

CHAPTER III

RESULTS AND DISCUSSION

The key industrial products of the extensive and varied chemistry of aromatic are benzene, toluene, ethylbenzene, and the *o*-, *m*-, and *p*-isomers of xylene. Aromatics are among the most widespread and important chemical raw materials; they are a significant portion of all plastic, synthetic rubber, and synthetic fiber manufacture.²⁴ This research mainly focuses on the selective oxidation of benzylic methylene compounds. Metal soluble complexes including chromium(III), manganese(II), iron(III), cobalt(II), nickel(II), and copper(II) stearate complexes were selected to screen for their catalytic capability. The advantage of this type of catalyst is its ability to be soluble in organic phase. Ethylbenzene was selected as a substrate for reaction conditions optimization. Other substrates such as tetralin, toluene, *sec*-butylbenzene, benzyl alcohol, benzaldehyde, 1,2,3,4-tetrahydroquinoline, acenaphthene, xanthene, dibenzyl ether and hexyl benzyl ether were chosen for verifying this developed oxidation system. In general, these systems are composed of metal carboxylate complex as a catalyst, 70% *tert*-butylhydroperoxide (TBHP) as an oxidant in a reaction medium. Isooctane was mostly used as a solvent. Other solvents such as *N,N*-dimethylformamide, ethanol, methanol, acetone, 1,2-dichloroethane, dichloromethane, chloroform, pyridine, tetrahydrofuran, acetonitrile and carbon tetrachloride and other oxidizing agents including 30% hydrogen peroxide (H₂O₂), 2-ethylbutyraldehyde, O₂ and Zn grit/AcOH were also employed in order to search for another alternatively appropriate oxidation system.

3.1 Syntheses and identification of metal carboxylate complexes.

Metal carboxylate catalysts such as chromium(III), manganese(II), iron(III), cobalt(II), nickel(II) and copper(II) stearate complexes were synthesized according to

previously reported protocol¹⁹ by reacting interested carboxylic acid with metal chloride under basic conditions. Furthermore, chromium(III) carboxylates; for example, chromium(III) palmitate, chromium(III) behenate, chromium(III) naphthenate and chromium(III) acetylacetonate were manipulated. Their identities were confirmed by IR technique. Generally, the absorption bands of free carboxylic acid ligands are visualized at 1700-1725 cm^{-1} respectively for C=O stretching and 1395-1440 cm^{-1} and 1210-1320 cm^{-1} for C-O stretching and OH deformation. In metal carboxylate catalyst complexes the C=O and C-O stretching vibration bands were shifted to 1735-1750 cm^{-1} and 1150-1200 cm^{-1} , respectively.²⁵

3.2 Study on the optimum conditions for selective oxidation of ethylbenzene.

3.2.1 Effect of metal stearate complexes

The search for appropriate transition metal stearate complexes for benzylic oxidation was first evaluated by using ethylbenzene as a chemical probe. The results are presented in Table 3.1 and Fig 3.1.

Table 3.1 The effect of various metal stearate complexes on the oxidation of ethylbenzene.

Entry	Metal stearate	% Yield of product		Selectivity (On/Ol) ratio
		acetophenone	1-phenylethanol	
1	Chromium(III)	94.82	Trace	ND
2	Manganese(II)	37.76	3.46	11
3	Iron(III)	31.42	25.13	1
4	Cobalt(II)	19.35	2.91	7
5	Nickel(II)	30.23	9.30	3
6	Copper(II)	31.64	2.66	12

Reaction conditions: ethylbenzene (5 mmol), catalyst (0.20 mmol), isooctane (5 mL), TBHP (9 mmol) at 70°C for 24 h.

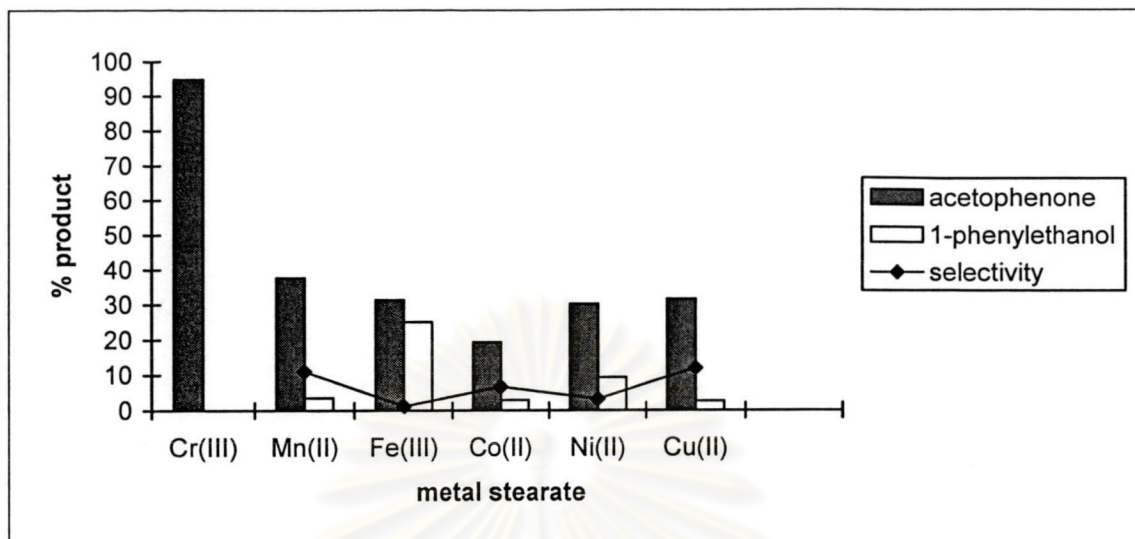


Fig 3.1 The effect of metal stearate catalyst on the oxidation of ethylbenzene.

