Chapter 1

Introduction
1. Introduction

Since the ancient age chemistry plays a key role in the progress of new civilizations. It is reflected in the history of various civilizations which were classified according to the development of new materials in that particular civilization viz. Copper age, Iron age etc. In short, progress of a civilization is widely influenced by the discovery of new materials. In this modern civilization, high demand for new materials, chemicals and medicines have resulted an increase in complexity of targeted molecules day by day. To synthesize such complex molecules development of new chemical processes has become an important aspect of organic chemistry. Development of new processes is receiving special interest in the context of green chemistry and sustainable development. It was Prof. Paul T. Anastas in 1991 who first introduced the term “Green Chemistry” to signify sustainable development of academic and industrial chemical processes [1,2]. According to him, green chemistry is defined as “utilization of a set of principles that reduces or eliminates the use or generation of hazardous substances in the design, manufacture and application of chemical products”. Prof. Anastas put forward a set of twelve principles for making a chemical process green [3,4] which are as follows:

1. Prevention of waste/by-products
2. Maximum incorporation of the reactants (starting materials and reagents)
3. Prevention or minimization of hazardous products
4. Designing of safer chemicals
5. Minimization of energy requirement for any synthesis
6. Selecting the most appropriate solvent
7. Selecting the appropriate starting materials
8. Avoiding the use of protecting groups whenever possible
9. Use of catalysts should be preferred wherever possible
10. Products obtained should be biodegradable
11. The manufacturing plants should be designed so as to eliminate the possibility of accidents during operations
12. Strengthening of analytical techniques to control hazardous compounds
According to IUPAC system, green chemistry is defined as “The invention, design and application of chemical products and processes to reduce or to eliminate the use and generation of hazardous substances” [5]. The term “sustainable technology” is often said with “Green chemistry” particularly applicable for industrial processes, is defined as “Meeting the needs of present generation without compromising the ability of future generation to meet their own needs”. It is said that sustainability is the goal where green chemistry is the way to achieve it. Therefore, green chemistry is a global term for a sustainable modern world [1,6].

**Figure 1.1**: Design of green synthesis in laboratory

Design of green methodologies is generally framed by use of less toxic solvents, recoverable catalyst systems, appropriate starting materials, optimized reaction parameters and simple reaction routes (Figure 1.1). Among these, solvent plays crucial role in various reactions. However, most of the traditionally used solvents are hazardous to human health and the environments. It is found that benzene can cause cancer in animals and humans while toluene can damage brain, liver as well as kidney in humans. Chlorofluoro- carbons (CFCs) used widely until 20th century are dangerous for depletion of ozone layers. Therefore, it is always desirable to replace the traditional hazardous
organic solvents by the non/less hazardous solvents. In this respect, use of supercritical \( \text{CO}_2 \), ionic liquids and water as solvents have solved the problems to a great extent. Supercritical \( \text{CO}_2 \) has become a new hope for textile and metal industries and for dry cleaning of clothes. It is non-flammable, cheap and easily available. Ionic liquids are easy to perform; they are liquids at or below room temperatures and non-volatile. Similarly, water has been applied in numerous reactions due to its benign nature \[7\]. Solventless synthesis is another strategy in this respect due to faster reaction rate, minimum costs for purification and in separation process. However, not all reactions can be performed without solvents. Thus, no any single strategy can be termed as universal for building benign synthetic methodologies. One of the most important factors of green chemical synthesis is the use of catalysts whenever possible.

1.1 Catalysis and its importance

The beauty of catalysis has revolutionary aspects in every domain of sciences since early days. The word “catalysis” coined by Jöns Jacob Berzelius in 1835 comes from Greek words \( \text{kata} \) (cata) means down and \( \text{lyein} \) (lysis) means loosen. It was a great German chemist named Friedrich Wilhelm Ostwald who got Nobel prize in chemistry in 1909 for his outstanding work on catalysis and developed the concept of catalysis which stated that a catalyst did not initiate a reaction but rather accelerated the rate of reaction without formation of intermediate compounds \[8\]. The phenomenon of performing a reaction in presence of catalysts is called \( \text{catalysis} \). According to the definition, a catalyst can provide a different reaction energy pathway and decreases the activation energy barrier between reactants and products. Most of the complex chemical reactions in human and animal body, plant physiology are catalyzed by some efficient catalysts found in nature. Similarly, most of the chemical reactions in laboratories and industries would not have been possible without the use of catalysts. For example hydrolysis of esters become rapid in presence of a small amount of an acid or a base and these are called acid or base catalyzed. In the entire process, \(-\text{OH}\) ions act as the catalyst and does not get consumed in the process. Therefore, catalysis has been an exciting area in the context of green chemistry. The importance of catalysis reflects from the outstanding work of various scientists who got Nobel prizes in the field of catalysis as listed in Table 1.1.
Table 1.1: List of Nobel Prize winners in the field of catalysis

<table>
<thead>
<tr>
<th>Serial No</th>
<th>Name of Scientists</th>
<th>Area of discovery</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Friedrich Wilhelm Ostwald</td>
<td>Catalysis, Chemical equilibrium and reaction rates.</td>
<td>1909</td>
</tr>
<tr>
<td>2</td>
<td>Fritz Haber</td>
<td>Synthesis of Ammonia from atmospheric $N_2$ and $H_2$ molecules.</td>
<td>1918</td>
</tr>
<tr>
<td>3</td>
<td>Karl Waldemar Ziegler and Giulio Natta</td>
<td>Controlled polymerization of Hydrocarbons by Ziegler-Natta catalyst</td>
<td>1963</td>
</tr>
<tr>
<td>4</td>
<td>William S. Knowles, Ryoji Noyori</td>
<td>Chirally catalysed hydrogenation reactions</td>
<td>2001</td>
</tr>
<tr>
<td>5</td>
<td>K. Barry Sharpless</td>
<td>Chirally catalysed oxidation reactions</td>
<td>2001</td>
</tr>
<tr>
<td>6</td>
<td>Yves Chauvin, Robert H. Grubbs and Richard H. Schrock</td>
<td>Development of the metathesis method in organic synthesis catalyzed by transition methods</td>
<td>2005</td>
</tr>
<tr>
<td>7</td>
<td>Gerhard Ertl</td>
<td>Chemical processes on solid surfaces</td>
<td>2007</td>
</tr>
<tr>
<td>8</td>
<td>Richard F. Heck, Ei-ichi Negishi and Akira Suzuki</td>
<td>Palladium-catalyzed cross couplings in organic synthesis.</td>
<td>2010</td>
</tr>
</tbody>
</table>

1.1.1 Types of catalysts

Catalysts are broadly classified into homogeneous and heterogeneous ones. The following diagram shows the sub-divisions of various types of catalysts (Figure 1.2). In homogeneous catalysis, the catalysts present in the same phase as that of the reactants and products and generally are liquids while in heterogeneous one, catalysts present in different phase from the reactants or products and these are generally solids. Most of the traditionally used catalysts are homogeneous in nature which is dominating some major catalytic processes in the industries till now [9]. In spite of some excellent benefits, serious difficulties arise in separation of the homogeneous catalysts from reaction
mixtures. Particularly, removal of heavy metal catalysts from reaction mixtures in various metal catalyzed reactions create severe problem to the environment due to their toxic nature [10].

**Figure 1.2:** Typical classification of catalysts

The use of heterogenized catalysts is found advantageous in many processes in which homogeneous catalysts are anchored onto heterogeneous surfaces to get benefits of both homogeneous (high activity) and heterogeneous system (recovery) [11]. However, major drawbacks with these catalysts lies in leaching of catalysts from the heterogeneous surfaces during the course of reaction or in recycling process [11]. Hence, design of efficient and environmentally benign catalysts have been a common issue in the field of catalysis. In this regard, heterogeneous catalysts play a major role in establishing the economic strength of industries as well as laboratories due to cleaner synthesis. The advantages of heterogeneous catalysts over homogeneous ones can be understood from Table 1.2 as shown below [12].

