2.1. Functional polymers

Functional polymers are macromolecules to which chemically bound functional groups are attached which can be utilised as reagents, catalysts, protecting groups, etc. The polymer support can be either a linear species which is soluble or a crosslinked species which is insoluble but swellable. For a polymer to be used as a support, it should have significant mechanical stability under the reaction conditions. Such properties of the support have greater importance for the functionalisation reaction and for the applications of the functional polymers. The polymer properties can be modified either by chemical reactions on pendant groups or by changing the physical nature of the polymers, such as their physical form, porosity and solvation behaviour. Such properties have a great importance for the functionalisation reactions for the eventual applications of the reactive polymers.
Chemical reaction for the introduction of functional groups in polymers and the functional group conversion in polymers are dependent on the nature of the polymer backbone, nature and degree of crosslinking, pore-volume and pore-size of the polymer particles, separation of the functional groups from the polymer backbone, hydrophobic-hydrophilic balance, solvation and swelling behaviour. The overall three-dimensional structure, stereochemistry of the polymer backbone and the variables of polymerisation conditions dictate the nature and reactivity of attached functional groups. Functionalised polymers can be prepared by chemical modification of polymers either under classical conditions or using phase transfer catalysis technique.

A functional polymer possesses the combination of the physical properties of the polymer support and the chemical reactivities of the attached functional group. The polymer support may be organic or inorganic and functional group attachment can be done either by physical interaction or through chemical bonds. The use of a functional polymer depends on the physical properties and the chemical constitution of the polymers. A functionalised polymer requires a structure which permit adequate diffusion of substrates to the reactive sites. Functionalised polymers were used as ion-exchange media far early in the mid 30s, but their systematic use started only after the introduction of Merrifield’s solid-phase peptide synthesis. Polymer-supported reagents are used in organic oxidations, reduction, halogenation, peptide condensation and have many applications as ion-exchangers, chelating agents, reagents for organic synthesis, synthesis of catalysts, heterocycles and media for trapping unstable reaction intermediates. Functionalised polymers possess many attributes for their use in combinatorial chemistry and automated synthesis. They may be recycled and are thus cost-effective; they are non-toxic and odourless, and hence mediate environmentally friendly chemistry. Combinatorial chemistry is a massive term include polymer-supported organic chemistry, combinatorial synthesis, new methods of structure elucidation based on
deconvolution, tagging and the growing awareness of structure-diversity and automation.

2.2. Advantages and limitations of functional polymers

The major advantage of the functional polymers which has attracted quite a large number of scientists to the field is the simplification of the product work up, facile separation, ease of isolation, the possibility of regeneration and automation of the functional polymers. They are easily separable from low molecular weight compounds by simple filtration. In the case of soluble polymers, ultrafiltration or selective precipitation removes soluble polymers. The crosslinked polymer can be easily cleaned off from soluble reactants and products. Usually an excess of polymeric reagent is taken, so that a high yield of product is obtained in solution. In some of these reactions, side products remain attached to the polymer thus facilitating the product purification. This permits the polymeric reagents to be used either in columns or in batch processes and they can be regenerated several times and reused. This is economically very important and can make it worthwhile to prepare complex supported reagents. If the reactions can be driven to completion, so that simple filtration and washing is required for reaction work up, automation of the process is possible leading to industrial significance.

When functional groups are attached to crosslinked insoluble polymeric support, it can bring about significant changes in reactivity by the possible restricted interactions of functional groups. A soluble, low molecular weight compound, when attached to a crosslinked polymer, acquires the latter's property of complete insolubility. In all common solvents, if the polymer support is of high porosity, the attached species will remain freely accessible to solvent and solute molecules and therefore do not lose much of the reactivity they exhibit in solution. The polymer support acts as an immobilising medium for the bound species. A high degree of
crosslinking, a low level of functionalisation, low reaction temperature and development of electronic charges near the polymer backbone tend to encourage this situation which may be similar to mimicking the solution condition of infinite dilution. Intramolecular reaction of the attached species are thus prevented which can lead to intramolecular reactions or reactions with soluble substrates.

The attachment to the polymer support can also solve the problem of liability, toxicity or odour which are often experienced with low molecular weight reagents. The toxic and malodorous materials can be rendered environmentally more acceptable when supported on an insoluble non-volatile polymer support. The reactivity of an unstable reagent may be attenuated when supported on a crosslinked polymer matrix and the corrosive action in the case of many conventional corrosive reagents can be diminished by this process. The polymer matrix contributes a special environment for carrying out chemical reactions. It will generally impose on molecules diffusing into it certain defined steric requirements determined by pore or channel structure by substituents on the polymer backbone and also by the distance between attached molecules and the polymer backbone. The polymer matrix can be so selected or tailor-made to provide a specific microenvironment and this may induce some specificity at the reaction site.

Along with the attractive advantages of polymer supported reactions, several serious drawbacks are inherent with the strategy. Some of the disadvantages are the high cost and additional time in synthesising a supported species, reduction of the degree of functionalisation during regeneration, low reactivities, low product yields and difficulties with separation of impurities. Reactions using the functional polymers are generally slow. The reaction condition should be mild and non-destructive to the polymer backbone or to product and selective, so that only the bond between the polymer and substrate may be formed or cleaved as desired. Monitoring of the chemical reactions taking place on the polymer is difficult.
using the usual chemical methods applicable to homogeneous solutions. Finally, in the use of functionalised polymers, there exists the possibility of side reactions with the polymer itself. Further crosslinking is a typical side reaction encountered during several polymer-supported reactions. In certain cases intrapolymeric reactions like cyclisations have also been observed as side reactions. Some of these limitations can be overcome by a proper choice of the support.

2.3. Design of functional polymers

After the introduction of the Merrifield's solid phase peptide synthesis in 1963, there has been an intense activity on polymer modification by functionalisation and their application in different fields of chemistry and technology. The first step towards the preparation of functional polymers is the attachment of functional groups to polymers. The required functional group can be introduced into support either by polymerisation of the monomer containing the desired functional group or by chemical modification of preformed polymer. Many functional linear polymers can be prepared by the former method by cationic, anionic, free-radical, coordination or group transfer polymerisation. But for most purposes, crosslinked polymers are more attractive than the linear ones. Crosslinked polymers can be prepared in good physical form by suspension polymerisation.

