# CHAPTER I

# INTRODUCTION

There are many chemical reactions that are favorable thermodynamically, yet occurring at extremely slow rates at room temperature. The presence of a catalyst dramatically increases the rate of the reactions, even those that may not have negative free energies of reaction. Those researches consider the role of transition metal complexes as catalyst for several transformations, many of which are industrially important.

The phenomenon of catalysis was recognized over 150 years ago by Berzelius who referred to the "catalytic power of substances" that were able to "awake affinities that are asleep at this temperature by their mere presence and not by their own affinity." Once the principles of thermodynamics were developed and the concept of equilibrium established by the turn of the twentieth century, scientists realized that catalysts are species that change the rate of the reaction without affecting the equilibrium distribution of reactants and products. Exactly how catalysts are able to speed up reactions without changing the free energy of either reactants or products remained a mystery for many years. Only in the last few decades has it been possible to elucidate mechanistic pathways.

Involving catalysts by using such tool as kinetics, stereochemical studies, and spectroscopy, it is now clear that catalysts interact with the reactants to provide a reaction pathway with a significantly lower free energy of activation than the corresponding uncatalyzed pathway. Figure 1.1 depicts the phenomenon with the solid line representing the uncatalyzed reaction and the dashed line the catalyzed reaction path.
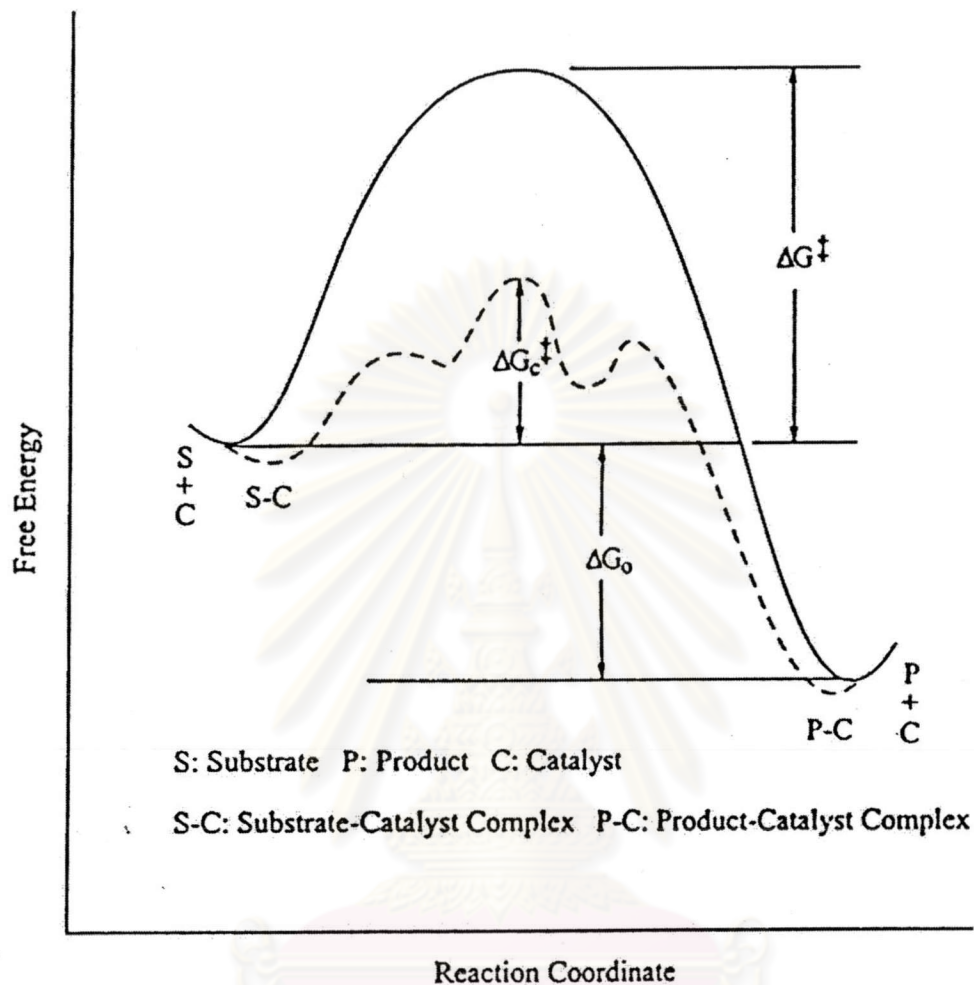
**Figure 1.1** Reaction coordinates for catalyzed and uncatalyzed chemical reactions.