It could clearly be seen that the oxidation of ethylbenzene could take place smoothly using various metal stearate complexes; however, with different extent. Chromium(III) stearate complex could provide the best results among six metal stearate tried for the oxidation of ethylbenzene in terms of acetophenone as the desired product and the selectivity point of view. In addition, switching from chromium(III) stearate to manganese(II), iron(III), cobalt(II), nickel(II) and copper(II) stearate complexes in benzylic oxidation reaction, the amount of the desired products were decreased.

To illustrate this observation, the oxidation of ethylbenzene with chromium(III) stearate catalyst provided acetophenone in high yield with excellent selectivity (On/Ol ratio) (entry 1). When the oxidation was performed with 0.20 mmol of manganese(II) and copper(II) stearates, the yield of acetophenone decreased (entries 2, 6). The use of iron(III) stearate could also convert ethylbenzene to the corresponding ketone and alcohol in moderate yield (entry 3). Among six metal stearate complexes tested, Co(II) stearate complex provided the least amount of the corresponding carbonyl compound (entry 4). It is worth noting at this point that the utilization of iron(III) stearate, unlike other metal stearate catalysts yielded 1-phenylethanol in a comparable amount to that of acetophenone. This observation strongly supported the concept of metal-dependence in the oxidation reaction.^{6,26} The role of metal stearate complexes in catalyzing the oxidation reaction was believed to involve two aspects.²⁷ The first involved the

acceleration step for the production of alkyl hydroperoxide intermediate *via* free radical process. The second important role concerned with the decomposition of the active intermediate to the oxidized product. However, some limitations for the substrate to be oxidized still exist. Because of the instability of the intermediate produced, the yield of desired product was decreased. Product yield was decreased because the catalyst deactivation may occur by the formation of metallic polymer or formation of stable complexes between metal salts and some electron donors such as unsaturated carbon-carbon bonds in the case of propargylic alcohol oxidation with Pd catalyst.²⁸

Related researches concerning the transformation of ethylbenzene to acetophenone were cited in literature. The use of Pd(OAc)₂ in DMSO with molecular oxygen and 2 equiv of NaHCO₃ was claimed to give the high yield of acetophenone.²⁹ Another efficient system comprising Co(OAc)₂-Ce(OAc)₃-Cr(OAc)₃ as a catalytic system was presented to oxidize ethylbenzene to acetophenone in good yield (76% yield) under 3 atm O₂ at 110°C for 3 h.¹⁸

From these present experiments, ethylbenzene could be converted to acetophenone in high yield (95%, entry 1) and free from by products. These preliminarily attractive results prompted for further investigation of this oxidation reaction.

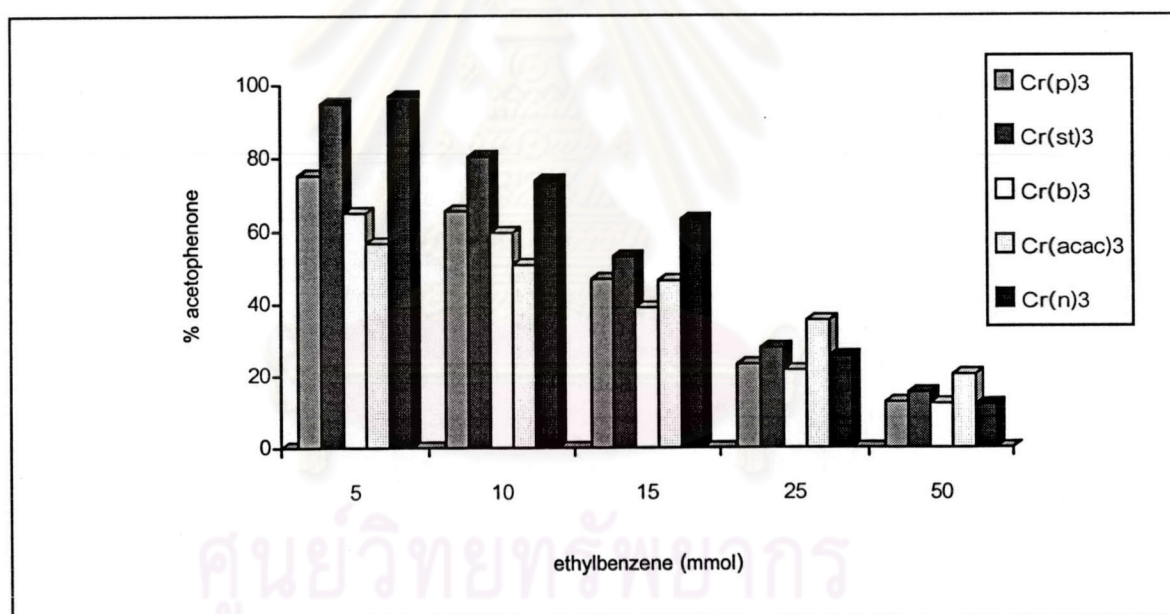
3.2.2 Effect of carboxylate ligands

With the aim to seek for appropriate metal carboxylate catalysts which could catalyze ethylbenzene to acetophenone, various carboxylate ligands in the class of alkyl, aryl and 1,3-dicarbonyl compounds were investigated. The results of the utilization of various carboxylate ligands of chromium(III) catalysts are summarized in Table 3.2 and Fig 3.2.