The chemical modification of the preformed polymer is the more accepted and most extensively used method for preparing reactive polymers as it allows a good control of the degree of functionalisation of the polymer. This method is particularly attractive for the preparation of crosslinked reactive polymers, for one can start with commercially available microporous or macroporous polymer beads of good physical form and size with a known percentage of crosslinking and porosity. Generally after the chemical modification, the functional polymer synthesised has the same physical form
as the original polymer. In the case of crosslinked polymers, the reactivity and accessibility of the reaction sites may be limited as compared to small molecules and in most cases it depends on the proper choice of a swelling or suspending solvent. So in order to get a good yield, more drastic conditions are required. Purification of the modified product is another associated problem. With low molecular weight substrate, distillation, crystallisation or chromatography can be applied. But these methods are not applicable for crosslinked polymers. Chemical modification of linear polymers can also give rise to problems resulting from local concentration effects. Many reviews on the chemical modification of polymers have been published.

The generation of polar environment in an originally non-polar support (and vice versa) by the introduction of appropriate functional groups can alter significantly the solvent compatibility of the system. An illustrative example for this is the sulphonation of styrene-divinylbenzene resins to form ion exchangers, where the support alters from being totally hydrophobic to totally hydrophilic. In certain cases, ionic groups generated on a lightly crosslinked non-polar support can actually aggregate or cluster into charged nuclei, increasing considerably the rigidity of the polymer matrix.

The most generally accepted methods of chemical modification of polystyrene are chloromethylation and bromination. Chloromethylation was originally carried out using chloromethylmethylether (CMME) and a Lewis acid such as stannic chloride or zinc chloride. Using methoxy acetic acid, Linderman et al. developed a new method for the generation of CMME. The technique is very safe as the product CMME is free from bis(chloromethyl)ether, a potent carcinogen that is produced along with CMME by the usual method. For preparing chloromethylaryl resin using methane-sulphonylchloride and Hunig's base, a more recent method was developed. It is a simple and efficient method for converting hydroxymethylaryl based resins to their corresponding chloromethylaryl derivative using methane sulphonyl chloride and Hunig's base. Chloromethylation can also be carried
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out using thionyl chloride and Lewis acid.\textsuperscript{96} Chloromethylated polystyrene referred to as Merrifield's resin play a significant role as a support in peptide synthesis\textsuperscript{99} and a precursor to numerous other functional polymers, in which a substrate is attached to the resin by nucleophilic displacement of chlorine.\textsuperscript{100} The study of chloromethylation have been reviewed by many researchers.\textsuperscript{101} Ring brominated polystyrene is also a very versatile intermediate in the synthesis of various other polystyrene resins. Heitzana Michels developed a common method\textsuperscript{102} for the bromination of polystyrene which involves the reaction of polystyrene with bromine in the presence of ferric chloride catalyst.

2.4. Polymer bound dyes

Organic dyes find extensive use as sensitizers in photooxygenation reactions.\textsuperscript{103-105} Halogenated fluorescein derivatives are parent molecules of xanthone, which forms a group of dyes whose photosensitizing ability has many applications such as singlet oxygen production, photoreduction of water and photoconversion of solar energy.\textsuperscript{106,107} Several xanthene dyes are good singlet oxygen sensitizers and among them Rose Bengal is the most efficient and widely used one in preparative photooxidations as well as in studies of the reactivity of singlet oxygen towards biological substrates.\textsuperscript{108-110}

Large absorption in the visible, high triplet and singlet molecular oxygen quantum yields and solubility in both water and moderately polar media are the reasons explaining the popularity of Rose Bengal.\textsuperscript{107} Rose Bengal has been shown to have virucidal activity against four different enveloped viruses [influenza, sendai, VSV (vesicular stomatitis virus) and HIV-1 (human immuno deficiency virus type 1)] due to photodynamic effects.\textsuperscript{111} The dye Rose Bengal in solution or as a suspension is a very suitable sensitizer for generating singlet oxygen.\textsuperscript{104,112} But it has some limitations in its application in solution phase. The use of solvents for
Reactions are limited, bleaching of the dye occurs when used for long period, the dye may react with the reactants or with the products and the separation of the products from the dye in the reaction mixture is difficult. These can be overcome by the immobilisation of the dye on a polymer support.\textsuperscript{1} The advantages\textsuperscript{1} of using the insoluble polymer bound Rose Bengal lie in the fact that facile separation and reusability of dyes, usability of a variety of solvents in which the polymer can swell and stability towards bleaching and photodecomposition. The polymer bound Rose Bengal can act as a polymeric photosensitizer catalyst\textsuperscript{1} to generate pure products than with the free dye sensitizer. There are three general ways to prepare a polymer bound photosensitizer. In the first method, the sensitizer is absorbed on the solid support such as silica gel.\textsuperscript{11-15} This technique is easy, except that the dye sensitizer may be eluted by polar solvents. In the second method, the sensitizer is covalently bound either to a crosslinked polymer gel prepared from styrene and DVB or to silica gel.\textsuperscript{116-119} In still another method, the sensitizer dye is incorporated into a thin polymeric film. This is done by dissolving the sensitizer and the polymer in a solvent and evaporating the solvent from the polymer-sensitizer solution on a flat surface.\textsuperscript{120}

Insoluble polymer supports were introduced several years by Merrifield\textsuperscript{121} and Letsinger\textsuperscript{122} to enhance the polypeptide synthesis. The technique involves the use of an insoluble styrene-divinylbenzene copolymer bead to provide a foundation upon which successive chemical transformations can be carried out. Immobilised photosensitizers derive ultimately from the work of Kautsky and deBraujin.\textsuperscript{123,124} The first UV sensitizer immobilized to a synthetic polymer for the purpose of actually carrying out a photosensitized process was reported by Moser and Cassidy.\textsuperscript{125} These workers reported poly(acrylophenone) photoreduced to the corresponding \(\alpha\)-phen ethyl alcohol. Peter Leermakers\textsuperscript{126} reported that poly(phenyl vinyl ketone)—a 'brittle plastic mass' was used for
heterogeneous energy transfer to three dienes: norbornadiene, cis-piperylene and myrcene. Schaap et al.\textsuperscript{116,119} used insoluble polymer support in photochemical reactions and reported the synthesis and use of the first example of a heterogeneous sensitizer for singlet oxygen formation in organic solvents. The polymer support may be used as a handle for easy separation and to carry a polar sensitizer into a nonpolar solvent. Schaap et al. have shown that Rose Bengal can be attached to Merrifield's resin via an ester bond, taking advantage of the carboxylate group of the sensitizer (Scheme 2.1). Of the 40 dyes tested in 1971 Rose Bengal immobilised to Merrifield resin was the most effective.\textsuperscript{127} This sensitizer is available under the trade name Sensitox I from Hydron Laboratories, Inc., Chemical Sales Dept., New Brunswick, New Jersey 08902.\textsuperscript{128}

\[
\text{Scheme 2.1. Synthesis of Sensitox I}
\]