Typically, catalysts are intimately involved with reactants (often called substrate) in a cyclic series of associative (binding), bond making and/or breaking, and dissociative steps. During each cycle, the catalyst is regenerated so that it may go through another cycle. Each cycle is called a turnover, and an effective catalyst may undergo hundreds, even thousands of turnovers before decomposing-each cycle producing a molecule of product. In a stoichiometric reaction, on the other hand, the "catalyst" (actually reagent) undergoes only one turnover per molecule of product produced.

## 1.1 Homogeneous *VS* heterogeneous catalysts.

A heterogeneous catalyst exists as a another phase in the reaction medium, typically as a solid in the presence of a liquid or gaseous solution of reactants. It was found in alkene hydrogenation reaction as the presence of a catalytic amount of Pd or Pt deposited on an inert solid. On the other hand, a homogeneous catalyst is dissolved in the reaction medium along with the reactants. The esterification catalyzed by conc. $H_2SO_4$ or HCl is among well known examples. Transition metal complexes as homogeneous catalyst have been found to increase importance in the petrochemical industry. Table 1.1 describes major differences between these two catalysis systems.

Table 1.1 Major differences between homogeneous and heterogeneous catalysts.

| Characteristic | Homogeneous | Heterogeneous |
|---|---|---|
| 1. Catalyst composition and nature of active site. | Discrete molecules with well-defined active site | Nondiscrete molecular entities: active site not well-defined |
| 2. Determination of reaction mechanism | Relatively straightforward using standard techniques. | Very difficult. |
| 3. Catalyst properties | Easily modified, often highly selective, poor thermal stability, mild reaction conditions. | Difficult to modify, relatively unselective, thermally robust, vigorous reaction conditions |
| 4. Ease of separation from product | Often difficult | Relatively easy |

### 1.1.1 Catalyst composition and nature of the active site.

The active sites on a heterogeneous catalyst are difficult to characterize because they are not discrete molecular entities. Instead, the active sites may be aggregations of solid support material (*e.g.,* silica gel or zeolites) coated with deposited metal atoms. Not all sites on the surface of catalyst have the same activity and physical or chemical characteristics. Analytical techniques (*e.g.,* Auger and ESCA spectroscopy) as well as scanning tunneling spectroscopy have been applied recently in attempts to

determine the nature of catalytic surface. Homogeneous catalyst, on the other hand, are discrete molecules that are relatively easy to characterize by standard spectroscopic techniques, such as NMR, IR, *etc.* The active site consists of the metal center and adjoining ligands.

### 1.1.2 Determination of the reaction mechanism.

Because the constitution of the active site of a heterogeneous catalyst is difficult to determine, the elucidation of reaction mechanisms involving these catalysts can be troublesome indeed. The field of homogeneous catalysis, in contrast, has advanced rapidly over the last few decades because chemists have developed many techniques useful for studying reaction mechanisms. Elucidating the mechanism of a homogeneously catalyzed reaction means studying the mechanism of each individual step in a series of relatively elementary chemical reactions by conventional methods. Each step must be shown to be kinetically and thermodynamically reasonable. While this can be a daunting task for a reaction involving several catalytic steps, it is not, at present, as difficult as determining exactly what goes on during a heterogeneous catalysis.

### 1.1.3 Catalyst : Ease of modification, selectivity, thermal stability, and reaction conditions.

Because homogeneous catalysts are typically organotransition metal complexes, it is relatively easy to modify these compounds in order to increase selectivity. As seen, phosphines appear commonly as ligands in homogeneous catalysts. Phosphines, of course, offer a wide variety of stereoelectronic properties that can substantially influence the course of a catalyzed reaction.

Homogeneous catalysts are often much less thermal stable than their heterogeneous counterparts. The use of a homogeneous catalyst rather than a heterogeneous one requires milder condition of temperature and pressure. If a sufficiently active homogeneous catalyst can be found that can do the job of a heterogeneous one, substantial savings in energy and initial capital cost accrue to the manufacturer that chooses to employ a homogeneously catalyzed process.
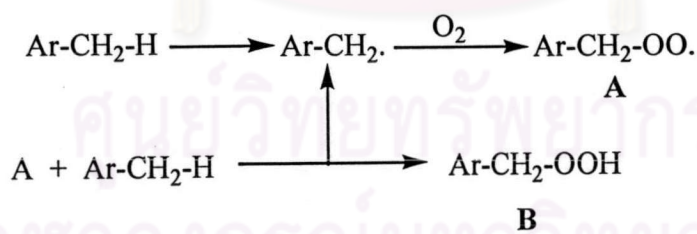
### 1.1.4 Ease of separation from reaction products.