Table 3.2 The effect of chromium(III) carboxylate catalysts on ethylbenzene oxidation.

Entry	Ethyl Benzene (mmol)	% yield of product									
		Cr(p) ₃		Cr(st) ₃		Cr(b) ₃		Cr(acac) ₃		Cr(n) ₃	
		Aceto phenone	1-phenyl ethanol	Aceto phenone	1-phenyl ethanol	Aceto phenone	1-phenyl ethanol	Aceto phenone	1-phenyl ethanol	Aceto phenone	1-phenyl ethanol
1	5	75.23	Trace	94.82	Trace	65.02	Trace	56.72	Trace	96.88	Trace
2	10	65.55	Trace	80.36	Trace	59.62	Trace	50.85	0.45	73.91	1.25
3	15	46.93	Trace	53.11	0.79	38.97	Trace	46.49	0.46	63.26	0.88
4	25	23.28	0.44	27.89	0.88	21.55	Trace	35.47	0.59	25.55	1.68
5	50	12.64	1.10	15.35	0.75	12.22	2.32	20.36	0.62	11.94	1.60

Reaction conditions: ethylbenzene (5-50 mmol), chromium(III) carboxylate (0.2 mmol), isoctane (5 mL), TBHP (9.0 mmol) at 70°C for 24 h.

**Fig 3.2** The effect of chromium(III) complexes on ethylbenzene oxidation.

The oxidation of ethylbenzene catalyzed by various chromium(III) carboxylate complexes was examined (Table 3.2). The high yield and high selectivity obtained from Cr(st)₃, Cr(p)₃, and Cr(n)₃ were observed (entries 1 – 2). When the oxidation being performed by Cr(acac)₃ and Cr(b)₃, the yield of the desired product decreased and the selectivity of the reaction was low. It could be observed that the oxidation was dependent

on counter anion (ligand) of catalysts. Cited in the literature for the oxidation of ethylbenzene has been carried out with $\text{Cr}(\text{acac})_3$ or metal acetylacetonate such as $\text{Co}(\text{acac})_2$, $\text{Mn}(\text{acac})_2$ and $\text{Fe}(\text{acac})_3$ with molecular oxygen. These reported reactions could convert ethylbenzene to acetophenone unfortunately with low yield.¹²

Some chromium esters have been examined as a catalyst in the oxidation of benzylic hydrocarbons. Among them, chromium (III) stearate was often exploited, chromium(III) acetate was less investigated while chromium(III) trifluoroacetate, chromium(III) naphthenate, and chromium(III) octoate have been rarely used. Chromium esters have been mainly used in conjunction with oxygen. The comparative study on the oxidation of ethylbenzene catalyzed by chromium complexes are tabulated in Table 3.3.

Table 3.3 Comparative study on the oxidation of ethylbenzene catalyzed by chromium complexes from this developed system and those reported in literature.

Entry	Catalyst	Oxidant	Condition	Yield (%)
1	$\text{Cr}(\text{st})_3$	TBHP	Isooctane, 70°C for 24 h	95 ^a
2	$\text{Cr}(\text{p})_3$	TBHP	Isooctane, 70°C for 24 h	75 ^a
3	$\text{Cr}(\text{b})_3$	TBHP	Isooctane, 70°C for 24 h	65 ^a
4	$\text{Cr}(\text{n})_3$	TBHP	Isooctane, 70°C for 24 h	97 ^a
5	$\text{Cr}(\text{acac})_3$	TBHP	Isooctane, 70°C for 24 h	57 ^a
6	$\text{Cr}(\text{acac})_3$	TBHP	Benzene, 90°C for 20 h	82 ^b
7	$\text{Cr}(\text{st})_3$	1-methylcyclohexyl hydroperoxide	Benzene, 125°C, 20 h	85 ^b
8	CrO_3	H_2O_2	MeCN, 20°C, 168 h	9.4 ^b
9	$(\text{Bu}_4\text{N})_2\text{Cr}_2\text{O}_7$	H_2O_2	MeCN, 20°C, 24 h	9.6 ^b
10	$\text{CrO}_3 + \text{RCO}_2\text{H}$	O_2 or air	MeCN, 25°C, 400 h	3 ^b
11	CrO_3	Iodosylbenzene	MeCN, 25°C, 300 h	2 ^b

^aPresent study, ^bReference 19

From Table 3.3, it was clearly seen that the oxidation of ethylbenzene catalyzed by $\text{Cr}(\text{st})_3$, $\text{Cr}(\text{p})_3$ or $\text{Cr}(\text{b})_3$ displayed high yield of desired product compared with $\text{Cr}(\text{acac})_3$ and $\text{Cr}(\text{n})_3$. These may derive from the electronic effect of ester ligand of catalyst.⁷

The effect of the amount of ethylbenzene was the next parameter to examine. The profile of the product yield is shown in Figure 3.2 and Table 3.4.