This Sensitox I is used to sensitize the generation of singlet molecular oxygen. Singlet molecular oxygen exhibits three modes of reaction with alkenes.\textsuperscript{104,112,129-132} 1,4-Cycloaddition with conjugated dienes to yield cyclic peroxides, an "ene" type reaction to form allylic hydroperoxides and 1,2-cycloaddition to give 1,2-dioxetanes which cleave thermally to carbonyl containing products. Examples of all of these three reaction types have been carried out utilising polymer bound Rose Bengal as a sensitizer are shown in Table 2.1.
Table 2.1. Photooxidation with polymer bound Rose Bengal

<table>
<thead>
<tr>
<th>Singlet oxygen acceptor</th>
<th>Product</th>
<th>% yield (isolated)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><img src="image1" alt="Chemical Structure" /></td>
<td><img src="image2" alt="Chemical Structure" /></td>
</tr>
<tr>
<td></td>
<td><img src="image3" alt="Chemical Structure" /></td>
<td><img src="image4" alt="Chemical Structure" /></td>
</tr>
<tr>
<td>H₃C = CH₃</td>
<td>H₂C = CH₃</td>
<td><img src="image5" alt="Chemical Structure" /></td>
</tr>
</tbody>
</table>

Blossey et al.\textsuperscript{116,119} reported that free singlet oxygen is efficiently formed by energy transfer from polymer bound Rose Bengal to oxygen. Photooxidations employing this heterogeneous sensitizer in place of a soluble dye, have been reported to be synthetically convenient and mechanically less complicated.\textsuperscript{133,134} Polymer bound Rose Bengal has proved particularly useful in the isolation of unstable primary photooxidation products such as 1,2-dioxetanes.\textsuperscript{135} Heterogeneous sensitizers permit the design of experiments which are not possible with soluble dyes. Foote's three-phase test\textsuperscript{136} for the intermediacy of singlet oxygen in photooxidation is an example for this. Berzman et al.\textsuperscript{137} reported the photodynamic inactivation of E.Coli by Rose Bengal immobilised on polystyrene beads. Polymer bound Rose Bengal has also been used to show that photodynamic inactivation of E.Coli requires diffusion of singlet oxygen into the cell. In addition to these unique features, heterogeneous sensitizers have a number of practical advantages over soluble sensitizer. The advantages\textsuperscript{1} of using the insoluble polymer bound Rose Bengal lie in the fact that facile separation and
reusability of dyes, usability of a variety of solvents in which the polymer can swell and stability towards bleaching and photodecomposition. Continuous photooxidation process should be feasible and that photooxidations may be followed spectroscopically in regions normally masked by dye absorptions. Though Sensitox I performs well in many non-aqueous solvents, it is a poor sensitizer in aqueous systems. The reason for this limited effectiveness is related to the observations that the hydrophobic polymer is not wetted by water, it is difficult to suspend in aqueous media and it does not swell in water.

Subsequently in 1979 Schaap et al. prepared a water-compatible resin from a hydrophilic resin coupled to Rose Bengal (Sensitox II). A water-compatible, covalently immobilised sensitizer would extend the utility of the method to biological media. Schaap et al. synthesised a hydrophilic polymer by the copolymerisation of chloromethyl styrene (60:40 mixture of meta and para isomers) (1) and the monomethacrylate ester of ethylene glycol (2) with the bis methacrylate ester of ethylene glycol (3) as the crosslinking agent and heating the resulting polymer beads with Rose Bengal in dry DMF at 60°C for 3 days.

CH=CH₂

CH₂=C(CH₃)COOCH₂CH₂OH (2)

(CH₂=C(CH₃)COOCH₂)₂ (3)

(CH₂Cl⁻)

(1)

The effectiveness of hydrophilic polymer bound Rose Bengal in sensitizing singlet oxygen formation in water is illustrated by the successful photooxygcnation of a number of substrates known to react with singlet oxygen in water. Unfortunately, this Sensitox II is not commercially
available and its synthesis is difficult involving multiple steps and a resin that is not generally available.

In 1984, soluble polymeric derivatives of Rose Bengal were prepared based on the Lamberts' work.\textsuperscript{139,140} It was observed that singlet oxygen formation in these soluble polymers depended on the number of Rose Bengal units attached to the polymer support. Absorption and emission spectra of the polymers indicated that for lightly loaded polymers, self-quenching process are controlled by solution concentration effects only. For more highly functionalised polymers, self-quenching becomes significant between Rose Bengal molecules on the same polymer chain.\textsuperscript{141} These self-quenching effects are most significant when the polymer is used as a heterogeneous sensitizer, i.e., in a solvent in which it is not soluble. Under these conditions both intramolecular and intermolecular self-quenching processes, i.e., a dye excited state being quenched by a proximate dye ground state decrease the quantum yield of singlet oxygen formation. In Merrifield beads, no self-quenching is observed because the dyes are effectively "site isolated."

In 1994, Amat-Guerri, Botija and Sastre reported the use of polymeric photosensitizer Rose Bengal covalently bound to linear polystyrene.\textsuperscript{142} With regard to linear (non-crosslinked) polymeric photosensitizers for photooxygenations, the xanthene dye Rose Bengal, Eosin Y,\textsuperscript{143} iodinated succinyl fluorescein\textsuperscript{144} and thionine\textsuperscript{145} have been attached to several polymeric frames and the resulting sensitizers have been evaluated as singlet molecular oxygen generators in solution.\textsuperscript{146} They reported that Rose Bengal covalently bound to linear polystyrene can be reused without detectable loss of efficiency and this sensitizer is photostable.