**Table 1.2:** Comparison of homogeneous versus heterogeneous catalysts

<table>
<thead>
<tr>
<th>Catalyst property</th>
<th>Homogeneous</th>
<th>Heterogeneous</th>
</tr>
</thead>
<tbody>
<tr>
<td>Catalyst recovery</td>
<td>Difficult and</td>
<td>Easy and cheap</td>
</tr>
<tr>
<td></td>
<td>Expensive</td>
<td></td>
</tr>
<tr>
<td>Thermal stability</td>
<td>Poor</td>
<td>Good</td>
</tr>
<tr>
<td>Selectivity</td>
<td>Excellent/good</td>
<td>Good/poor</td>
</tr>
<tr>
<td>Active sites</td>
<td>Single active site</td>
<td>Multiple active site</td>
</tr>
</tbody>
</table>
1.1.2 Acid and Base catalysis

Acid and base catalysis occupy a cardinal position in the domain of organic synthesis [13,14]. The use of traditional acids such as BF$_3$, AlCl$_3$, TiCl$_4$ and HF create severe difficulties in the chemical and industrial processes due to their corrosive nature, toxicity and problems associated with effluent disposal and product separation. Similarly, traditional liquid bases such as NaOH, LiOH etc. are disadvantageous for human health and to the environment. It is found that aqueous hydroxide solution having pH $>$ 11 cause saponification of fats and solubilization of proteins when comes in contact with skin [15]. Concentrated caustic solutions are corrosive in nature and leads to cracking of tanks and vessels. Disposal of caustic solutions both in concentrated and dilute form are dangerous to the environment due to their strong basic nature. Neutralization of these basic solutions by other acidic solutions is generally employed for this problem prior to their disposal to the environment. However, this is quite problematic and costly. Again, commonly used molecular liquid bases such as ammonia and amines have sufficient volatility and gives toxic vapors. Due to these serious difficulties with the commonly used liquid acids and bases, the use for solid acid and solid base catalysts have emerged in vast number of chemical processes. Solid acid catalysts have got large attentions due to their high demand in petrochemical industries for catalytic cracking. Over the past 40 years, large varieties of solid acid catalysts such as Al$_2$O$_3$, ZSM-5, zeolite-Y, SiO$_2$ and P$_2$O$_5$ have been extensively studied for wide spectrum of reactions such as alkylation, biodiesel production, catalytic cracking, isomerization, hydration, dehydration and polymerization reactions. On the other hand, the number of use of solid bases is very less in comparison to solid acids. According to the survey made by Kozo Tanabe and Wolfgang F. Hoelderich in the industrial processes till 1999, it was found that out of 127 acid and base catalyzed commercial processes, 103 were catalyzed by solid acid catalysts, 14 were catalyzed by solid acid-base bifunctional catalysts while only 10 were catalyzed by solid bases [16] (Figure 1.3). Thus, solid base catalysts are not well explored in comparison to solid-acids. Ground-breaking paper on the use of solid base catalysts was reported by Pines and is co-workers in 1955 [17], where they found that the sodium metal dispersed on alumina effectively catalyzed double bond migration of alkenes. Since then, a good number of solid bases including single component metal oxides such as MgO and CaO
to porous zeolites, mesoporous aluminosilicates and clays have been developed [18] over the period.

![Figure 1.3: Comparison of solid acid and solid base catalysis](image)

Heterogenization of the classical base catalysts and supporting basic guests over these single component oxides hosts and porous hosts have been applied over the years to prepare a variety of base catalysts [13, 19]. Table 1.3 shows some of the important solid bases developed in last 50 years.

The most important reasons for recognizing the listed materials as solid bases can be evidenced from the following points [20].

(i) Evidence of the existence of basic sites on the surfaces are found from different surface characterizations such as colour change of the acid-base indicators, adsorption of acidic molecules on the surface, and spectroscopic studies (UV, IR, XPS, ESR, etc.).

(ii) The catalytic activities correlate well with the amount of basic sites, strength of the basic sites and these are usually poisoned by acidic molecules such as HCl, H₂O and CO₂.
(iii) The materials exhibit similar activities to “base-catalyzed reactions” similar to homogeneous basic catalysts and the mechanisms are similar to the homogeneous system.

(iv) Mechanistic studies of the reactions, product distributions, and spectroscopic observations of the surface species indicate that anionic intermediates are involved in the reactions.

Table 1.3: Types of solid base catalysts

<table>
<thead>
<tr>
<th>Types</th>
<th>Typical types</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1. Single component metal oxides</strong></td>
<td>Alkaline earth metal oxides</td>
<td>CaO, MgO</td>
</tr>
<tr>
<td></td>
<td>Rare earth oxides</td>
<td>La₂O₃, YbO₂</td>
</tr>
<tr>
<td></td>
<td>Transition metal oxides</td>
<td>ZrO₂, TiO₂</td>
</tr>
<tr>
<td><strong>2. Zeolites</strong></td>
<td>Alkali ion-exchanged zeolites</td>
<td>NaY</td>
</tr>
<tr>
<td></td>
<td>Alkali metal or metal oxide</td>
<td>KF/NaY, KNO₃/NaX</td>
</tr>
<tr>
<td></td>
<td>occluded zeolites</td>
<td>Cs-occluded zeolite</td>
</tr>
<tr>
<td><strong>3. Supported catalyst</strong></td>
<td>Alkali metal or metal ions such as Na, K, KNO₃, K₂CO₃ etc. supported on alkaline earth oxides, SiO₂, Al₂O₃ etc.</td>
<td>KF/MgO, KF/ Al₂O₃</td>
</tr>
<tr>
<td><strong>4. Clay minerals or modified clays</strong></td>
<td>Hydrotalcite, Sapiolite, Chrysolite etc</td>
<td>Mg-Al-Hydrotalcite</td>
</tr>
<tr>
<td><strong>5. Mesoporous material</strong></td>
<td>Modified mesoporous functionalized material</td>
<td>MgO/SBA-15</td>
</tr>
<tr>
<td></td>
<td>MCM-41 functionalized with amino groups</td>
<td></td>
</tr>
<tr>
<td><strong>6. Others</strong></td>
<td>Oxy nitride, phosphate, Natural</td>
<td>Silicon oxynitride (SiON)Aluminophosphaphosphate oxynitride (AlPON)</td>
</tr>
</tbody>
</table>

PhD Thesis of Ms Rasna Devi, Tezpur University, Assam, India.
However, most of the solid surfaces are not as strong as the liquid bases under ordinary conditions and thus requires proper pretreatment method before utilizing them in reactions. Hence, creating basic sites through their proper pretreatment is an essential step for solid catalysts. Generation of strong base sites is usually carried out by two methods: activation of the materials at high temperatures and supporting various guest species over porous materials. High temperature activation is necessary to activate the solid surfaces, since adsorption of CO\(_2\) and water vapors poisons the surface basicity when exposed to air. Supporting guest species on porous hosts is attractive for the fact that the amount of basic sites as well the base strengths can be adjusted by varying the ratio of guest host amount and their activation temperature according to the need of a particular reaction. Besides, porous hosts have the ability to accommodate varieties of guest species inside their structures. Among various supports, porous oxides such as ZrO\(_2\) and Al\(_2\)O\(_3\) are widely used as host materials to generate strong basic sites [21,22]. Handa et al. have shown that metal and alkali metal compounds supported on γ-Al\(_2\)O\(_3\) are much more active than a variety of single component solid bases such as BaO, Al\(_2\)O\(_3\), KY zeolite and mixed oxide like 4MgO.Al\(_2\)O\(_3\) for isomerization of 2,3-dimethyl-but-1-ene at 313K [23]. They have found that among varieties of catalysts tested, RbNH\(_2\)/Al\(_2\)O\(_3\) and KNH\(_2\)/Al\(_2\)O\(_3\) are the most active for this reaction while potassium exchanged zeolite Y is inactive under same reaction conditions. They have also found that KY zeolite is weaker than alkali amides on alumina, alkali compounds loaded alumina, MgO and CaO. Potassium amide supported on alumina (KNH\(_2\)/Al\(_2\)O\(_3\)) is a promising solid base for various other base catalyzed reactions [24-26]. Moreover, ZrO\(_2\) and Al\(_2\)O\(_3\) in presence KNO\(_3\) can create superbasic sites after activation [27,28]. However, relatively low surface area of these oxide hosts limits their use in many cases. Similarly, ordered mesoporous silica, in spite of their use as support for creating strong basicities [29], face limitations due to poor stability of the amorphous walls due to guest-host interactions [30]. Zeolites, due to their high surface area, high thermal stability, ordered pore architecture and surface acid-base properties can be good alternative for generating strong basicities. Therefore, searching of suitable guest hosts for preparation of strong, reusable solid bases is an ongoing research in the field of catalysis. Some of the important industrial processes catalyzed by supported and unsupported solid bases are listed in Table 1.4 [20].
Table 1.4: Important industrial processes catalyzed by solid bases

<table>
<thead>
<tr>
<th>Process</th>
<th>Reaction</th>
<th>Catalyst</th>
<th>Company/Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alkylation</td>
<td>1. Alkylation of phenol with methanol</td>
<td>MgO</td>
<td>Gen.1 Elect./1970, BASF/1985</td>
</tr>
<tr>
<td></td>
<td>2. Alkylation of cumene with ethylene</td>
<td>Na/KOH/Al₂O₃</td>
<td>Sumitomo/1988</td>
</tr>
<tr>
<td>Isomerization</td>
<td>3. Isomerization of 2,3-dimethyl-1-butene</td>
<td>Na/NaOH/Al₂O₃</td>
<td>Sumitomo/1988</td>
</tr>
<tr>
<td></td>
<td>5. Isomerization of 1,2-propadiene to propyne</td>
<td>K₂O/Al₂O₃</td>
<td>Shell/1996</td>
</tr>
<tr>
<td>Dehydration/</td>
<td>6. Dehydration of 1-cyclohexylethanol</td>
<td>ZrO₂</td>
<td>Sumitomo/1986</td>
</tr>
<tr>
<td>Condensation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>8. Isobutyraldehyde to Isobutyl-isobutyrate</td>
<td></td>
<td>Chisso/1974</td>
</tr>
<tr>
<td>Others</td>
<td>10. Thiols from alcohols with Alkali/Al₂O₃</td>
<td></td>
<td>Orgsinteż</td>
</tr>
</tbody>
</table>

1.1.3 Determination of basic properties of catalysts

Investigation of basic properties of solid bases such as strength of basic sites and concentration of basic sites is a necessary tool for understanding their catalytic activities, nature of solid surfaces as well as the guest-host interactions. The existence of surface basic character was first understood through the indicator technique followed by a number of methods such as temperature-programmed-desorption (TPD) of CO₂ [31], NMR studies [32], poisoning by CO₂ and NH₃ [33], XPS binding energy of probe molecules adsorbed on solid surfaces [34] and adsorption of organic acids [35]. Among
these, TPD technique and indicator techniques are commonly employed for measurement of basic sites and base strengths, respectively.