Table 3.4 The effect of chromium(III) catalysts on ethylbenzene oxidation in terms of efficiency of TBHP.

Entry	Ethylbenzene (mmol)	% Yield of desired product									
		Cr(p) ₃		Cr(st) ₃		Cr(b) ₃		Cr(acac) ₃		Cr(n) ₃	
		E*	TBHP*	E*	TBHP*	E*	TBHP*	E*	TBHP*	E*	TBHP*
1	5	75.2	41.8	94.8	52.7	65.0	36.1	56.7	31.5	96.9	53.8
2	10	65.5	72.8	80.4	89.3	59.6	66.2	50.9	56.5	73.9	82.1
3	15	46.9	78.2	53.1	88.5	40.0	65.0	46.5	77.5	63.3	99.9
4	25	23.3	64.7	27.9	80.3	21.6	59.9	35.5	98.5	25.6	71.0
5	50	12.6	70.2	15.4	85.3	12.2	67.9	20.4	97.0	11.9	66.3

Reaction conditions: ethylbenzene (5-50 mmol), chromium(III) carboxylate (0.2 mmol), isoctane (5 mL), TBHP (9.0 mmol) at 70°C for 24 h.

E* %yield of desired product based on ethylbenzene, TBHP* %yield of desired product based on TBHP

It was revealed that the amount of substrate affected the product yield. Considering based upon the efficiency of TBHP, the more substrates were used, the better yield of desired product based on the oxidant was observed. Cr(st)₃ was found to be a remarkable catalyst for this purpose.

The effect of the amount of Cr(st)₃ as a catalyst on ethylbenzene oxidation was explored and the results are tabulated in Table 3.5.

Table 3.5 The effect of the amount of catalyst in ethylbenzene oxidation

Entry	Catalyst (mmol)	% Yield of product		Selectivity (On/Ol ratio)	Catalytic Turnover (mmol/mmol)
		acetophenone	1-phenyl ethanol		
1	0.05	89.70	0.89	101	89.7
2	0.15	81.70	Trace	ND	27.2
3	0.20	94.82	Trace	ND	23.7
4	0.25	55.30	Trace	ND	11.1

Reaction conditions: ethylbenzene (5 mmol), chromium(III) stearate (0.05-0.25 mmol), isooctane (5 mL), TBHP (9.0 mmol) at 70°C, for 24 h.

In the present study, it was found that the amount of Cr(st)₃ affected on the amount of desired product. The selectivity (on/ol ratio) of benzylic oxidation was increased with increasing amount of Cr(st)₃.¹² In the case of Cr(st)₃ 0.25 mmol, the desired product was lower than that utilized 0.20 mmol of catalyst. That may be because the overoxidation was found in these reaction medium. Taking to an account on catalytic turnover, it was found that catalytic turnover approximately 90 was attained when 0.05 mmol of catalyst was used. However, it seemed to be 1-phenylethanol was oxidized to acetophenone efficiently when the amount of catalyst was lifted up.

3.2.3 Effect of solvents

During the course of this research, the solvent that could provide a homogeneous reaction was required. From the experiments described above, isooctane was chosen as a reaction medium because it was inexpensive and commercially available and could well dissolve both ethylbenzene (organic substrate) and metal carboxylate complex (catalyst). Other solvents such as *N,N*-dimethylformamide, tetrahydrofuran, dichloromethane, 1,2-dichloroethane, ethanol, methanol, carbon tetrachloride, acetone, chloroform, acetonitrile and pyridine were also selected to examine whether they could be employed or affected on this oxidation reaction. The effects of various solvents are shown in Table 3.6, Figs 3.3 and 3.4.

Table 3.6 The effect of solvents on the oxidation of ethylbenzene catalyzed by chromium(III) stearate.

Entry	Solvent	% acetophenone				%1-phenyl ethanol	Selectivity On/Ol ratio
		1 h	2 h	3 h	24 h	24 h	24 h
1	DMF	Trace	Trace	Trace	6.12	Trace	-
2	THF	0	0	0	Trace	Trace	-
3	Dichloromethane*	Trace	Trace	48.87	47.82	4.10	12
4	1,2 – dichloroethane	Trace	Trace	Trace	28.59	4.00	7
5	Ethanol	1.23	2.30	3.41	9.14	0.88	10
6	Methanol	0.72	2.20	3.36	14.00	1.62	9
7	CCl ₄	25.90	37.77	39.15	41.46	2.59	16
8	Acetone*	Trace	Trace	1.25	77.62	1.87	42
9	Chloroform	3.56	5.66	6.43	15.39	5.54	3
10	Pyridine	1.86	4.97	9.67	57.11	Trace	-
11	Acetonitrile	Trace	1.59	3.74	100.51	Trace	-
12	Isooctane	28.22	41.90	43.16	94.82	Trace	-

Reaction conditions: ethylbenzene (5 mmol), chromium(III) stearate (0.2 mmol), solvent (5 mL), TBHP (9.0 mmol) at 70°C for 24 h.