Preparative scale photosensitized reactions can be performed with crosslinked polymeric photosensitizers as light absorbing components. These polymers usually act with efficiencies high enough for synthetic purposes, and they present the additional advantage of being readily separated from the liquid medium by simple and direct filtration of the reaction mixture.\textsuperscript{146}
In 1998, Foote and Prat\textsuperscript{147} reported a resin-sensitizer system and this can be easily prepared from available starting materials and is useful for aqueous photooxidations. They used a resin which is a combination of chloromethylated styrene-divinylbenzene copolymer linked to a polyethylene glycol (PEG) chain and terminated by an amino group (NovaSyn\textsuperscript{R} TG amino resin, Novabiochem). The PEG chain interacts strongly with water, making the resin wettable. The linkage to Rose Bengal is accomplished using standard peptide reagents as shown in Scheme 2.2.

\begin{center}
\includegraphics[width=0.5\textwidth]{scheme_2.2}
\end{center}

\textbf{Scheme 2.2.} Synthesis of NovaSyn\textsuperscript{R} TG amino resin bound Rose Bengal

The performance of this resin-bound photosensitizer was evaluated by photooxidising histidine and disodium 3,3'-{(naphthalene-1,4-diyl)dipropionate (NDP) in water.\textsuperscript{147} Though it suffers the limitation of bleaching of the sensitizer during the photooxidation process, it has got the advantage of easy removal of polymeric sensitizer from the reaction mixture by simple filtration as shown in Scheme 2.3.

\begin{center}
\includegraphics[width=0.6\textwidth]{scheme_2.3}
\end{center}

\textbf{Scheme 2.3.} Photooxidation by a polymer-supported photosensitizer
Paczkowski and Neckers\textsuperscript{148} reported that in solution, the interaction between Rose Bengal units on different polymer chains was controlled both by the structure of the polymer chain and by the dispersal of the polymer chain in that solvent (Scheme 2.4).

![Scheme 2.4. Interaction between Rose Bengal units on different polymer chains](image1)

The situation is completely different when the polymers are used in solvents in which they are not soluble or even swollen and the energy transfer is heterogeneous. Because there is no solvent between the polymer chains, self-quenching processes are more likely to occur intermolecularly (Scheme 2.5). It seems clear that for very lightly loaded polymers, the moieties of Rose Bengal are sufficiently isolated by the interspersing aromatic residues of the polymer (styrene units) so that self-quenching, both intramolecular and intermolecular, does not occur. But when polymer loading is increased, both

![Scheme 2.5. Intermolecular interaction of Rose Bengal units](image2)
intramolecular and intermolecular interactions between the dyes are increased (Scheme 2.5). In solid state, for the polymer bound Rose Bengals, the polymer chains are closer to one another than they are in solution and energy transfer between chains is observed. In the solid state, the polymer chains are coiled about one another (Schemes 2.4a and 2.5) and the distance between different Rose Bengal molecules diminishes and the effective photochemical energy transfer radius is decreased by the presence of the second polymer chain—a polymer chain that lies much closer than it does in solution even with the same polymer. In solution the polymer chains are surrounded by solvent and self-quenching processes are possible only for highly loaded polymers (Scheme 2.4b). Eventually dye-dye self-quenching also increases even for polymer blends (Scheme 2.6).

It is well-known that the bleaching of Rose Bengal in the presence of oxygen is prevented by polymer immobilisation. Since bleaching is thought to be the result of bimolecular electron transfer followed by oxidation, it may seem that the rates of secondary reactions or the radical cation or radical anion are prevented by the polymer matrix. The polymer bound sensitizers have a particular important property. The lifetime of the excited triplet state is much longer in the solid phase, i.e., that of the monomeric dye in solution. This can increase the efficiency of energy transfer processes from excited dye molecules to oxygen.
Electronic absorption spectra, emission spectra and quantum yields of singlet oxygen formation of polymer bound Rose Bengal suggest that hydrogen bonding between Rose Bengal moieties and protic solvents leads to a blue shift in the absorption maxima, an increase in the quantum yield of phosphorescence and an increase in the quantum yield of singlet oxygen formation.\textsuperscript{149}

Schaap et al.\textsuperscript{116} prepared several insoluble polymer bound dyes and these heterogeneous sensitizers were used for photochemical generation of singlet molecular oxygen.\textsuperscript{113,115} In addition to Rose Bengal, other sensitizers that have been attached to chloromethylated styrene-divinylbenzene copolymer beads include eosin Y (4), fluorescein (5), chlorophyllin (6) and hematoporphyrin (7).

\begin{align*}
\text{(4)} & \quad \text{(5)} \\
\text{(6)} & \quad \text{(7)}
\end{align*}
These sensitizers may be used for photooxidations in water. The other polymeric photosensitizers are found to be less efficient than the polymer bound Rose Bengal. The polymer bound chlorophyllin and polymer bound hematoporphyrin sensitizers may be particularly valuable in investigations of biological oxidations.\textsuperscript{116}

Photophysical process of photosensitizers involves the following steps (Scheme 2.7).

![Scheme 2.7. Photophysical process of photosensitization](image)

**Steps**

1. Excitation of a sensitizer to a singlet state
2. Intersystem crossing (ISC) from singlet ($S_1$) to triplet state ($S_3$)
3. Deactivation of singlet and triplet states of a sensitizer to ground state
4. Energy transfer from the triplet states of the sensitizer to the photosensitive chromophore ($P_3$).

The application of polymeric photosensitizers in photochemistry for the excitation of molecules into the excited state have received considerable interest owing to their potential use in solar energy storage.\textsuperscript{1} In these processes, the polymeric sensitizer is excited by high energy into the triplet state and can then activate the substrate molecules while the sensitizer itself return to the ground state. The use of polymers in solar collectors in order to use solar energy on economically large scales has also received considerable attention in the quest to replace petroleum products. Although the use of polymers for collection and concentration of solar energy is economically
advantageous because of their light weight, low cost and good mechanical strength, their durability is the major problem associated with this use.

Because in the present study, the emphasis is given to the dye binding characteristics by crosslinked polymers, this review is confined to the macromolecular characteristics on the interaction of low molecular weight compounds towards functional polymers. Even though photosensitizers are found to be attractive, only very few reports are available in them. The synthetic difficulty and processing of the photosensitized reactions may be the reason for this.

2.5. Macromolecular characteristics on the reactions of functional polymers

In the preliminary stage of the development of polymer-supported solid-phase reactions, polymers were considered only as a heterogenizing media for anchoring low molecular weight substrates without having much influence on the course and extent of the reactions. But later experiments revealed that the polymer support has significant influence in deciding the kinetics and extent of functional group conversions in polymer-supported reactions. The binding of an active species to a polymer support with different structure, reactivity and selectivity. The overall nature of the polymer matrix, its hydrophobic or hydrophilic nature and linear or crosslinked structure determine whether a synthesis can be carried out under a particular set of reaction condition. The polarity of the support is one of the important features, influencing the reactivity of the bound species with the substrate. The topographical nature of the gel network and the degree of crosslinking affects the chemical reactivity of the attached functional group.