Studies on basicities of solid surfaces have been reviewed well in different literatures [36,37]. The theory behind the indicator technique is similar to simple acid-base indicator in the solution phase chemistry where the colour of an acidic indicator change when it get adsorbed onto a basic surface. Base strength of a solid surface is defined as its ability to convert an adsorbed electrically neutral acid to its conjugate base [38]. If a neutral acidic indicator (InH) transfers the proton to the basic sites (B) of the catalyst, base strength is represented by Hammett basicity function (H_) as shown below:

\[ H_\_ = pK_{\text{InH}} + \log [\text{In}^-]/[\text{InH}] \] ……………….. (i)

where [InH] and [In\(^-\)] are the concentrations of acidic indicator and its conjugate base respectively. Table 1.5 lists some commonly used indicators for measurement of basicity along with their respective colours in acidic and basic surface.

<table>
<thead>
<tr>
<th>Indicators</th>
<th>Colour</th>
<th>Acid form</th>
<th>Basic form</th>
<th>H_ range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bromothymol blue</td>
<td>Yellow</td>
<td>Green</td>
<td>7.2</td>
<td></td>
</tr>
<tr>
<td>Phenolphthalein</td>
<td>Colorless</td>
<td>Red</td>
<td>9.3</td>
<td></td>
</tr>
<tr>
<td>Tropaeolin-O</td>
<td>Red</td>
<td>Yellow</td>
<td>11.1</td>
<td></td>
</tr>
<tr>
<td>2,4,6,Trinitroaniline</td>
<td>Yellow</td>
<td>Reddish orange</td>
<td>12.2</td>
<td></td>
</tr>
<tr>
<td>2,4,Dinitroaniline</td>
<td>Yellow</td>
<td>Violet</td>
<td>15.0</td>
<td></td>
</tr>
<tr>
<td>4Chloro-2-nitroaniline</td>
<td>Yellow</td>
<td>Orange</td>
<td>17.2</td>
<td></td>
</tr>
<tr>
<td>4-Nitroaniline</td>
<td>Yellow</td>
<td>Orange</td>
<td>18.4</td>
<td></td>
</tr>
<tr>
<td>4-Chloroaniline</td>
<td>Colorless</td>
<td>Pink</td>
<td>26.5</td>
<td></td>
</tr>
</tbody>
</table>

Hammett basicity function (H_) was proposed for the first time by Paul and Long in 1957 [39]. Practically, base strength of a basic surface is determined by addition of a known concentration of indicator solution in non-polar solvent to the tested solid and checking well to ease adsorption. When the indicator gets adsorbed onto the solid, the
colour of the indicator will change provided the solid surface has enough strength to convert the indicator into its conjugate base form and thus shows the colour of its basic form. Similarly, quantitative determination of amount of basic sites is determined by using the theory of acid base indicators. We have found that titration method is commonly employed for this purpose. In this method, titration of a suspension of the solid base in a non-polar solvent such as benzene, containing the indicator in its conjugate base form is titrated with benzene solution of benzoic acid. Here, the acid neutralizes the conjugate base and shows end points from which amount of basic sites are measured in mmol g\(^{-1}\) of the titrated acid.

1.2 Microwave heating for chemical reactions

Microwave heating technology is gaining special interest in the last few years for improving the organic transformations [40]. Using microwave technology traditional organic transformation can be carried out within short period of time. It is well known that enhancement of reaction rate and conversions are achieved through heating of reaction mixtures under thermal heating conditions in oil bath. Microwave irradiation as non-conventional energy source provides an alternative way to activate reaction systems. The direct use of microwave energy in chemical reactions was started in 1986 from the pioneering papers by Gedye and co-workers [41] and Giguere and co-workers [42]. Since then it has become an essential tool for faster synthesis for wide areas of sciences like organic synthesis, polymer synthesis, material sciences, medicinal chemistry and nanotechnology [43-47]. The main advantage of the protocol lies in its “core heating” mechanism or dipolar mechanism [48]. The acceleration of reactions is due to interaction of dipolar molecules with microwave energy leading to both thermal and nonthermal effects. To be active for microwave adsorption, a substance or a molecule must possess some dipole moment. A dipole is sensitive to an external electric field and tries to orient itself with the direction of field. When microwave is irradiated, due to rapidly oscillating electric field of strength of about 2450 MHz, the dipoles try to orient themself along with the oscillating field and thus induce some rotation and intermolecular friction between them (Figure 1.4). Internal core heating is the result of dissipation of microwave energy as heat due to these induced rotations. The ability of a substance to convert
electromagnetic energy into heat at a given temperature and frequency can be calculated by using the formula,

\[
\varepsilon''/\varepsilon' = \tan \delta,
\]

where \(\delta\) is the dissipation factor of the molecule, and \(\varepsilon''\) is the dielectric loss and measures the efficiency with which heat is generated from electromagnetic radiation and \(\varepsilon'\) is the dielectric loss which gives the ability of a molecule to be polarized by an electromagnetic field [49].

\[
\varepsilon'':/\varepsilon'=\tan \delta,
\]

Figure 1.4: Effect of electric field on dipolar molecules (a) without any field (b) under influence of continuous electric field (c) under influence of alternating electric field at high frequency.

The high value of \(\delta\) indicates high susceptibility to microwave energy [50]. This has special advantage for polar solvent molecules where “superheating effect” occurs under microwave and boiling point increases than their conventional values [51]. Both solvent free and solvent mediated microwave synthesis have been reviewed in the recent years describing the advantages of microwave heating over classical heating [52,53].

### 1.3. Aqueous phase reactions

Being non-toxic, cheapest and safest solvent in the world, water plays an important role in green chemical synthesis [54,55]. The replacement of volatile organic solvents with environmentally friendly solvents is essential due to unlimited use of solvents in various purposes like reactions, extractions and separations in both
laboratories and chemical industries. Although aqueous media reactions were tried in the beginning of 19th century, water was not utilized for organic synthesis due to low solubility of organic reactants and reagents in it. It was Breslow in 1980 who showed for the first time the enhancement of reaction rate with H_2O as solvent and made a remarkable beginning for utilization of water in organic synthesis [56,57]. He observed that the rate of Diels-Alder reaction of cyclopentadiene and butenone with water medium was more than 700 times faster than that with isoctane. The unique properties of water have been understood well during these times and have been utilized for green synthetic methodologies. Water has low volatility due to association of the molecules through hydrogen bonding and thus becomes an interesting replacement to the commonly used volatile organic solvents. Water being a small molecule, large cohesive energy density due to three dimensional hydrogen-bonded structures, high dielectric constant and high heat capacity, gives rise to an important property called hydrophobic effect. This hydrophobic effect is the driving force for interaction of organic reactants in aqueous medium, formation of micelles and bilayers, determination of the structures of proteins and nucleic acid, binding of substrates to enzymes, binding of antigens to antibodies etc. [58,59]. High cohesive energy of water drives the non polar organic molecules in organic reactions to aggregate in water and thus help in the progress of the reaction and increases selectivity [60,61]. In spite of the large cohesive energy of water, some solute molecules cannot aggregate and interact in water due to hydrophobic hydration [62,63]. This effect is responsible for decrease of reactions in aqueous medium. The properties of water are also controlled by pressure and temperature. On increasing temperature, hydrophobic hydration effect decreases and the association of hydrophobic molecules becomes easier i.e. hydrophobic interaction effect comes into play. Water behaves differently under high temperature and pressure. At high pressure, electrical conductance of aqueous solutions increases on increasing pressure due to their peculiar associative properties while for all solvents, electrical conductance decreases on increasing pressure. On increasing temperature, density of water goes on decreasing due to thermal expansion of the molecules. This value of dielectric constant is comparable to the commonly used organic solvents such as acetone at ambient temperatures [64]. Thus water can behave like pseudo-organic solvents at high temperature and high pressure. This increases solubility.
of hydrophobic molecules and speed up reactions. At critical temperature, water called supercritical water, the density of water becomes 0.3 g/cm$^3$. At the supercritical region, the heat capacity at constant pressure becomes very high and electrical conductance rises sharply. Therefore, supercritical water is used as green solvent in many processes. Despite of these advantages, water mediated synthesis are limited due to insolubility of most of the organic substrates. Again, evaporation of water from the reaction medium requires further difficulty in the process. Hence, efforts have been going on to add advantages of water with other strategies to get benefited from the combined effect. In this respect, microwave heating of reaction mixtures in presence of water medium is quite impressive.