*Dichloromethane at 40 °C and acetone at 56 °C for 24 h.

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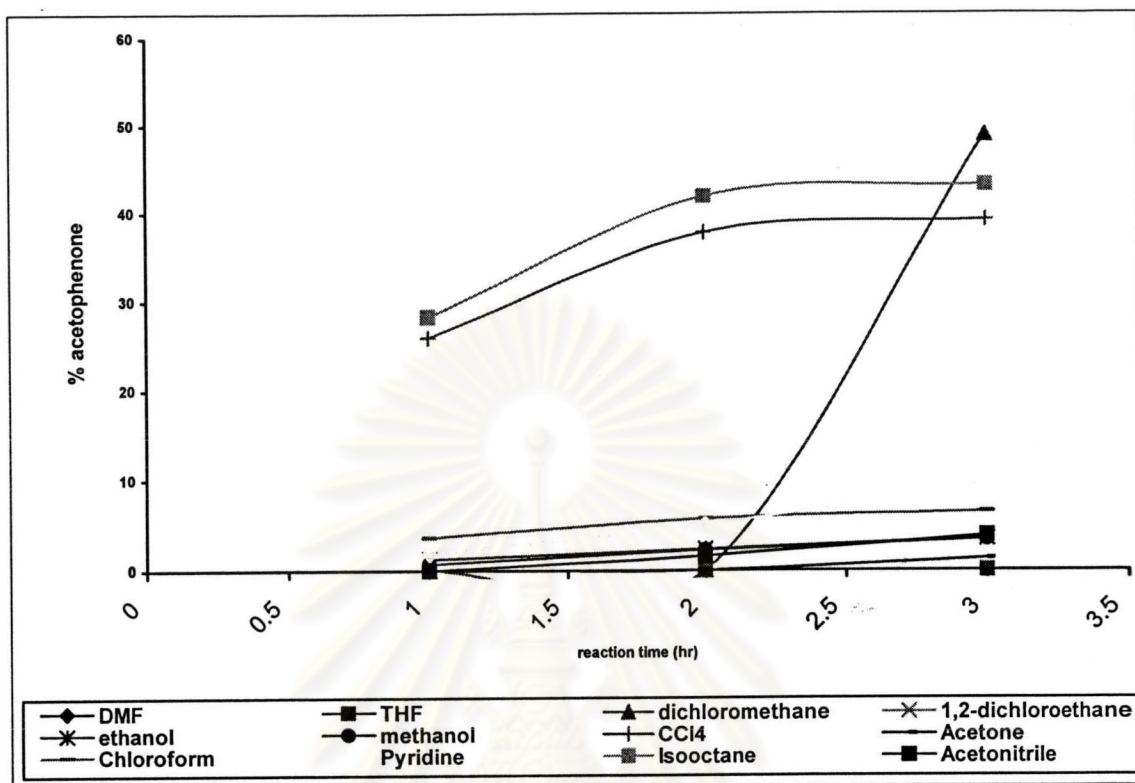


Fig 3.3 Comparative kinetic study on the oxidation of ethylbenzene catalyzed by Cr(III) stearate in various solvents

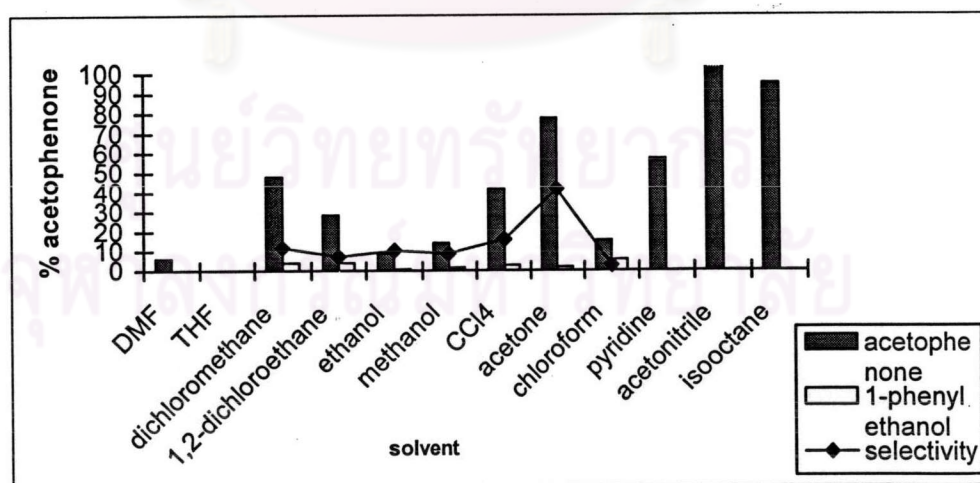


Fig 3.4 The effect of solvents on the selectivity of ethylbenzene oxidation for 24 h

Isooctane was generally employed as a solvent in ethylbenzene oxidation. When acetone was used as the reaction medium, the oxidation reaction provided higher amount of the desired product and free from byproduct. In the case of employing pyridine, dichloromethane and carbon tetrachloride, the oxidation reaction provided only a small amount of product; however, the reaction was performed and the catalyst could easily be separated from the mixture after the oxidation was over. These solvents infact provided informative clues for the mechanistic pathway of the reaction which will be discussed in the following section. If tetrahydrofuran was used as the reaction medium, the oxidation reaction was not taken place. In the case of ethanol and methanol as solvent, low yield of carbonyl compound (9% and 14%, entries 4 - 5) was detected. These observation gave a hint that under this particular conditions, alcohol could perhaps be oxidized to carbonyl compounds. That made the yield of the desired product (acetophenone) lower.