2.5.1 Nature of the polymer support

The proper choice of the polymer support is a significant factor for the successful utilisation of functional polymers. In determining the performance
of an attached species, the nature of the polymer backbone plays an important role. The polymer support should be either a linear species which forms molecular solution in suitable solvents or a crosslinked network which is macroscopically insoluble in the usual solvents but capable of solvation in good solvents. The advantage associated with the use of linear polymers include the fact that the reaction can be carried out in solution in a homogeneous medium without much diffusion problems and with uniform accessibility of the reactive sites in the polymer. These advantages of linear polymers were demonstrated by the use of N-chloronylons for chlorination and oxidation. But linear polymers are handicapped with the tedious procedures for the separation, purification after each synthetic step which limits the automation of the technique and the possibility of side reactions producing unwanted crosslinks during reaction. Though the crosslinked polymers are practically insoluble in all solvents, they are experimentally attractive because of their ease of separation and purification. Along with the development of the organic polymer supports, a large number of inorganic supports based on alumina, glasses and silica have been widely employed in large scale applications.

The polymer backbone used may be either hydrophobic polymers derived from styrene and its homologues or hydrophilic polymers, like polyacrylamide and poly(N-vinylpyrrolidone). The supports experimented such as poly(methyl methacrylate), polyvinyl alcohol and cellulose were rejected later due to the synthetic inconveniences associated with them. The commercial availability, ease of functionalisation and resistance to degenerative chain scission make polystyrene a convenient support for polymer-supported reactions. Polystyrene, crosslinked with varying amounts of divinylbenzene (DVB) is the most studied and most utilised matrix for reactive polymers. Polystyrene crosslinked with divinylbenzene (DVB) were chosen by Merrifield for the solid phase synthetic strategy. Copolymers of styrene with ethyleneglycol dimethacrylate, tri- and tetraethyleneglycol diacrylate were introduced in peptide synthesis and in
the development of polymeric reagents.\textsuperscript{162} Due to the strong hydrophobic nature, polystyrene appeared to be incompatible with polar solvents and substrates. Polymeric reagents based on poly(acrylamide),\textsuperscript{163} polyvinyl pyridine\textsuperscript{164,165} and poly(N-acryloyl pyrrolidone)\textsuperscript{166} were found to be much superior to those based on polystyrene due to better hydrophobic/hydrophilic balance they could provide.\textsuperscript{167-169}

For the preparation of crosslinked polymers, suspension polymerisation is the general method adopted.\textsuperscript{87} The size of the polymer beads obtained by this method depends on several factors like the speed of stirring, the shape of the reaction vessel and stirrer, the droplet density, temperature and the volume fraction of the dispersed phase. Smaller particles are obtained by increasing the water/monomer ratio or diluting the organic phase with a solvent. Crosslinked polymers can also be prepared by popcorn polymerisation. Here, mixtures of a monovinyl compound and a small amount of divinyl species are warmed gently in the absence of any polymerisation initiator and solvent. This type of polymerisation results in white, opaque, glassy and granular materials referred to as popcorn or cauliflower polymers\textsuperscript{170-173} which are insoluble and extremely porous capable of absorbing large quantities of solvents.

Depending on the method of preparation and on the degree of crosslinking, crosslinked polymers exhibit considerable difference in properties. Based on the porosities of the crosslinked polymers, they are classified into microporous (gel type) and macroporous resins. Gel type resins are generally prepared by suspension polymerisation and are lightly crosslinked (1-5\% DVB) and appear translucent and have no permanent porosity,\textsuperscript{93} but swell to varying degrees in many organic solvents. Here the space between the crosslinks are occupied by the swelling solvents and are considered as small pores. As the degree of crosslinking is increased, the mobility of polymer chain is reduced.\textsuperscript{174} Macroporous resins are also prepared by suspension polymerisation using higher amounts of crosslinking
agents (5-6% DVB) and in the presence of diluents. During the polymerisation, after the extraction of diluent, phase separation occurs and on drying, permanent pores or holes of various sizes are created.\textsuperscript{175} An advantage of macroporous resins is their dimensional stability which makes them ideally suitable for column applications. Another major advantage of macroporous resins is their large interior surface area. This makes the easy accessibility of the reagents to the reactive sites which are buried within the polymer networks. The macroporous resins are swellable in good solvents.\textsuperscript{176}

The physical properties of the support can exert a strong influence on the performance of the polymer bound dyes. For a polymer to be used as a support, it should have significant mechanical stability under the reaction conditions. A balance has to be achieved between the mechanical stability of polymer support and reactivity. The mobility of the polymer chain and the supported active functional groups is restricted for crosslinked polymers. Lightly crosslinked polymers are desirable as supports for dyes, since diffusion control of the reactions inside the polymers are limited. But they are too soft to handle and to be used in column applications.

2.5.2 Microenvironmental effects

Functional groups anchored to polymer supports experience a different local environment than in free solution. The chemical reactivity of an immobilised functional group is governed by its distribution and accessibility on the polymer support. Groups surrounding the active sites can influence product formation.\textsuperscript{177} The topographical nature of the polymer matrix exerts a significant influence on the reactivity of the attached functional groups.\textsuperscript{178} The reactivity depends on the degree of crosslinking which affects the extent of functionalisation and also on the mechanical integrity and stability of the polymer support. The topography of a polymer support is determined by the crosslink density, the chemical nature of the monomers and the monomer dilution ratio. The polymeric network creates a
particular microenvironment which mimic the ease of infinite dilution. It can lead to a change in the mechanism of the reaction. The oxidation reactions with polyacrylamide systems were found to be increased by crosslinking acrylamide with limited amounts of N,N'-methylene-bis-acrylamide. Here the incorporation of the crosslinking agent decreased the hydrophilic nature and thus a better hydrophobic-hydrophilic balance is obtained, thereby making the functional group more accessible to the solvents and substrates. Due to the increased hydrophobic nature of the polymer matrix, polystyrene-based N-haloamide was found to be less efficient in carrying out the oxidation reactions. Favourable interactions between the supported phase and a given substrate may enhance the effective concentration within the support, producing rate acceleration. On the other hand, where the support and the substrate are relatively incompatible, there may be significant diminution of substrate concentration within the support's volume, leading to a reduction in the rate of reaction relative to the analogous non-supported system.