When water is heated under microwave, due to its polar nature it can absorb microwave radiation easily and thus convert microwave energy into heat energy as a result of dissipation of absorbed energy in the form of heat. This can lead to rapid heating of the reaction mixtures and accelerates reactions faster than conventional heating. The use of water is further advantageous for reactions with nonpolar solvents under microwave. Addition of small amount of water with non-polar solvent like toluene can heat the reaction mixture as a whole. Besides, polar molecules can easily dissipate energy to the non-polar molecules and heats the whole reaction mixture rapidly [65]. Hence, addition of small amount of polar solvents to non polar solvents is an effective way to use non polar solvents for accelerating reactions under microwave. With these beneficial properties, water has been used in a good number of organic reactions.

1.4 Introduction of Zeolite

Zeolites form an important class of solid catalysts in the fine chemical industries as well as in the laboratories. It was Weisz and Frilette who reported the pioneering work on catalysis by zeolite in 1960 when they found some “unexpected intrinsic catalytic activities” of a faujasite like synthetic zeolite [66]. After the discovery, rapid increase of publications has been noticed year after year with practice of zeolite catalysts in all fields of sciences. It was Swedish mineralogist Axel Fredrik Cronstedt who discovered zeolite mineral “stilbite” for the first time in 1756. Cronstedt in 1756 coined the term “zeolite” (comes from Greek words “zeo” meaning “to boil” and “lithos” meaning “stone”) when
he observed that heating stilbite mineral produced large amount of steam from water which was contained in their structure [67].

Structurally, zeolites are crystalline aluminosilicates having general formula $\text{M}^{n+}_{\infty}[\text{(AlO}_2\text{)}_x\text{(SiO}_2\text{)}_y]\text{zH}_2\text{O}$, where $\text{M}^{n+}$ is the cation, $x,y,z$ are numbers and the ratio of $y/x$ is the governing factor of acidity or basicity of zeolites. The primary building block of zeolites is the SiO$_4$ tetrahedron with each apical oxygen atom shared with an adjacent tetrahedron. In zeolites, some of the SiO$_4$ tetrahedra are replaced by AlO$_4$ tetrahedra which create extra negative charge in the structure and thus the resulting imbalance of charge is compensated by some positive ions. Some of these compensating cations are called the extra framework cations of zeolites and are exchangeable by other positive ions. Structurally, zeolites are complex inorganic polymers with infinite three dimensional network of TO$_4$ tetrahedra ($T =$ tetrahedral atom, e.g., Si, Al) and each apical oxygen atom is shared with an adjacent tetrahedron.

Figure 1.5: Structures of four large pore zeolites, faujasite, zeolite-L, mordenite and ZSM-12

The three dimensional network of zeolites possess intracrystalline porous channels containing water molecules and the replaceable cations. Removal of these water molecules through heat treatment leaves the void space free and makes them porous. The porous nature of zeolites is the principal reason why these are charming in the field of catalysis. In zeolites, the primary building units join in different ways to form secondary
building unit such as cubes, hexagonal prism and simple polyhedra which again join to form varied types of zeolite frameworks (Figure 1.5). The structural nomenclature of zeolites was given by Structure Commission of International Zeolite Association (IZA) [68]. The international zeolite association (IZA) was formed in 1973 at the third international molecular sieve conference to develop the field of zeolite science and technology. This was followed by the formation of “Structure Commission” in the 4th international conference on molecular sieves in 1977 [69]. The Structure Commission was given authority by IUPAC to assign framework type codes (consisting of three capital letters) to all unique and confirmed framework topologies. Accordingly, each distinct framework type was assigned a three letter code called Framework Type Code (FTC) by the IZA Structure Commission irrespective of their compositions and published the details in *Atlas of Zeolite Framework Types* [70, 71].

Table 1.6: Classification of zeolites based on pores or channel system [72].

<table>
<thead>
<tr>
<th>Zeolite Type</th>
<th>Channel system Å (Number of oxygen atoms in the ring, channel dimension)</th>
<th>Porous Cavity, Å</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Small Pore</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Linde A</td>
<td>4.1 (8, 3D)</td>
<td>6.6, 11.4</td>
</tr>
<tr>
<td>Erionite</td>
<td>3.6 × 5.2 (8, 3D)</td>
<td>6.3 × 13</td>
</tr>
<tr>
<td><strong>Medium Pore</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ZSM-5</td>
<td>5.3 × 5.6 (10, 1D)</td>
<td>Interconnected</td>
</tr>
<tr>
<td></td>
<td>5.1 × 5.5 (10, 1D)</td>
<td>channels</td>
</tr>
<tr>
<td>Ferrierite</td>
<td>3.4 × 4.8 (8, 1D)</td>
<td>Interconnected</td>
</tr>
<tr>
<td></td>
<td>4.3 × 5.5 (10, 1D)</td>
<td>channels</td>
</tr>
<tr>
<td><strong>Large Pore</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fauzasite</td>
<td>7.4 (12, 3D)</td>
<td>6.6, 13</td>
</tr>
<tr>
<td>Mordenite</td>
<td>2.9 × 5.7 (8, 1D)</td>
<td>Interconnected</td>
</tr>
<tr>
<td></td>
<td>6.7 × 7.0 (12, 1D)</td>
<td>channels</td>
</tr>
<tr>
<td>Zeolite L</td>
<td>7.1 (12, 1D)</td>
<td>10.7</td>
</tr>
</tbody>
</table>
Till date more than 200 types of framework structures of zeolite are identified. According to the nomenclature, “FAU” was given to the fauzasite type framework (e.g. NaY, zeolite Y, NaX etc), “LTA” for Linde Type A framework and MOR was given to mordenite topology. The most important features of zeolite framework are the presence of pores upto 8-12 member oxygen rings and variations in Si/Al ratio from member to member. The entire surface areas of zeolites are nearly inside the micropores and are accessible to molecules of varying dimensions. Reactant molecules can access through the pores and give selective products. Depending upon the pore sizes, zeolites are classified as small pore, medium pore and large pore zeolites as shown in Table 1.6.

1.4.1 Catalysis by zeolites

Historically, zeolites have been widely used as solid acid catalysts in the industries for petroleum refining applications such as catalytic cracking and oil refining [73]. Besides, zeolites are used extensively in the chemical processes such as conversion of benzene to ethylbenzene, production of xylene, side chain alkylation of toluene; gas conversions such as methanol to gasoline (MTG), methanol to olefins (MTO), conversion of light petroleum gas (LPG) to aromatics and in oil conversion processes like hyrodewaxing and hydrocracking [74]. Zeolite ZSM-5 has been commercialized as additive for increasing octane numbers in fluidized catalytic cracking (FCC) [74]. Similarly, zeolite Y in its rare earth exchanged from was found admirable for FCC processes where the low octane number was further improved by utilizing ultrastable zeolite Y (USY i.e. high silicon zeolite Y) or a mixture of both USY and zeolite Y in the processes. However, zeolite as base catalysts was not practiced until the end of 19th century. It has been found that zeolites were used as solid base catalysts in their ion-exchanged form and impregnated form in the beginning of 1990s [75]. In spite of their great potential as shape selectivity and green catalysts, use of zeolites as solid bases are limited due to their weak base strengths and difficulty in generating strong basic sites in their structures. Therefore, tuning of basic properties through modification has been an exciting field of research till now.
1.4.2 Basic properties of zeolites

There are two main kinds of base zeolites i.e. alkali ion-exchanged zeolites and metals or metal oxides loaded zeolites. In general, the basic sites in alkali ion-exchanged zeolites are the framework oxygens adjacent to the alkali cations and therefore related to the negative charge density on the oxygen atoms, which depend on the zeolite structure and chemical composition [76]. The base strength and the density of basic sites in alkali ion-exchanged zeolites decrease with an increase in framework Si/Al ratio, while base strength increases with an increase in electropositivity of the counter cation in zeolites [77]. High aluminum content of zeolite X (Si/Al = 1–1.5) increase the framework negative charges, which make zeolite X an excellent base catalyst in its alkali exchanged form [78,79]. It is found that the base strength of alkali ion-exchanged zeolites decreases in the following order: Cs$^+$ > Rb$^+$ > K$^+$ > Na$^+$ > Li$^+$ and these are regarded as weak bases. Therefore they can be handled in ambient atmosphere, since adsorption of carbon dioxide or water is not too strong and they can be removed by high-temperature treatment. Occlusion of alkali metal oxide clusters in zeolite cages via decomposition of impregnated alkali salts results in a further increase in the basicity of base zeolites. Preparation of fine particles of alkali oxides inside the cavities of zeolites was developed by Hathaway and Davis [80-82]. They impregnated CsNaX and CsNaY zeolite with cesium acetate aqueous solution and calcined at 723 K to decompose cesium acetate into cesium oxide inside the cavities. Highly active basic sites were formed by this method. The work of Hathaway and Davis was extended by Tsuji et al. and found that potassium and rubidium oxide could be formed in addition to cesium oxide [83,84]. The resulting zeolite created basic sites stronger than those of simple ion-exchanged zeolites and could isomerize 1-butene to 2-butene at 273 K with high cis/trans ratios. Recently, alkali earth oxides such as MgO and BaO are introduced into zeolites to produce strong basic sites [85,86].