Homogeneous catalysts suffer from one key disadvantage when compared to their heterogenous counterparts. They are often quite difficult to separate from reaction products.[3-4] Catalyst recovery is cleary important, not only in ensuring product purity but also in conserving often-used precious metals such as palladium and rhodium.[1-2]

## 1.2 The chemistry of chromium(III)

Chromium (III) complexes with a few exceptions are all hexacoordinate.[5] The principal characteristic of these complexes in aqueous solutions is their relative kinetic inertness.[6] The advantage of $Cr^{II}$ complexes is shorter time of ligand displacement reaction compared with $Cr^{III}$ because of this kinetic inertness that complex species can be isolated as solids and persist for relatively long periods of time in solution, even under conditions of marked thermodynamic instability.[7-8]

## 1.3 Oxidation of substituted aromatics

Autoxidation of alkylsubstituted aromatics possessing benzylic hydrogen affords benzylic hydroperoxides as the primary product formed with high selectivity according to a free-radical mechanism.

$$Ar\text{-}CH_2\text{-}H \longrightarrow Ar\text{-}CH_2\cdot \xrightarrow{O_2} Ar\text{-}CH_2\text{-}OO\cdot \quad \mathbf{A}$$

$$A + Ar\text{-}CH_2\text{-}H \longrightarrow Ar\text{-}CH_2\text{-}OOH \quad \mathbf{B}$$

The ready formation of benzylic hydroperoxides is used in industrial oxidations, as the synthesis of propylene oxide and phenol. Chain termination of A may lead to an alcohol and aldehyde, and the rapid autoxidation of the latter may produce the corresponding carboxylic acid. In the non - catalyzed autoxidation the further oxidation of the aldehyde is much faster than the hydrogen abstraction to form the benzylic radical. As a result, carboxylic acids become the main product.

$$2\ Ar\text{-}CH_2\text{-}OO. \longrightarrow Ar\text{-}CH_2\text{-}OH + Ar\text{-}CHO + O_2$$
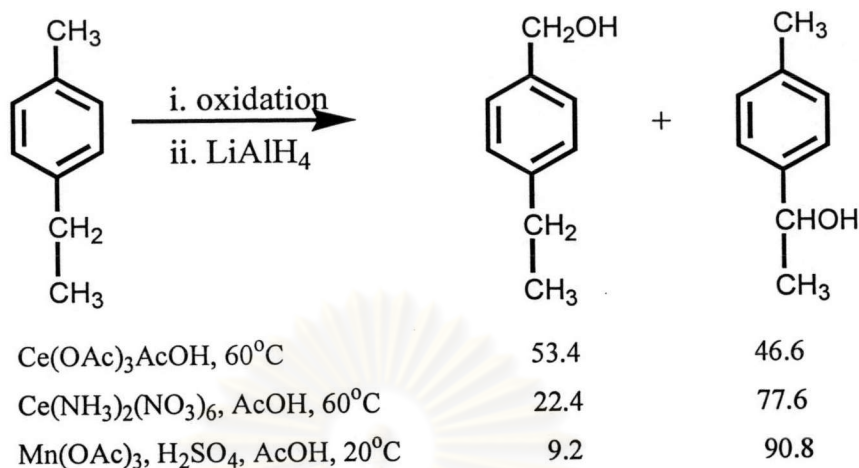
$$Ar\text{-}CHO + O_2 \longrightarrow Ar\text{-}COOH$$

Metal ions, Co(III), Mn(III), and Cu(II) have a pronounced effect on the rate and product distribution of autoxidation. In the presence of metal ions, secondary transformations become dominant and selectivity in the formation of benzylic hydroperoxide decreases.

Co(III) and Mn(III) acetates are mainly focused on the selectivity of the transformation of methylbenzenes to aldehydes. While metal ion catalysis usually favors the formation of carboxylic acids, aldehyde oxidation becomes the rate determining step in the presence of high concentration of Co(III) ions, resulting in the selective oxidation of methylbenzenes to aldehydes. The main role of the metal is the decomposition of hydroperoxide, but it also catalyzes hydrogen abstraction.