The microenvironmental effect can affect the binding constants of soluble molecules interacting with polymeric substrates and can also shift the ionic recognition properties of functional polymers. Linear polymers are soluble in good solvents, but the crosslinked polymers, due to their insolubility, the accessibility of functional groups are diffusion controlled. For example, in the oxidation of alcohol using polymethyl methacrylate (PMMA) supported izoxazolinium Cr(VI) reagents, the reactions are faster with NN MBA-crosslinked reagents compared to the DVB-crosslinked PMMA-supported reagents. The presence of hydrophilic and flexible NN MBA crosslinking agent in the polymer support reduced rigidity of the system and increased the swelling property, is the reason for the enhanced reactivity of NN MBA-crosslinked PMMA-supported species. But the presence of hydrophobic and rigid DVB in the polymer matrix, decreased the swelling property and reactivity of the system. Another example is the
addition reaction of olefins with polymeric benzyl triethyl ammonium dichloroiodate and dibromoiodate. Here the reaction of styrene is faster than the conversion of cyclohexene.140 This is due to the fact that the compounds having unhindered terminal double bonds are attacked faster than the double bonds in alicyclic rings. The slow reactions of large molecules can be attributed to the molecular sieving phenomena. Here, due to the diffusion limitation, the large and rigid molecules may be unable to penetrate more effectively into the gel network.

2.5.3 Swelling characteristics of the polymer support

The swelling studies are important for identifying good solvents in order to select the suitable reaction medium for performing reactions on polymer support. The hydrophobic or hydrophilic character of the polymer can be changed by changing the nature and ratio of the comonomer units. Thus, solvent compatibility with the polymer support can be adjusted by the proper selection of the comonomer units in the polymer.

The effectiveness with which a functional polymer can act as an alternative to its low molecular weight counterpart is governed by the accessibility of the reactive functional groups immobilised on it. The solvent plays a significant role on the physical and chemical nature of the anchored species.

The solvation properties of a polymer support are not so important in the case of linear polymers which can form a homogeneous solution where the concentration of the polymers can be made to zero. Linear polymers are soluble in good solvents. The polymer chain exists as random coils which can be highly expanded or tightly contracted depending on the nature of the solvent. Generally a highly compatible or good solvent where polymer-solvent contacts are highly favoured to give rise to an expanded coil
conformation. As the solvating medium is made progressively poorer the coil contracts and eventually precipitation takes place (Scheme 2.8).

\[\text{(a) In a good solvent} \quad \text{(b) In a poor solvent}\]

**Scheme 2.8.** Conformation of a linear polymer in good and poor solvents

In dilute solutions, polymer coils are effectively separated and as the concentration is increased, interchain penetration commences and eventually result in gross entanglements. In a suitable solvent, linear polymer molecule can dissolve to form a true molecular solution. The ability of a solvent to dissolve a linear polymer will depend on the nature of the polymeric backbone and in particular, its polarity, the molecular weight, crystallinity, the nature of the solvent, the polymer-solvent interaction forces and temperature. The solubility of a macromolecule, the size of its coil in solution, the point at which entanglement commences are all dependent on the length of the polymer chain or its molecular weight. Sufficiently large intermolecular forces hinder the solubility of linear polymers. The absence of solubility does not imply crosslinking.

Crosslinked polymers are macroscopically insoluble in almost all the solvents. In the case of crosslinked polymers, the reactivity of the species immobilised on the polymer is determined by the extent of swelling properties of the polymer backbone. Swelling of the crosslinked system is very important as it brings the polymer to a state of complete solvation.
allowing easy permeation of the substrate molecules through the networks. Even though, the solvent is compatible, the crosslinked polymer cannot dissolve due to the three dimensional network structure, but the chains get expanded. The swelling of the polymer support to varying degrees depends on the thermodynamic affinity of the polymer, temperature and also on solvent.\textsuperscript{182}

When a compatible solvent is added to a crosslinked polymer, it can expand greatly and become extremely porous forming a pseudo gel. Hydrogels are polymeric materials which are able to swell in water and retain a significant fraction of water within their macromolecular structure but do not completely dissolve in water.\textsuperscript{183} This is due to the existence of crosslinks which at least in water bind macromolecules or their segments either by permanent bonds or through more extensively organised regions which can be formed from molecular associations, usually hydrogen bonds.\textsuperscript{184} The crosslink ratio controls the behaviour of a resin in contact with a solvent and is inversely proportional to the degree of swelling\textsuperscript{185} at low degree of crosslinking. The solvent-swollen polymer may resemble a homogeneous solution such that the gel network consists largely of the solvent with only a small fraction of the total polymer backbone.

\[ \text{Lightly crosslinked} \quad \overset{\text{Good Solvent}}{\longrightarrow} \quad \text{Network expanded} \]

\( \checkmark = \text{permanent crosslink} \)
As the degree of crosslinking is increased, the ability of the network to expand in a good solvent becomes reduced and penetration of the reagents into the interior may become impaired.

![Diagram showing network expansion](image)

Chain entanglement due to the higher concentration of the crosslinking agent, reduces the extent of swelling in presence of good solvents. Polymers with large pores, macropores and macroreticular resins also absorb reasonable amount of solvents simply filling the available voids. Good solvents may penetrate and solvate highly entangled areas of the polymers as well. The compatibility of the solvent with the polymer support can be adjusted by the use of copolymers.

With 'bad' solvents, crosslinked matrices display little tendency to expand and the movement of reagents within such a network may become diffusion-controlled. The rate of diffusion of a reagent into the polymer matrix depends on many factors including whether the polymer is microporous or macroporous. In the case of macroporous polymers, the degree of swelling is significant in accessing the uniformity. Microporous resins possess porosity only in a swollen condition and is also known as gel porosity. Swelling of the more highly crosslinked parts of macroporous resins may also be important. In order to proceed the reaction smoothly with linear or crosslinked polymers, the polymer must not only be swollen initially by the reaction solvent, but must remain swollen throughout the reaction as reactive species is transferred into other groups which may have a very different polarity than the reactive species. The most effective solvent for a
polymer-supported reaction may differ from that commonly used for analogues low molecular weight reactions.

Either by chemical reaction on the pendant groups or by alteration of the physical nature of the polymer, the factors that control the solvation of the reactive polymers and transport of the reactants in the polymer can be modified. The accessibility of functional groups present in the functionalised polymer supports for chemical modification is an important parameter for deciding its utility. The degree of swelling of the polymer determines the effective pore size and the molecular weight exclusion limit for penetration of the substrate. It is possible to cause a reaction to occur at a fraction of the available sites by controlling the swelling of the polymers. However, such reactions on partially swollen resins give functional polymers in which the reactive sites are not distributed evenly throughout the bead but concentrated in the more accessible sites only.