The basicity (amount and strength) of base zeolites have been extensively studied by theoretical approaches and experimental characterizations, including infrared (IR) spectroscopy of adsorbed probe molecules such as carbon dioxide [87], pyrrole [88,89], chloroform [90] and characterization techniques like TPD [91], XPS [92,94], UV-Vis spectroscopy [95,96], microcalorimetry [97,98] and NMR [99,101]. By generating
framework and/or extra-framework basic sites mentioned above, it is possible to prepare base zeolites having medium to strong basicities. Depending on the reaction to be catalyzed, it is possible to tune and select the most suitable base zeolite. Therefore, zeolites have been used as base catalysts in a number of base-catalyzed reactions, such as toluene alkylations with methanol or ethylene [102,103], dehydrogenation of alcohols [104], double bond isomerizations [105], Knoevenagel condensations [106,107], aldol condensations [108,109], cycloaddition of CO$_2$ to epoxides [2] and nitroaldol condensation [110,111].

In the flow of current research, a group of basic materials have been prepared by exchanging extra framework cations of zeolites with alkali and alkaline earth metal cations [112] and loading alkali metal salts over a variety of solid supports where potassium salt is the most common among other alkali salts [113-116]. Supported catalysts have gained considerable attention in these days due to their superior properties. Various supports such as porous oxides Al$_2$O$_3$, ZnO, ZrO$_2$ and SiO$_2$, zeolite NaX, NaY, ZSM-5, KL zeolite etc. are used to prepare solid bases by using potassium salts as guest material [117-119]. Although Al$_2$O$_3$ and ZrO$_2$ have been found as excellent basic materials in presence of potassium salts, their use is limited due to low surface area and disordered pore arrangements. Zeolites having aluminosilicate compositions, high surface area, well organized pore channels; stability towards heating and its benign nature are preferred as host material over the low surface area oxide hosts. Potassium fluoride has been supported onto a variety of solid host materials due to its different advantages such as it is easy to handle, inexpensive, thermally stable and can be easily dried.

According to the report by Weinstock et al. in 1986, the high basicity of KF/ Al$_2$O$_3$ is responsible for KOH formed as a result of interaction of KF with Al$_2$O$_3$ where F$^-$ ions form H-bonding to the -OH group of hydroxylated surface of alumina and exert high basicity [120]. Zhu et al. loaded KF over Al$_2$O$_3$ and found higher basicity and higher catalytic activity than KOH/Al$_2$O$_3$ for isomerization of 1-butene at 273K [121-124]. Yamaguhci et al. in 1997 showed that potassium compounds such as KNO$_3$ loaded on Al$_2$O$_3$ and activated at 773-873K is highly basic and active for isomerisation of but-1-ene [125]. Similarly, KF loaded over SiO$_2$ was reported by Jhu et al. and showed that F$^-$
reacted with the surface of SiO$_2$ to give a crystalline phase of K$_2$SiF$_6$ and liberated KOH similar to KF/Al$_2$O$_3$ according to the equations-1 and 2 [126].

\[
\begin{align*}
6\text{KF} + \text{SiO}_2 + 2\text{H}_2\text{O} & \rightarrow \text{K}_2\text{SiF}_6 + 4\text{KOH} & \text{(1)} \\
12\text{KF} + 3\text{H}_2\text{O} + \text{Al}_2\text{O}_3 & \rightarrow 6\text{KOH} + 2\text{K}_3\text{AlF}_6 & \text{(2)}
\end{align*}
\]

In their study, acidic SiO$_2$ became basic after loading of KF and basicity was responsible on concentration of F$^-$ ion. Since zeolites have both AlO$_4$ and SiO$_4$ units in their structure, similar type of basic nature and reaction with F$^-$ ions can be expected from loading fluoride support. Zeolite Y having high surface area attracted the chemists from long time to support various guest species over it. Due to unique properties [127,128] and benign nature, it would be a potential solid base catalysts if strong basic sites can be generated onto it. In this issue, potassium salts such as KOH, KF and KNO$_3$ are practiced by a number of groups in the past years. Supported fluorides have been found as potential base catalysts for a long time [129].

In 1979, Yamawaki et al. supported KF over fauzasite zeolite and utilized it for O-alkylation of phenol. In the experiment the basic properties was not well understood and the activity was found very low [130]. In 1998, Zhu and his co-workers reported only mild basicity of NaY zeolite ($H_\ell = 9.3$) after loading 16 wt % KF and activated at 400 °C. They observed that 16 wt % KF over alumina coated NaY zeolite and activated at 400 °C generated strong basic sites ($H_\ell = 17.2$) without significant change in zeolite pore architecture. Again, Sun et al. in 2009 have reported quite low basicity of KF/NaY ($H_\ell = 7.2$) after activation at 600 °C. They have showed that the zeolite structure collapsed upon activation at 600 °C [131].

Similarly, zeolite KL has been loaded with potassium salts like KOH and KNO$_3$ to increase the basic properties [132-134]. Jo et al. showed that KL zeolite loaded with KOH and calcined at 500 °C increased base strength from $H_\ell = 7.2-9.6$ of parent KL to $H_\ell = 9.6-15$ of the loaded one and showed high catalytic activities for transesterification of soyabean oil [135].

Recently, we have modified NaY zeolite with 2-20 wt % KF and found that low loading of KF zeolite over NaY and their activation can generate strong basic sites
without damaging the framework structure. We have observed that zeolite structure remain intact upto 10 wt % loading of KF and activated at 450 °C without forming any other crystalline phase. Consequently, loading of NaY zeolite with different amount of KF and activation at 450-800 °C were done to observe their effect upon the structure, base strengths and catalytic activities.

1.5 Henry reaction

Henry (or niroaldol) reaction is a classic example of atom economic C-C bond forming reaction between a nitroalkane and an aldehyde or a ketone in presence of a base to give β-nitroalcohols as the major product [136] (Scheme 1). It was L. Henry who discovered this reaction for the first time in 1895 which become a useful reaction for various chemical and biological syntheses since then [137,138].

\[
\begin{align*}
R_1R_2HNO_2 + R_3R_4^\text{O} &\rightarrow \text{Base} \rightarrow R_3R_4R_2O\text{HNO}_2
\end{align*}
\]

**Scheme 1.1:** Henry reaction between nitroalkane and carbonyl compound

The mechanism of the reaction involves abstraction of a proton by the base from the active methylene center of the nitroalkane to form a reactive nitronate species in the first step followed by attack of the nitronate species on electrophilic centre of the carbonyl compound to form corresponding β-nitroalcohol [139] (Scheme 2). The reaction has got considerable interests from very early days due to synthetic utility of the product β-nitroaldol which can be easily converted into various important compounds such as β-amino alcohols, ketones, carboxylic acids, nitroalkenes etc [140-143]. Moreover, it can act as suitable intermediate for synthesis of various biologically important compounds such as aminosugars, anti-HIV drug amprenavir and α-hydroxy-β-amino acids which is a valuable backbone for peptide formation [144-148] (Scheme 3).
Typically, nitroaldol reactions were performed in presence of homogeneous bases such as NaOH, KOH, NaOMe etc. in either alcoholic or aqueous medium [149,150]. However, these traditional catalysts have got limitations in formation of nitroalkenes and polymerized products as side products due to strong basic nature of the catalysts. On the other hand, removal of the homogeneous catalysts from the reaction mixture is a difficult task.