The order of reactivity of alkyl-substituted benzenes is toluene > ethylbenzene > isopropylbenzene, which is opposite to the general reactivity expected from the C-H bond energies. This was explained in terms of an initiating electron transfer equilibrium between Co(OAc)$_3$ and the arene being the rate-determining step.

Studies of the internal selectivities of the oxidation of methyl and ethyl groups in the same molecule led to a similar conclusion, suggesting that selectivities depend on the nature of the metal ion.[9]

|  | | |
| --- | --- | --- |
| Ce(OAc)$_3$AcOH, 60$^o$C | 53.4 | 46.6 |
| Ce(NH$_3$)$_2$(NO$_3$)$_6$, AcOH, 60$^o$C | 22.4 | 77.6 |
| Mn(OAc)$_3$, H$_2$SO$_4$, AcOH, 20$^o$C | 9.2 | 90.8 |

Strong acids enhance oxidation, and extensive transformation can be achieved at room temperature. In the absence of oxygen side-chain acetoxylation and hydroxylation take place.

Stoichiometric oxidations may also lead to aldehydes from methyl-substituted arenes. Chromyl chloride applied in the classic Etard reaction forms a 2:1 insoluble adduct with the possible structure.
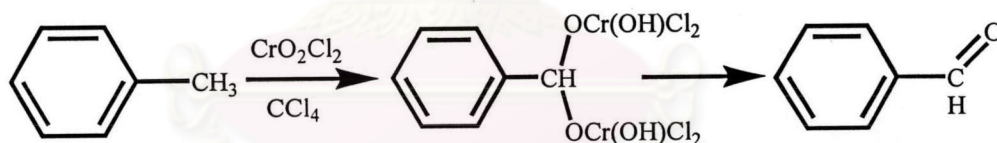


CrO$_3$ in AcOH produces benzylidene diacetates that can then be hydrolyzed to the corresponding aldehydes. Cr(V) and Cr(IV) species were shown to be involved in the reaction. Silver(II) in acidic solution, Ce(NH$_3$)$_2$(NO$_3$)$_6$, and photooxidation in the presence of TiO$_2$ and Ag$_2$SO$_4$ are also used to accomplish aldehyde formation.

Methyl-substituted aromatics may also be converted to the corresponding carboxylic acids. A shift in the selectivity of the autoxidation of methyl-substituted arenes is brought about by metal ions eventually producing carboxylic acids. Carboxylic acids may also be formed by the base-catalyzed autoxidation of methyl-substituted arenes. Oxidation with tert-butylhydroperoxide (TBHP) in HMPA affords carboxylic acids in moderate yields with very high selectivities.

In addition, aromatic compounds with longer alkyl side chain can be converted to ketones or carboxylic acids. All the previously discussed reagents except $CrO_2Cl_2$ usually afford the selective formation of ketones from alkyl-substituted arenes. Oxidation with $CrO_2Cl_2$ usually gives a mixture of products.

The permanganate ion is a strong oxidant when used under phase-transfer conditions, it converts benzylic methane groups into alcohols, and benzylic methylene compounds to ketones. Convenient oxidations can be carried out when $KMnO_4$ is applied in $Et_3N$, an organic solvent ($CHCl_3$), and trace of water at room temperature.

The Jones reagent and TBHP catalyzed by chromium(VI) complexes were found in the oxidation of tetralin and indanes. Oxidation with 2,3-dichloro-5,6-dicyanobenzoquinone (DDQ) occurs with an exceptional mechanism. In contrast with the radical processes observed in other oxidations, DDQ generates a carbocation by hydride abstraction that is trapped by water to form an alcohol. Further oxidation of the latter furnishes the product ketone.