In the swelling or dissolution of a linear or crosslinked polymer, the driving force is due to contribution of normal entropy and enthalpy changes associated with mixing of solvent and solute molecules added with configurational entropy resulting from dilution of flexible chain molecules. For linear molecules, the contribution from configurational entropy change is favourable until complete dissolution occurs when the entire solvent volume is uniformly filled with polymer. In the case of crosslinked polymers, the tendency to disperse is opposed by a decreased configurational entropy of the polymer chains held between crosslink points where they are forced to assume a more elongated less probable configuration as the networks expand. Thus at higher crosslink ratio, the lower is the swollen volume.

The water binding properties of crosslinked copolymer of acrylamide with tetraethyleneglycol diacrylate (TTEGDA), triethyleneglycol dimethacrylate (TEGDMA), N,N'-methylene-bis-acrylamide (NNMBA) and divinylbenzene (DVB) showed that the freezing water contents of these copolymers depend on the nature of the monomers and crosslinkers, as well
as on the extent of crosslinking. As the hydrophilicity of the polymer increases, the freezing water content increases rapidly. The total water imbibed by the hydrogel is related to the steric effects of the backbone substituents and also to the hydrophilic-hydrophobic balance of the copolymer. Equilibrium water content (EWC) decreases as the hydrophobicity of the monomers increases. Among the various bifunctional crosslinked polyacrylamides, DVB-crosslinked polyacrylamide was found to be the most hydrophobic and TTEGDA-crosslinked polyacrylamide the most hydrophilic. It was observed that the amount of water taken up by the glassy polymer depends on the concentration of hydrophilic groups and their accessibility to hydration.

2.5.4 Effect of spacer arms

Reactive functional polymers suffer a major disadvantage of the low reactivity of the functional groups which can be attributed to the close proximity of the polymer backbone. This problem is more crucial in the case of crosslinked polymers where the active functional groups are either flanked by the crosslinks or buried in the interior of the polymers. Such groups are not readily accessible to low molecular substrates in the continuous phase. The mobility and the rate of reaction involving the functional polymer can be enhanced by increasing the separation between polymeric backbone and reactive site via spacer groups.\textsuperscript{45,187,188}

Spacers have also been employed in other fields of polymer utilisation such as latex supported immunoassays, comb-like polymer liquid crystals and drug delivery system.\textsuperscript{51} The commonly used spacers are hexamethylene diamine,\textsuperscript{189} Br(CH\textsubscript{2})\textsubscript{n}Br\textsuperscript{190} and polyethyleneglycol.\textsuperscript{191} If the functional groups initially present in the polymer are not sufficiently isolated, the spacer may become doubly coupled with the polymer and is effectively lost. Such reactions have been used to study site isolation.\textsuperscript{84} For this reason, the spacer carrying two different chain ends is chosen. The procedure for using a spacer
has recently been extended by Tomoi via the preparation of a monomer carrying a spacer. The monomer was prepared by attaching hexamethylene dibromide into the $p$-position of styrene. The same theme is currently exploited by Guyot et al. using a styrene derivative with a polyoxyethylene spacer.

In reactions of functional groups attached to crosslinked polymer matrices, it should be expected that the reactivity increases with increasing separation from the polymer backbone. The role of the spacer in binding the metal coordination of pyridine has been investigated by introducing pyridine group far away from the rigid polystyrene backbone through a spacer (8) or graft chain (9).

The presence of spacer groups between the polymer matrix and the ligand function influences the complexation with the metal ion. An increase in the catalytic activity by insertion of spacer groups between polystyrene backbone and the catalytic centre was reported. By increasing the length of spacer arm, the reactivity of polystyrene resin was found to be increased. This is due to the relief of steric hindrance imposed by the crosslinked polymer support and also due to the increased flexibility and
mobility of the attached function. In most cases, a few methylene groups will serve the purpose of the spacer arm which makes the active function protrude away from the polymer matrix into the solution phase where they can become accessible to low molecular weight species and solvents. The rate of oxidation of alcohols using polymer-supported hypochlorite reagent (10) was found to be increased drastically by the introduction of spacer methylene groups between the resin and hypochlorite function.

The reagent with higher number of methylene groups as spacer groups exhibited the higher reactivity in terms of reaction time and product yield and the reactivity gradually decreased with decreasing the number of spacer methylene group. The reactivity was found to be least in the case of reactive polymers with no spacer.

Ion exchange was enhanced by an increased distance between the active site and the polymer backbone. Recently much attention has focussed on the use of immobilised enzymes supported on ion exchange resins as biocatalysts for asymmetric synthesis. Phase transfer catalysts based on polystyrene-supported phosphonium salts and crown ethers showed an increase in activity, when these catalysts were bound to the polymer matrix with longer spacers. Such spacers permit the reaction sites to protrude into the solution so that it was more solvated due to hydrophobic-hydrophilic balance and the approach by the soluble substrate was more facilitated. In the asymmetric Robinson cyclisation reaction using polymer-supported L-proline as catalyst, the catalytic efficiency was found to be increased by the incorporation of spacer.
2.5.5 Effect of the nature and degree of crosslinking in the polymer support

The nature of the crosslinking agent and the degree of crosslinking have significant influence in determining the reactivity of the attached functional group and is governed by the distribution and accessibility of the functional group on the polymer backbone. The reactive polymers should have a porous structure to allow diffusion of low molecular weight species and solvents into the interior of the polymer matrix. This depends on the physical parameters such as total surface area, total pore volume and the average pore diameter, which are closely interrelated. These factors depend on the degree of crosslinking and the method of preparation of the polymer. In an appropriate solvent, linear polymers can dissolve to form a true molecular solution. Linear polymers can provide their functional groups free in the solution as they can attain homogeneous macromolecular solutions. Because of the insolubility of the crosslinked polymers, the accessibility of the functional groups is diffusion controlled and penetrant transport causes some sort of molecular relaxation making the functional groups buried deep within the crosslinked polymer matrix available to low molecular weight substrates. A relaxation diffusion coupling is observed at penetrant transport because the characteristic diffusion time depends on the size of the polymer sample.

The degree of crosslinking determines the solubility, extent of swelling, pore size, total surface area and mechanical stability of the polymer. That is solvation of the bound species, diffusion of the matrix are highly influenced by the crosslink density of the support. The physicochemical properties like swelling, compatibility with different solvents, rigidity and flexibility of these crosslinked polymers have a definite correlation with the variables of the macromolecular matrix.