Scheme 1.2: General mechanism of Henry reaction

A good number of homogeneous catalysts have been found successful for this reaction over the years. In 1989, Watt et al. studied the reaction with 1,1,3,3-tetramethylguanidine (TMG) in presence of diethyl ether and tetrahydrofuran [151,152]. Besides, amines such as triethylamine and diisopropylethylamine were used in presence of alcoholic solvents [153]. Verkade et al. in 1999 reported efficient promotion of nitroaldol reaction of ketones and aldehydes by a series of proazaphosphatranes [154]. They showed that the competitive self-condensation reaction of ketones was suppressed to a greater extent due to the protonated structure of phosphatranes and gave good yield of nitroaldol product with ketonic substrates. Youn et al. in 2000 reported that LiAlH₄ (10 mol %) in THF can
effectively catalyze the nitroaldol reaction between a variety of aliphatic and aromatic aldehydes with simple nitroalkanes such as nitromethane and nitroethane [155]. The reaction gave 71 % yield within 2-8 hours. The promotion of the reaction by moisture and impurity LiOH was ruled out by carrying out the reaction with 10 mol % LiOH with dried THF.

**Scheme 1.3:** Application of Henry product β-nitroaldol

A variety of catalysts like tetramethyl guanidine, NaOH in presence of cetyltrimethylammonium chloride (CTACl) [156], tetramethylethylene diamine (TMEDA) are found successful for this reaction [157]. The impressive works on Henry reaction has been carried out by different groups like Chisholm et al. with trialkyl phosphine catalysts [158], Desai et al. with potassium phosphate [159] and Morao and Cossio with dendritically encapsulated amine complexes [160].
Demand of green chemical synthesis led various group of chemists to improve the reaction conditions as well as to minimize side products with the help of new catalyst systems and suitable reaction media [161-164]. Use of solid base catalysts, solventless reaction, water mediated reaction and use of microwave as alternating heating source have solved this problem to a great extent. Ballini et al. in 1994 used Amberlyst A-21 to synthesize nitroaldols with good to moderate yield of the product (65-86 %) from a series of aldehydes and 4-nitro-2-butanol under solvent free conditions [165]. In 2008, Ballini et al. used Al₂O₃ in supercritical CO₂ to get controlled product with good yield [166]. They showed that nitroaldol product predominates at low temperature and low pressure (40 °C) while nitrokene predominates on increasing temperature and pressure (60 °C, 100 bar). In the recent years, a group of catalysts like hydrotalcites, MgO catalysts, silica etc. have been practiced for this reaction under suitable reaction conditions. Bulbule et al. have reported that activated MgAl-hydrotalcite in THF solvent can effectively catalyze nitroaldol reaction to afford threo isomer in a highly diaestereoselective manner. At the same time Choudhary et al. found high yield of nitroaldol product with activated MgAl-O-tBu catalyst under mild condition [167]. Despite of a variety of solid bases used for this reaction, searching of better catalyst is an ongoing research to obtain high yield and simultaneous control of the side reactions. Particularly, solid base catalysts like alkali and alkaline earth metal exchanged zeolite X and zeolite Y, supported zeolites and metal oxides, hydrotalcites etc. have been used for this reaction to take advantage of their tunable basicity, easy product isolation and catalyst recycling [168-171]. We have observed that zeolite catalyzed nitroaldol reactions is not very common. In 2014, Keller et al. have found that cation free high silica containing ultrastable zeolite Y (USY) shows high catalytic activities for liquid phase nitroaldol reaction [172]. On the other hand, functionalized mesoporous silica materials were found to catalyze this reaction selectively. The high selectivity of mesoporous silica is controlled by the typical coordination of the heterogenized group on the surface of silica where the silica acts as inert host for the reactions [173,174]. Anan et al. showed that grafting of aminopropyl group on mesoporous silica in polar solvent like ethanol formed selective nanoporous catalysts which gave nitroaldol product upto 100 % conversion and selectively within 15-30
minutes [175]. In another report, Huh et al. found high selectivity of the product with bifunctionalized mesoporous silica nanospheres [176].

Therefore, it is believed that KF loaded NaY zeolite can selectively catalyze nitroaldol condensation reaction. Further improvement of yield has been achieved through microwave irradiation of the reaction mixture. Henry reaction under microwave has been practiced in the years under solventless conditions with both homogeneous and heterogeneous catalytic systems. Verma et al. in 1997 obtained high yield of the dehydrated nitroalkene from NH$_4$OAc as catalysts under solventless conditions without isolation of intermediate β-nitroalcohols [177]. Gan et al. found high yield of nitroaldol product with 1,4-diazabicyclo[2,2,2]octane (DABCO) as base under microwave [178]. Powdered KOH can also furnish good yield of the product within few minutes for both aliphatic and aromatic aldehydes [179]. In another report, Kumar et al. have shown that reaction of aromatic aldehyde and nitroalkanes on activated SiO$_2$ affords 2-nitroalcohols in moderate to high yields [180]. However, the use of solvents along with heterogeneous base under microwave is not very common for this reaction. Herein, we have coupled the benefits of aqueous medium with alcoholic solvents under microwave for this reaction.

1.6 Layered Double Hydroxides (LDHs)

Another important class of solid base materials are the layered double hydroxides (LDHs) or commonly known as hydrotalcites [181]. The word “hydrotalcite” was derived from the word “talc” and its high water content because it can be easily crushed into powder like “talc” and it possesses high water content in the interlayers [182]. These are two dimensional anionic clays whose structures can be derived from brucite like Mg(OH)$_2$ structures as shown in Figure 1. The divalent (Mg$^{2+}$) cations are surrounded octahedrally by hydroxyl groups in the brucite structures [183]. When some of the divalent Mg$^{2+}$ cations in the brucite like layers are replaced isomorphously by trivalent cations like Al$^{3+}$, generation of extra positive charge occurs in the structures and thus accommodates some charge balancing anions in the hydrated interlayer region to form hydrated layered structures or hydrotalcite structure [183]. The structure of LDHs can be represented by the general formula [M$^{II}_{1-x}$M$^{III}_x$(OH)$_2$]$^{x+}$ (A$^{n-}$)$_{x/n}$ yH$_2$O, where M(II) are divalent cations.
(M=Mg, Fe, Co, Ni, Cu, Ni etc.), M(III) are the trivalent cations (M=Al, Cr, Mn, Fe, Cr etc.), $A^{n-}$ are the charge balancing anions such as $\text{CO}_3^{2-}$, $\text{NO}_3^-$, $\text{Cl}^-$, $\text{SO}_4^{2-}$ and $\text{OH}^-$ in the interlayer regions and $x$ is the ratio of $\text{M(II)}/[\text{M(II)} + \text{M(III)}]$ which generally lies in the range of 0.2-0.33 [184]. Among the varied possibility of anions in hydrotalcite structure, $\text{CO}_3^{2-}$ is the most common among naturally occurring hydrotalcites. What makes these materials most fascinating in the field of catalysis are due to the typical acid-base properties and possibility of synthesizing a large number of this family in the laboratory by varying the aforementioned compositions. Besides, physicochemical properties of these materials can be easily tuned by varying the synthesis procedures as well as their thermal treatment. Hydrotalcites possess different properties in three different forms namely as synthesized form, activated form and rehydrated form due to which they are found as important materials for various purposes such as catalysts, catalysts supports, pharmaceuticals, ion-exchange materials, absorbers etc. The as synthesized hydrotalcite generally possesses low surface area and low base strengths due to the presence of water and charge compensating anions in the interlayer galleries. Therefore, they are generally activated to create strong basic sites and larger surface area. However, due to the presence of interlayer anions, they can act as catalysts for anion exchange reactions. In the halide ion exchange reactions between alkyl chloride and $\text{Br}^-$ or $\text{I}^-$ ions, use of hydrotalcites possessing $\text{Cl}^-$, $\text{Br}^-$ or $\text{I}^-$ ions in the interlayers act as catalysts for this reaction [185]. As synthesized hydrotalcites are also used as flame retardant and adsorbent for waste water in the industries [186]. The activated form of hydrotalcites are obtained upon thermal treatment of the as synthesized form in temperature ranges 450-500 °C, when the hydrotalcite phase converts to the most widely used mixed oxide phase. The mixed oxide form possesses the most important properties as catalytic materials i.e. high surface area, strong basic properties as well as memory effect [187]. Mixed oxides are used in catalytic applications such as aldol condensation, polymerization, epoxidation, hydrocarbon stream reforming, transesterification etc. [188,189]. When calcined hydrotalcites are rehydrated directly in water or in presence of water vapor, rehydrated forms of hydrotalcite occurs and the OH$^-$ ions occupy in the interlayer galleries [190]. This property of hydrotalcites is called the memory effect [191]. It has been reported that reconstructed hydrotalcites having OH$^-$ ions are stronger bases than
the as synthesized hydrotalcite possessing CO$_3^{2-}$ ions [192]. These \(-\text{OH}^-\) ions on the surface are claimed to be responsible for excellent catalytic activities of a number of base catalyzed reactions such as Knoevenagel condensation, Michael addition, nitroaldol reaction etc [193,194].