Even though the oxidation of ethylbenzene in acetone gave high yield of the desired product (78%, entry 8), acetone was easily volatiled. Therefore, it was not appropriate for being a solvent under this circumstance.

From these results, it was observed that isooctane was found to be appropriate solvent for performing selective benzylic oxidation under this particular condition. Furthermore, the variation of the amount of the isooctane was examined and the effect of the amount of isooctane in ethylbenzene oxidation is shown in Table 3.7.

Table 3.7 The effect of the amount of isooctane in ethylbenzene oxidation

Entry	Isooctane (ml)	% yield of product		Mass balance
		acetophenone	1-phenyl ethanol	
1	5	94.82	trace	100
2	10	66.39	trace	100
3	15	30.89	trace	100

Reaction conditions: ethylbenzene (5 mmol), chromium(III) stearate (0.2 mmol), isooctane (5-15 mL), TBHP (9.0 mmol) at 70°C for 24 h.

It was observed that when the amount of isooctane was increased, the yield of the desired product was decreased. This may be because the probability of collision between

substrate and oxidant was decreased when the amount of isooctane increased. According to these experiments, isooctane 5 mL was found to be the most appropriate amount of solvent to provide the highest yield of the desired product.

3.2.4 Effect of the oxidants

A number of methods have been available for allylic and benzylic oxidations using chromium(VI) complexes. Some of these traditional oxidation methods suffered from drawbacks such as the use of a very large excess of reagent, large volume of solvent, and long reaction time. There is a continual search for milder, inexpensive, and more convenient methods for affecting these transformations. For instance, the use of $\text{Cr}(\text{CO})_6$, 2,4-dimethylpentane-2,4-diol cyclic chromate, pyridinium dichromate³⁰ and PCC on celite as catalyst in the oxidation reaction of ethylbenzene with TBHP in benzene under reflux has been reported to give good yields of the desired product.

Many procedures using a variety of metal and co-oxidants have been reported. Oxygen gas has been used as the sole oxidant in combination with Ru, Co, Cu, Pt, Zr and Rh catalysts.²⁹ TBHP was a primary oxidant used for the oxidation of benzylic methylene compound in this study. Various oxidants such as hydrogen peroxide, aldehyde/ O_2 were tried to investigate in this oxidation reaction. The effects of the variation of oxidants in ethylbenzene oxidation using chromium(III) stearate catalyst are presented in Table 3.8 and Fig 3.5.

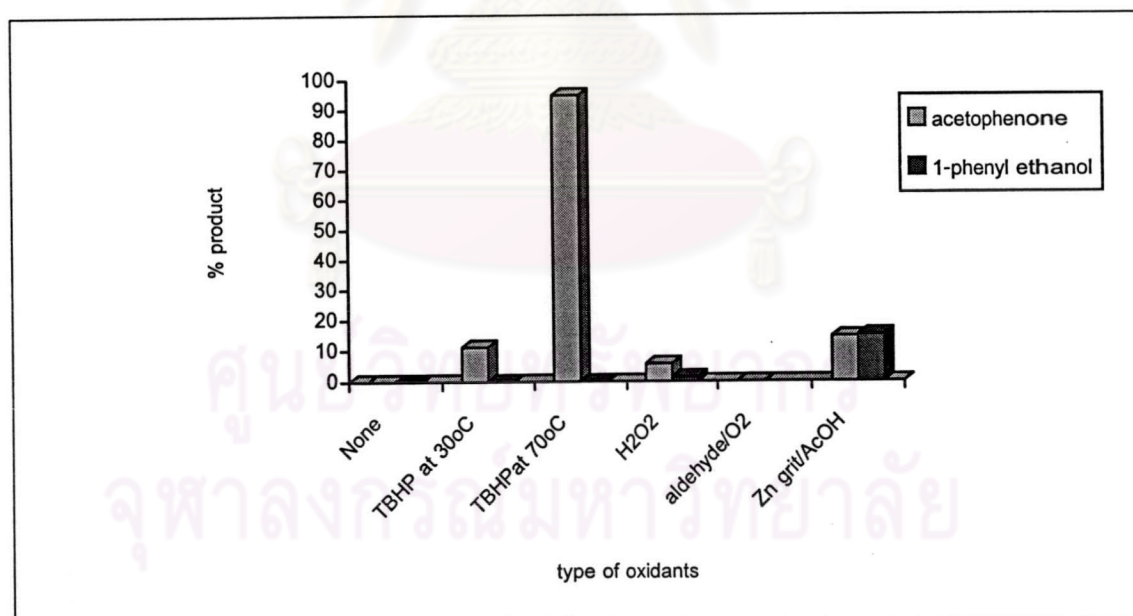
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Table 3.8 The effect of oxidant in ethylbenzene oxidation

Entry	Oxidant	% Yield of product		Selectivity On/Ol ratio
		acetophenone	1-phenyl ethanol	
1	None	0.0	0.0	ND
2	TBHP ^a	11.17	-	ND
3	TBHP	94.82	trace	ND
4	H ₂ O ₂	5.68	1.46	4
5	2-ethylbutyral dehyde / O ₂	trace	trace	ND
6	Zinc grit/AcOH	14.51	15.11	1

Reaction conditions: ethylbenzene (5 mmol), chromium(III) stearate (0.2 mmol), isooctane (5 mL), Oxidant (9.0 mmol) at 70 °C for 24 h.