Mechanical stability of the polymer matrix is found to be dependent on the degree of crosslinking. Lightly crosslinked resins appear to be fragile and even mechanical stirring can cause considerable mechanical degradation of the support. Physical stability of the support can be achieved by increasing
the crosslink density, but there always exists a balance between the required mechanical properties and the porosity of the network. The accessibility of functional groups in highly crosslinked networks is considerably diminished as these reactive groups are flanked by large frequencies of crosslinks leading to a decreased reactivity.\textsuperscript{207,208}

Some lightly crosslinked resins being able to absorb many times their own weight of an appropriate solvent. This is referred to as swelling or gel porosity. As the degree of crosslinking decreases, gel networks result which consist largely of solvents with only a small fraction of the polymer backbone. The degree of swelling varies inversely proportional to the crosslink density. As the crosslink ratio increases, the swelling decreases and hence the penetration of the low molecular species becomes difficult. The swelling of the bound resin is different from the unbound resin and this difference depends on the nature of the crosslinking agent and the attached species.

The nature of the crosslinking agent determines the diffusion of the substrate into the interior of the polymer networks. The diffusion becomes difficult with increasing crosslinking.\textsuperscript{209} In the case of highly swollen gel-type resin, pools of solvent appear within the polymer matrix through which molecules can diffuse more quickly without the requirement of molecular motion of the polymeric backbone. With higher crosslink density, the gel-type resins are associated with inefficient use of bound functional groups buried in the interior of resin particles. In the case of crosslinked polymer networks, the distribution of the functional groups on the polymer backbone is non-homogeneous and there is some extent of non-equivalence of the functional groups. It might be expected that groups placed in the vicinity of the crosslink points are very less accessible to substrate and solvents than groups situated away from the crosslinks.\textsuperscript{50} With higher extents of crosslinking, the polymer matrix become more rigid and the penetration of the solvent and substrate molecule to the reactive sites of the functional polymers is difficult. Gel polymers when compared with linear polymers are found to be slightly
less reactive as reaction will be limited by diffusion of the substrate within the resin pores. The yield of the reaction can be affected by the degree of crosslinking. For highly crosslinked resins, lower yields are observed. These facts suggest that polymers with very low crosslink density would be most suitable as increased swelling would result in higher accessibility through enhanced diffusion properties. Sometimes it is possible to increase the accessibility of the functional groups by using a more hydrophilic crosslinking agent.

With the chemical nature and the amount of crosslinking agent in the polymer matrix, the extent of functionalisation of a crosslinked polymer varies. The nature of the crosslinking agent in the polymer support exerts a definite influence on the reactivity of the attached functional groups. With increasing flexibility and hydrophilicity of the crosslinking agent, the reactivity of attached functional groups increases. In the metal ion complexation as well as the immobilisation of small molecules into crosslinked polymers, the performance of the crosslinked polymers depends on the nature and degree of crosslinking in the polymer support. Because of the presence of aromatic benzene ring, DVB is hydrophobic and rigid. NNMBBA is polar by the presence of amide groups. HDODA is flexible due to the presence of methylene groups. Crosslinking agents based on ethyleneglycol derivatives are highly flexible and polar. Thus TTEGDA imparts hydrophilicity and flexibility to the polymer matrix. It was found that the aminolysis of TTEGDA-crosslinked polyacrylamide occurred at a faster rate than those of DVB- or NNMBBA-crosslinked polyacrylamide. In these crosslinking agents with increasing methylene units (Scheme 2.9), the spacing between the connecting polymer chains increases. Introduction of these crosslinking agents into polymers in varying proportions would vary the physicochemical properties of crosslinked polymers.


Scheme 2.9. Relative rigidity/flexibility of the various crosslinking agents used in the present study

2.6. Characterisation of functional polymer supports

The conventional methods of chemical analysis applied to low molecular weight species are applicable to linear polymers. But they are no longer useful for the crosslinked polymers because of solubility problem. Various techniques have been used for the characterisation of functional polymers. The most widely used are the following.

*Elemental analysis:* By means of elemental analysis, detection and estimation of specific elements such as nitrogen, phosphorous, halogens or sulphur can be done.

*Gravimetric analysis:* If the reactions are carried out with reasonable degree of gravimetric accuracy, from the mass difference obtained during chemical transformations, reliable measurement of transformed functional group could be achieved. This analysis is most useful for reactions of functional polymers which are expected to lead to substantial weight changes. In such cases,
provided no physical breakdown of the polymer occurs and the polymer is dried and recovered with ease, the weight changes can be determined with considerable confidence.

**Titration of reactive groups:** Quantitative detection of different functional groups can be done by non-aqueous volumetric methods almost irrespective of the type of support to which it is attached. In some cases, the functionalised resins can be titrated directly. In the results of such titrations will only be meaningful if the reagent used in the titration can penetrate fully the pores of the functional polymer.55 Polymer bound groups such as acidic, basic, phenolic groups, oxidising and reducing agents can be titrated by the usual methods.213,214 For example, a strong nucleophile can displace chloride ion from chloromethylated polystyrene supports. Volhard's titration can readily estimate the liberated halide.215

**IR spectroscopy:** IR spectroscopy could be used as a confirmatory tool for the characterisation of functional polymers. IR spectroscopy is the most powerful and widely used technique not only for following the chemical reactions carried out on crosslinked polymers, but also for structural identification. By using Fourier Transform Infrared Spectrometers, the sensitivity of the method could be increased.

**ESR spectroscopy:** With ESR spectroscopy216-218 considerable success has been achieved by the use of nitroxide spin labels bound to the polymer support or added to solvents used to swell the samples. This method has not been directed at evaluating structure, but for measuring molecular mobility.219

**NMR spectroscopy:** One of the recent developments in the characterisation of crosslinked polymers is solid state high resolution NMR technique. Proton NMR has been used for the investigation of relaxation properties of solid polymers.220,221 The principal advantage of $^{13}$C-NMR is the wide chemical shift dispersion. Highly swollen, lightly crosslinked polymers can give excellent $^{13}$C-NMR spectra. $^1$H and $^{13}$C-NMR are useful for soluble polymers.
$^{13}$C-NMR spectrum of polystyrene gels highly swollen in CDCl$_3$ may have line widths of < 10 Hz for peaks of the pendant functional groups. $^{13}$C Spin lattice relaxation times and Nuclear Overhausser Effects have been determined for toluene in crosslinked gel beads substituted with tri-n-butyl phosphonium chloride groups.$^{222,223}$

**Scanning electron microprobe analysis:** The presence of functional groups within the polymer beads can be determined by scanning electron microscopic (SEM) analysis. It has been shown that chloromethylation of 2% crosslinked polystyrene beads followed by phosphination with lithium-diphenylphosphide gives beads with a uniform distribution of phosphorous.$^{224}$ SEM can be used for the determination of porosity characteristics of ion-exchange resins. The bead size, shape and surface can be observed from these micrographs.