![Schematic diagram of Hydrotalcite and reconstructed hydrotalcite](image)

Figure 1.6: Schematic diagram of Hydrotalcite and reconstructed hydrotalcite

Thus, LDHs in *activated form*, *rehydrated form* and *as synthesized form* are excellent materials for large number of applications in the areas such as catalysis, photochemistry, pharmaceuticals, adsorption, electrochemistry etc. (Figure 1.6) [195]. Over the past years, considerable attentions are given to occlusion of guest species inside layered structure to enhance basic properties. Interestingly, use of MgAl mixed oxides as host materials to generate strong basicities by loading of solid guest species such as alkali or alkaline earth metals are proving to be beneficial for base catalyzed reactions. Among various guest species, potassium salts are the most common [196]. However, selection of the metal salt to suit the host material, effect of guest over the structure and generation of basicity are not well studied for hydrotalcite like compounds. Besides, conditions for a suitable catalyst in terms of its base strength, catalytic activity, stability of the host material,
recovery etc. are not easily met. Therefore, synthesis of hydrotalcites and their modification by impregnating metal salts would be interesting in the field of base catalysis. Herein, we aim to synthesize MgAl hydrotalcite and to modify them with different potassium salts for knoevenagel condensation reaction.

1.7 Knoevenagel condensation reaction

Knoevenagel condensation reaction occupies a cardinal position in the domain of organic chemistry [198]. It is a versatile C–C bond forming reaction between a carbonyl compound and an active hydrogen compound in presence of a base catalyst to furnish \(\alpha,\beta\)-unsaturated carbonyl compounds [199] (Scheme 1.4).

\[
\begin{align*}
R_1 & \quad \text{Aldehyde or ketone} \\
R_2 & \quad \text{Active methylene compound} \\
X & \quad \text{Base}
\end{align*}
\]

\[
\begin{align*}
R_1 & = \text{Alkyl group}, \quad R_2 = H, \text{Alkyl or Aryl group}, \quad X, Y = \text{electron withdrawing groups (e.g. CHO, CN, COOEt etc.)}
\end{align*}
\]

**Scheme 1.4:** Knoevenagel condensation reaction of carbonyl compound and active methylene compound in presence of base catalyst

It was a German chemist named Heinrich Emil Albert Knoevenagel who established the Knoevenagel condensation reaction in 1896 and first reported the condensation of benzaldehyde with ethyl acetoacetate at room temperature in presence of piperidine [200]. Doebner modified the reaction by taking acrolein and malonic acid in presence of pyridine base to get trans-2,4-pentadienoic acid and subsequent release of CO\(_2\) [201]. Following these reports, Knoevenagel reactions have been practicing with varying catalysts and reaction media [202]. The beauty of this reaction lies in the possibility of formation of various chemically and biologically important intermediates such as alpha-cyanocinnamates and \(\alpha,\beta\)-unsaturated esters which are useful for synthesis of drugs like...
niphendipine and nitrendipine, α,β-unsaturated nitriles useful for anionic polymerizations, cinnamic acid etc [203].

The mechanism of the reaction involves deprotonation of the active hydrogen compound by the base to form a nucleophile in the initial step followed by nucleophilic attack at the carbonyl carbon atom of the carbonyl compound to form an aldol type intermediate in the second step (Scheme 1.5). The aldol type intermediate eliminates water to form the corresponding α,β-unsaturated carbonyl compound.

Traditional catalysts for this reaction are mainly alkali metal hydroxides (NaOH, KOH), piperidine and pyridine. Demand of green chemistry has led to the development of varieties of solid base catalysts and different strategies for this reaction [204]. McCluskey et al. in 2002 reported that solvent free synthesis is the superior to traditional water reflux and ethanol reflux methods in presence of piperidine catalyst [205]. Use of solid bases with solventless synthesis is interesting in the field of green chemistry. Gawande et al. prepared MgO/ZrO$_2$ composite and performed solvent free Knoevenagel condensation and reported high yield of product [206]. It has been reported that basic zeolites such as GeX, Cs-exchanged NaX and Cs and Ln impregnated mesoporous MCM-41 can effectively catalyze this reaction under mild condition [207-210]. However, more basic
sites in comparison to ion exchanged method were generated in zeolites upon nitridation of zeolites with ammonia and after activation, where –OH groups of zeolites were replaced by amino groups [211]. Zhang et al. grafted amino group onto NaX and CsNaX zeolite and found them as excellent catalysts for Knoevenagel condensation reaction under solventless condition [212]. Bigi and co-workers showed water mediated synthesis [213] of this reaction without any catalyst. In another report, Wang et al. found that use of water as solvent can catalyze the reaction of ketones and malononitrile [214]. Banothu et al. shows that use of solid base SeO$_2$/ZrO$_2$ catalysts under water medium and solventless condition gives better result for Knoevenagel condensation than commonly used polar solvents DMF, EtOH and acetonitrile where the high catalytic activity of selenium promoted ZrO$_2$ is believed to be due to the lattice defect created by promoter selenium and considerable redox properties [215]. Other solid bases like ZnO, MgO, alumina, potassium carbonates, zeolites and modified zeolites, natural phosphates etc. are reported as potential catalysts for this reaction [216]. These are considered as more benign in comparison to traditionally used alkaline hydroxides [217]. Kantam et al. reported a modified method for the activation of MgAl-hydrotalcite and quantitative formation of Knoevenagel condensation product in liquid phase at a faster rate with these catalysts [218]. In another report [219], Ebitani et al. have also showed that reconstructed hydrotalcite is more active than untreated hydrotalcite and provide a unique acid-base bifunctional surface capable of promoting the Knoevenagel and Michael reactions. They have also found that reconstructed hydrotalcite gives almost three times more yield than untreated hydrotalcites for aldol and Knoevenagel condensation reaction. Besides, other catalysts such as modified Mg-Al hydrotalcite with tert-butoxide anion, layered double hydroxide fluoride, hydrotalcite in ionic liquid medium etc. are also reported to be efficient catalyst for this reaction [220].

1.8 MgO catalysts for Claisen-Schmidt condensation reaction

Among various solid base catalysts practiced in the recent years, nano crystalline metal oxides such as MgO, CoO, CuO, ZnO, TiO$_2$ etc. have got considerable interests due to their structural variances that allow them to exhibit outstanding properties of chemical,
physical or material research interests like acid-base, radox, metallic, semiconductors and insulator properties. In particular, nanostructured MgO have extensively been studied as promising catalysts, catalysts supports and promoters in the field of heterogeneous catalysis due to its unique chemical and physical properties. Magnesium oxide or magnesia (MgO) is a hygroscopic white solid mineral occur naturally as periclase. The formula of MgO consists of lattice of Mg$^{2+}$ and O$^{2-}$ ions held together by ionic bonds. It reacts with water according to the reaction MgO + H$_2$O = Mg(OH)$_2$, which can be reversed to get MgO through thermal treatment. Some of the fascinating properties of MgO include its high thermal stability, high melting point (2850 °C) and high boiling point (3600 °C). MgO is generally obtained by calciation of magnesium hydroxide [Mg(OH)$_2$], magnesium carbonate [MgCO$_3$] or reaction of magnesium chloride with lime followed by heating. The basic properties of MgO are due to the presence of O$^{2-}$ ions on the surface. Coluccia et al showed a surface model of decarbonated and dehydrated MgO where Mg$^{2+}$-O$^{2-}$ ion pairs present in different co-ordination environment. They have shown that Mg$^{2+}$-O$^{2-}$ ion pairs with co-ordination number three is the most active, less stable and requires high pretreatment temperature for their appearance [221]. Thus, activation temperature is crucial for tuning basic properties of MgO [222]. The superior catalytic performances of these materials are mainly governed by their physicochemical properties like morphologies, particles size, shapes, crystallinities as well as their surface area and basic properties. MgO having the aforementioned properties can be achieved through alteration of synthetic strategies.

1.8.1 Synthesis procedures of MgO

In the recent years, MgO having large variations of morphologies have been successfully synthesized via different synthetic routes such as solution phase hydrothermal and solvothermal methods, chemical precipitation, chemical vapour deposition, combustion, thermal evaporation and solid stabilized emulsion method [223-226]. However, most of the above methods require sophisticated equipments and are not cost effective. Moreover, MgO materials prepared through these methods exhibits relatively large crystallite sizes, low surface area, inhomogeneous morphologies, and low surface to volume ratio which make them disadvantageous in the field of catalysis. It has
been reported that sol-gel method of synthesis can give MgO having improved surface area, high surface to volume ratio, narrow particle size distributions and smaller crystallite sizes. However, requirement of environmentally hazardous and costly metal-organic precursors make this process inconvenient in view of green chemistry.

