Polymerization.", *Macromolecules*, Vol. 36, pp. 3861-3873, 2003.
58. Dufour, P., "Radiation Curing in Polymer Science and Technology 1", (J. P. Fouassier and J. F. Rabek Eds) p. 1, 1992.
59. Ellerstein, S. M., S.A. Lee and T. K. Palit, *J. Macro. Sci. Rev. Macro. Chem.* Vol. 4 pp. 73.
60. Bernhard, P., M. Hoffman, M. Hunziker, B. Klingert, A. Shultess and B. Steinmann, *J. Macro. Sci. Rev. Macro. Chem.* IV, 195.
61. Loughnot, D. J., "Radiation Curing in Polymer Science and Technology 4" (J. P. Fouassier and J. F. Rabek Eds), pp. 367, Plenum Press, 1992.
62. Decker, C., *Europ. Polym. Paint Col. J.* Vol. 182, pp. 383, 1992.
63. Linden, L. A., "Radiation Curing in Polymer Science and Technology 4", (J. P. Fouassier and J. F. Rabek Eds), pp. 387, Plenum Press, 1992.

64. Bellobono, I. R. and L. Righetto, "Radiation Curing in Polymer Science and Technology 4", (J. P. Fouassier and J. F. Rabek Eds), pp. 151, Plenum Press, 1992.
65. Ramström, O. and R. J. Ansell, "Molecular Imprinting Technology: Challenges and Prospects for the Future", *Chirality*, Vol. 10, pp. 195-209, 1998.
66. Bouwhuis, G., "Principles of Optical Disc Systems", Adam Hilger, Bristol, 1985.
67. Zwiers, R. J. W. and G. C. M. Dortant, *Appl. Opt.* Vol. 24, pp. 4483, 1985.
68. Wulff, G., *Angew Chem. Int. Ed. Engl.*, Vol. 34, pp. 1812-1832, 1995.
69. Spivak, D. A. and M. Sibrian-Vazquez, "Contributions of Mechanism and Morphology to Selectivity in Novel Molecularly Imprinted Polymers", accepted for publications in *Journal of Polymer Science Part A: Polymer Chemistry*.
70. Spivak, D. A. and J. Campbell, *Analyst*, Vol. 126, pp. 793-797, 2001.
71. Nicholson, J. and M. Anstice, "The Development of Modified Glass-ionomer Cements for Dentistry", *Trends in Polymer Science*, Vol. 2, No. 8, pp. 272-276, 1994.
72. Wilson, A. D., *Chem. Soc. Rev.*, Vol. 7, pp. 265, 1978.
73. Wasson, E. A. and J. W. Nicholson, *Br. Polym. J.*, Vol. 23, pp. 179, 1990.
74. Wasson, E. A. and J. W. Nicholson, *J. Dent. Res.*, Vol. 72, pp. 481, 1993.
75. Combe, E. C. "Notes on Dental Materials" (6th edn), Churchill Livingstone.
76. Bowen, R. L., *J. Am. Dent. Assoc.*, Vol. 66, pp. 57, 1963.

77. Watts, D. C. "In Materials Science and Technology-a Comprehensive Treatise", Vol. 14, pp. 209-258, VCH, 1992.
78. Antonucci, J. M., J. E. McKinney and J. W. Stansbury, US Patent Application 160856 [Chem. Abstr. (1989) 110:179572], 1988.
79. Merianos, J. J., in *Block, S. S. eds.*, "Disinfection, Sterilization, and Preservation", 4th edn., Pennsylvania: Lea & Febiger, pp. 225-262, 1991.
80. Spivak, D. and K. J. Shea, "Molecular Imprinting of Carboxylic Acids Employing Novel Functional Macroporous Polymers", *J. Org. Chem.*, Vol. 64, pp. 4627-4634, 1999.
81. Mathias, L. J., B. Shemper, S. Alirol and M. Morizur, J-F submitted.