87 %
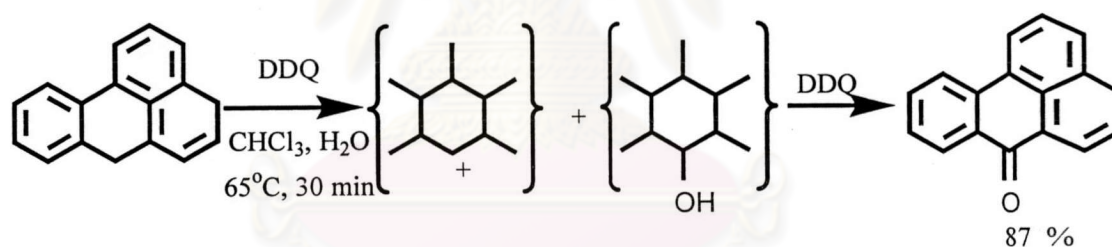
Selective formation of ketones may be achieved through base-catalyzed oxidations. Transformation of 9,10-dihydroanthracene catalyzed by benzyltrimethyl ammonium hydroxide (Triton B) starts with proton abstraction. The highest yield of anthraquinone (85% at 100% conversion) was achieved in 95% aqueous pyridine.

Aromatic carboxylic acids such as diarylmethane carboxylic acid may be formed with the oxidative cleavage of the side chain; however, it usually stops at the ketone stage. Such oxidations are usually carried out with permanganate, hexavalent chromium, or nitric acid. Since $CrO_3$ in acidic medium readily attacks the ring in polycyclic aromatics to yield quinones, only alkyl-substituted benzenes and isolated ring systems are oxidized exclusively at the benzylic position. Working under neutral conditions, as with aqueous

sodium dichromate, can allow one to avoid ring oxidation, and selective benzylic oxidation of polynuclear aromatics occur.[9]

## 1.4 Chromium-based reagents for organic transformation

In 1975, Corey and Suggs[10] found that pyridinium chlorochromate, $C_5H_5NHCrO_3Cl$, a readily available, stable reagent, oxidizes a wide variety of alcohols to carbonyl compounds with highly efficiency. Yields of aldehydes and ketones obtained were typically equal to or greater than those obtained with the Collins reagent. For example, it catalyzed the oxidation of benzhydrol to benzophenone 100%yield.

Fleet and Little[11] in 1977 showed that pyridine oxodiperoxychromium (VI), $C_5H_5N:CrO_5$ is a deep blue solid, readily soluble in organic solvents. It could catalyze the oxidation of 4-nitrobenzyl alcohol to 4-nitobenzaldehyde more than 90% yield but the limit of these catalysts was upon spontaneous explosive.

In 1978 Mizukami[12] discovered that metal-ion catalyzed oxidation of tetralin and metal-ion catalyzed decomposition of α-tetralin hydroperoxide (THP) were carried out in acetic acid in both the presence and absence of an additive. It was found that the rate-determining step in the oxidation of tetralin is the decomposition of THP. The results also suggested that the catalysis occured by first row transition metal ions, except vanadium. Co showed the highest activity and Cr showed the highest selectivity in terms of the ratio of α-tetralone to α-tetralol (On/Ol). The order of the activities of metal acetates in producing oxidation is in agreement with that of the activities of the metal acetates responsible for decomposition. Such agreement was also found for $Co(acac)_3$, $Cr(acac)_3$, $Mn(acac)_3$ and $Fe(acac)_3$ catalysts. For oxidation with $Co(OAc)_2.4H_2O$ and $Cr(OAc)_3$, the product distributions were examined for various conversions of tetralin.

In 1980 Chakraborty and Chandrasekaran[13] reported that the oxidation of primary and secondary alcohols to carbonyl compounds were usually carried out with chromium(VI) reagents. Chromium(V) is postulated as an intermediate in all the oxidations with chromium(VI). Two stable complexes of oxochromoium(V), $(phen)H_2CrOCl_5$, $(phen)CrOCl_3$ (phen = phenanthroline) were used for the oxidation of some primary and secondary alcohols. The pentavalent chromium complex was comparable to pyridinium chlorochromate in its oxidizing power and the yield of

aldehydes and ketones with the molar equivalents of the reagent is usually high. In contrast, the pentavalent chromium(V) proceeded with slower reaction rate than hexavalent chromium(VI) which gave high yield of desired product. For example, oxidation of benzyl alcohol to benzaldehyde. The desired product was 90% yield at 25°C.

In 1983, Kanemoto and coworkers[14] presented that pyridinium dichromate-Me₃SiOOSiMe₃ system has been found to be effective for the oxidation of alcohols to the corresponding carbonyl compounds. Selective oxidation of primary alcohols in the presence of secondary ones with $RuCl_2(PPh_3)_3$-Me₃SiOOSiMe₃ gave the desired product 30 – 55 % yet still high selectivity.