^a At 30°C for 24 h

**Fig 3.5** The effect of oxidants in ethylbenzene oxidation

The present method for ethylbenzene oxidation employing TBHP is extremely useful in terms of both yield and operational simplicity (entry 3). From the result, it could

be observed that the reaction at higher temperature gave superior yield of acetophenone to that performed at room temperature. Furthermore, it was revealed that the increasing of temperature affected the desired product yield, suggesting that the main reaction course may involve a radical pathway. Radical cleavage was increased when temperature was increased. The results attained from the use of H₂O₂, 2-ethylbutyraldehyde and Zn grit/acetic acid were not appreciated because of low yield of acetophenone. Nevertheless, Zn grit/acetic acid as an oxidant provided an interesting alternative route for the benzylic oxidation which gave high yield of product as 1-phenyl ethanol in comparable amount to acetophenone.

Thus, TBHP was chosen as an oxidant for benzylic oxidation and believed that it will find broad spectrum of applications in organic synthesis.

Since the high cost of TBHP, the attempts to reduce the amount of TBHP were performed. In addition, the variation of the ratio of ketone to alcohol (On/Ol) may be affected by the oxidant employed. Thus, the variation of the amount of TBHP was examined and the results are shown in Table 3.9 and Fig 3.6.

Table 3.9 The effect of the amount of TBHP in ethylbenzene oxidation

Entry	TBHP (mmol)	% yield of product		Selectivity On/Ol ratio
		acetophenone	1-phenyl ethanol	
1	0	2.47	0.57	4
2	3	46.38	1.31	35
3	6	46.43	0.81	57
4	9	94.82	trace	ND
5	12	53.54	trace	ND

Reaction conditions: ethylbenzene (5 mmol), chromium(III) stearate (0.2 mmol), isooctane (5 mL), TBHP (vary 0.0 – 12.0 mmol) at 70 °C for 24 h

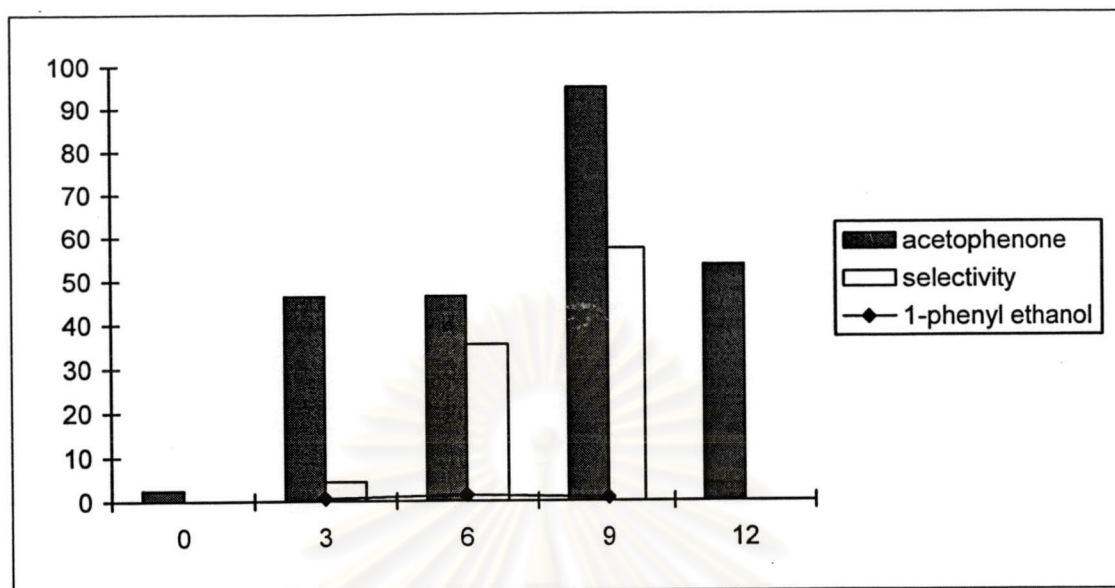


Fig 3.6 Effect of the amount of TBHP on ethylbenzene oxidation

Cited in the literature, the CrO_3 (0.05 equiv) combined with 70%TBHP was reported to use in the oxidation of ethylbenzene in methylene chloride for 21 h yielding acetophenone in moderate yield.⁶ The use of anhydrous TBHP instead of aqueous TBHP afforded similar results in isooctane and benzene.¹⁷

In terms of selectivity of the reaction based on the amount of TBHP, it was observed that employing 9.0 and 12.0 mmol of TBHP gave high selectivity of the desired product (on/ol ratio). 1-Phenylethanol could be converted to acetophenone under this optimized reaction. While the use of 3.0 and 6.0 mmol of TBHP converted 1-phenylethanol to acetophenone in low yield and selectivity.