(a) Hydrothermal Synthesis

Solution based synthesis, particularly hydrothermal and solvothermal routes are the most conventionally used route for this purpose and thus provide an important technique to synthesize MgO with controlled size and shape [227,228]. The hydrothermal synthesis can be understood from the name itself as “hydro” means water and “thermal” means heat. Hydrothermal synthesis involves various techniques of crystallization in which crystals are allowed to grow from high temperature aqueous solutions of the metal salts at high vapour pressure. The term hydrothermal was first used by British geologist Roderick Murchinson to describe the formation of rocks and minerals due to the action of water with earth’s crust at elevated temperature and pressure [229]. According to Morey and Niggli, hydrothermal synthesis is defined as the process in which “components are subjected to the action of water at temperatures generally near though often considerably above the critical temperature of water, and therefore, under the corresponding high pressure developed by such solutions” [230]. Different scientists have presented the definition in different ways where the basic definition of all of them describes the action of water at high temperature or at ambient temperatures [231-234]. A variety of precursors like Mg(NO$_3$)$_2$, MgCO$_3$, MgCl$_2$, Mg(OH)$_2$ etc. have been synthesized via hydrothermal method to synthesize MgO powder. General method of hydrothermal preparation of MgO involves homogeneous mixing of Mg salt solution of water with a basic solution of water under normal temperature and stirring condition, transferring the homogeneous mixture to a special stainless steel apparatus called autoclave and allowing crystal growth at the required temperature. In the method, a temperature gradient is maintained at the opposite ends of the growth chamber where the high temperature end favours dissolving the salts and the low temperature end favours crystal growth [235]. The growth of crystals and their physicochemical properties are dependent on the temperature, amount of salts in the
mixture, concentration of base, time of hydrothermal treatment, precursor types as well as treatment of the precursors after synthesis.

**(b) Solvothermal Synthesis**

Solvothermal route is again an important method of synthesize MgO nanoparticles [236, 237]. In this method, similar to the hydrothermal route, nutrients are supplied along with different solvents into the growth chamber and crystals are allowed to grow at particular temperature. Numerous structures such as cubes, ellipsoids, spheroids, pyramids and bipyramids are synthesized via this route. Control over growth and agglomeration has been achieved through addition of suitable capping agents like long chain amine or thiols in the mixture [238]. Various MgO morphologies have been successfully synthesized through this route by solvent mediated, surfactant mediated or pH dependent growth of crystals [239,240].

**(c) Synthesis of MgO from precursors**

Magnesium oxide is generally synthesized by thermal decomposition of magnesium carbonate or magnesium hydroxides [241,242]. Among various basic precursors, magnesium carbonate hydrates (MCH) is interesting for its fascinating morphologies. It has been found that nesquehonite phase i.e. Mg(HCO₃)OH.2H₂O crystallizes as needle and rods [243-245], hydromagnesite phase i.e. 4MgCO₃·Mg(OH)₂·4H₂O crystallizes as sheet [246] and MgCO₃ forms rhombohedral crystals [247]. Recently, Sutradhar et al. have synthesized different MCH morphologies from clear solutions of Mg(NO₃)₂(NH₄)₂CO₃ and nesquehonite rods via hydrothermal, solvothermal and supercritical hydrothermal approaches [248]. They have found that CO₃²⁻ ion concentration have crucial role over the formation of different morphologies such as cards, random nanoflakes, arranged nanoflakes, flowers and spherical under hydrothermal method. The obtained morphologies have quite different basic properties and surface areas and high catalytic activity for Claisen-Schmidt condensation reaction. In another report, Ding et al. have shown the formation of rod, tube, needle and lamella like morphologies of Mg(OH)₂ through hydrothermal route from different Mg sources namely Mg powder, MgSO₄, and Mg(NO₃)₂·6H₂O [249]. A good number of reports on
synthesis of MgO are found in the literature to obtain varied shapes and sizes through this method.

It is found that Mg(OH)$_2$ is also an equally important starting material like the carbonate precursors for synthesis of MgO with controlled sizes and shapes [253]. Synthesis of Mg(OH)$_2$ are generally prepared by different methods to get various shapes and sizes which after thermal treatment gives MgO structures with the retained shapes. Jeevanandam et al. have converted magnesium oxychloride nanorods i.e. (Mg$_x$(OH)$_y$Cl$_z$.nH$_2$O) to Mg(OH)$_2$ nanorods which were previously synthesized from MgCl$_2$.6H$_2$O and MgO powder with NaOH solution of EtOH-H$_2$O or H$_2$O [250]. Li et al. also synthesized Mg(OH)$_2$ nanorods from Mg powder and distilled water or ethylenediamine solvents under pressure in autoclave at 180 °C [251]. Similarly, Zhuo et al. synthesized Mg(OH)$_2$ nanotubes in an autoclave taking 1:1 ratio of water: methanol (v/v) from MgCl$_2$ salt. They dissolved MgCl$_2$ in distilled water and added ammonia water to precipitate and transferred the mixture to autoclave containing water methanol to get the corresponding Mg(OH)$_2$ [252]. Makhluf et al. reported the use of ethylene glycol as solvent to synthesize nanocrystalline MgO under microwave irradiation and calcination in air at 600 °C [253]. In another report, Aslani et al. synthesised ZnO-MgO mixed oxide nanoparticles with ethanol water solvent under solvothermal route in an autoclave [254].

Thus, research on synthesis of MgO is centered on synthesis of its precursor salts via various synthetic strategies which in turn gives varieties of MgO shapes and sizes after thermal treatment.

1.9 Claisen-Schmidt condensation reaction

It is found that MgO exhibits excellent catalytic activities for a good number of base-catalyzed organic reactions such as Claisen-Schmidt condensation reaction [255], Nitroaldol reaction [256], Tishchenko reaction [257] and Aldol condensation reaction [258]. Claisen-Schmidt condensation reaction or cross-aldol condensation is an important C-C bond forming reaction in the domain of organic chemistry [259]. Aldol condensation is an acid or base catalyzed reaction between two molecules of carbonyl compounds, either identical or different and at least one of them containing $\alpha$-H atom to give $\beta$-
hydroxy carbonyl compound (a dimer called aldol) or an \(\alpha, \beta\)-unsaturated carbonyl compound (Scheme 1.6). The cross-aldol condensation reaction of an aromatic aldehyde with another carbonyl compound containing an \(\alpha\)-H atoms to give \(\alpha, \beta\)-unsaturated carbonyl compound is called as Claisen-Schmidt reaction.

Mechanism of this reaction involves abstraction of a proton by the base from the \(\alpha\)-C atom of the carbonyl molecule (A) to form a resonance stabilized carbanion (I) in the first step followed by addition of the carbanion to the second carbonyl molecule (B) to form an oxide ion in the second step (II) (Scheme 1.7). The oxide ion takes a proton from water to form \(\beta\)-hydroxy carbonyl compound (III) which dehydrate to give \(\alpha, \beta\)-unsaturated carbonyl compound (IV).

![Scheme 1.6: General scheme of Aldol Condensation and cross-aldol reaction](image)

![Scheme 1.7: Mechanism of Claisen-Schmidt condensation reaction](image)
Base catalyzed Claisen condensation is usually carried out in aqueous solutions of NaOH and KOH. It has been found that MgO catalyst under proper reaction conditions can effectively catalyse Claisen-Schmidt condensation reaction. Sutradhar et al. have shown that MgO catalyst calcined at 500 °C and sizes having 6-7 nm with different morphologies catalyzes the reaction between acetophenone and benzaldehyde to give high conversion (85 % - 99 %) and selectivity (100 %) within 2 hours. On the other hand bulk MgO shows low conversion (13 %) under similar condition. Selvamani et al. found that calcination of rectangular hydromagnesite microsheet at 450 °C showed strong catalytic activity for solvent free Claisen-Schmidt condensation of benzaldehyde and acetophenone with 99 % conversion within 4h [260]. The catalytic activity of regular microsheets were found higher than commercial MgO catalyst and the reaction was favoured by their small crystallite sizes due to the presence of large number of lewis basic sites (O\(^2-\)) on the surface.

Thus, synthesis of size and shape controlled MgO through hydrothermal and solvothermal routes and their post synthesis modification would be quite interesting for improving the Claisen-Schmidt condensation reaction under different reaction conditions.

1.10 Objective of the present study

Having been gone through the literature reviews as described above, we have set the following objectives for the research work:

(i) To prepare solid base zeolite catalysts by post synthesis modification of NaY and KL zeolites. i.e. by impregnating alkali or alkaline earth metal salts into zeolite structure.

(ii) To prepare and modify solid base catalysts like metal oxides and mixed metal hydroxides by hydrothermal and solvothermal methods and to modify them via routes (a) impregnation of metal salts and (b) thermal treatment to observe their structural changes and change in basicity.
(iii) To characterize the obtained basic materials by using techniques like FTIR, XRD, SEM, TEM, DSC, TGA, $N_2$-adsorption desorption method etc.

(iv) To check the catalytic activity and selectivity of these materials in base catalyzed organic reactions i.e. knoevenagel condensation, Henry reaction and Claisen-Schmidt condensation reaction.
1.11 References


[Chapter 1] Introduction

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