In 1987 Muzart[15] reported that benzylic oxidations were induced by small quantities of 2,4-dimethylpentane-2,4-diol cyclic chromate and excess of TBHP under anhydrous conditions. However, both the chromium complex and anhydrous TBHP have to be prepared and only partial conversion of the starting hydrocarbon has been obtained. Using 70% TBHP and catalytic amount of chromic anhydride, benzylic methylene groups were oxidized at room temperature to carbonyl functions in fair yields. Oxidation of alcohols to carbonyl compounds was carried out by using catalytic amounts of $CrO_3$ and excess of aqueous TBHP. This system is highly efficient in the case of secondary benzylic alcohols.[16]

In 1988 Muzart and colleagues[17] reported that using TBHP with catalytic amounts of $CrO_3$ and p-toluenesulfonic acid (TsOH), regioselective α-oxidation of alkynes to conjugated ynones was observed at room temperature with yields superior to those of stoichiometric chromium procedures. Yields were slightly decreased in the absence of TsOH.

Kitajima and coworkers[18] reported that the liquid–phase oxidation of p-methoxytoluene to p-anisaldehyde in the presence of Co based catalysts has been studied with $Co(OAc)_2$ alone in acetic acid as a solvent, only a trace amount of p-anisaldehyde could be obtained; however, upon the addition of a second metal salt (e.g., $Mn(OAc)_2$ or $Ce(OAc)_3$) a considerable improvement in the yield (up to 66%) was observed. The synergism of Co and the second component as $Co(OAc)_2$-$Ce(OAc)_3$-$Cr(OAc)_3$ (3:1:2) as well as the optimization of the reaction conditions was finally found to be the most

effective catalytic system, which gave a high yield of $p$-anisaldehyde under 3 atm $O_2$ at $110^{\circ}C$ for 3 h.

In 1992 Muzart[19] reported that the oxidation of ethylbenzene with hydrogen peroxide as oxidant could be performed in low yield of desired product with $CrO_3$ in acetonitrile at $20^{\circ}C$, 168 hours. Toluene was converted to benzaldehyde in high yield with $Cr(naph)_3$ in pyridine at $100^{\circ}C$, 1 hour.

In 1997 Ishihara and coworkers[20] found that bis(pentafluorophenyl)borinic acid is a suitable Oppenauer catalyst (OPP) for primary and secondary allylic and benzylic alcohols oxidation carried out in benzene.

In 2001, Man and colleagues[21] reported the oxidation of ethylbenzene to acetophenone using air in a batch with sulphuric acid, molecular sieves and silica gel as dehydrants provided high yield. The effect of a continuous increase in the temperature of the oxidation process, compared with isothermal operation, was shown to improve the oxidation performance.

In 2001 Shi and his groups[22] reported that benzyl chloride can be directly oxidized to the corresponding benzoic acid in an eco-safer way using 30% hydrogen peroxide with $Na_2WO_4.2H_2O$ as a catalyst and $[CH_3(n-C_8H_{17})_3N]^+HSO_4^-$ as a phase transfer agent (PTC) without any organic solvents.

In 2002 Nicolaou and his groups[23] found that $o$-iodoxybenzoic acid, a readily available hypervalent iodine(V) reagent, was highly effective reagent in carrying out oxidations to furnise $\alpha,\beta$-unsaturated carbonyl compounds. In addition, this reagent could oxidize preferentially and at benzylic and related carbon centers to form conjugated aromatic carbonyl systems.

It was obviously seen that in the mid of $19^{th}$ century, chromium complexes have been exploited as a catalyst for various organic transformation, particularly oxidation reaction. The conditions employed at that time were quite severe. Chromium reagents were normally used in a stoichiometric amount; thus chromium waste was invariably espied. Moreover, the yield of the desired product was low. The development of utilizing this class of catalyst has been carried on form stoichiometric amount required to a catalytic amount needed for the reaction. Nonetheless, the utilization of soluble

chromium carboxylate complexes as catalyst for the oxidation of organic substrates has couple with TBHP not much addressed in chemical literature. This work will focus on the systematic oxidation study of benzylic methylene compounds employing soluble chromium stearate and TBHP under mild conditions.

## 1.4  The goal of this research

The purposes of this research can be summarized as follows:

1. To synthesize soluble chromium(III) carboxylate complexes

2. To study systematic optimization conditions for the oxidation of ethylbenzene using chromium(III) stearate complex.

3. To study the scope of this developed reaction for the oxidation of benzylic methylene compounds under optimum conditions