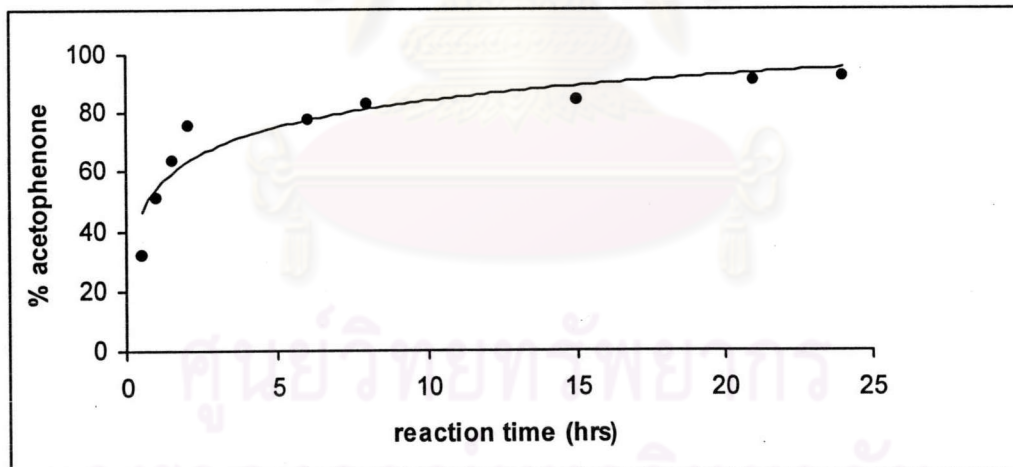
3.2.5 Kinetic study on the oxidation of ethylbenzene catalyzed by Cr(III) stearate.

The kinetic study of the reaction was performed in order to find the optimum time for the progress of the reaction. The rate of ethylbenzene oxidation catalyzed by chromium(III) stearate complex using TBHP as an oxidant in isooctane was examined. The kinetic analysis results are shown in Table 3.10.

Table 3.10 The kinetic study of ethylbenzene oxidation catalyzed by Cr(III) stearate.

Entry	Time (hr)	Acetophenone (%)
1	0.5	31.93
2	1	50.79
3	1.5	63.35
4	2	75.42
5	6	77.51
6	8	83.09
7	15	84.30
8	18	86.24
9	21	90.51
10	24	92.17

Reaction conditions: ethylbenzene (5 mmol), chromium(III) stearate (0.2 mmol), isooctane (5 mL), TBHP (9 mmol) at 70°C for 24 h.

**Fig 3.7** The kinetic study of ethylbenzene oxidation catalyzed by Cr(III) stearate.

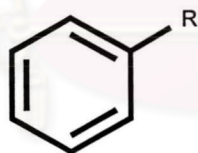
From Fig 3.7, with the variation of time, it was found that the reaction time around 21 hours was the most appropriate time for the oxidation of ethylbenzene under this particular system. In terms of kinetic study, the results displayed that the half life of the reaction under this optimum conditions was approximately 2 hours.

From the overall results obtained, the structure of carboxylate ligand, transition metal that binded with ligand, oxidizing agent, solvent system, additive, reaction time and reaction temperature affected the oxidation reaction. The optimum conditions for the oxidation of ethylbenzene were as follows: ethylbenzene 5 mmol as substrate, isooctane 5 mL, TBHP 9 mmol as oxidant and Cr(st)₃ as catalyst at 70°C for 24 hours. This improved catalytic system was applied for other benzylic methylene compounds which will discuss in the following topics.

3.3 Oxidation of various benzylic methylene compounds

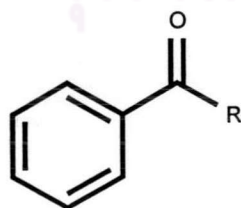
3.3.1 The oxidation of alkylbenzene.

Stemmed from the above results, it was demonstrated that Cr(st)₃ was the most appropriate catalyst for the oxidation of ethylbenzene, *i. e.*, it provided the highest yield of the desired product with high selectivity in terms of On/OI ratio. To extend the scope of this developed oxidation system, various benzylic methylene compounds were selected as chemical models. Seven alkylbenzenes with different side chain on a benzene ring were oxidized under the same optimized conditions. The results are summarized in Table 3.11.

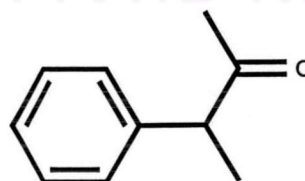


- (1) R = CH₃
- (2) R = C₂H₅
- (3) R = C₃H₇
- (4) R = *n*-C₄H₉
- (5) R = *sec*-C₄H₉
- (6) R = *tert*-C₄H₉
- (7) R = *n*-C₅H₁₁

Alkylbenzene



- (8) R = OH
- (9) R = CH₃
- (10) R = C₂H₅
- (11) R = C₃H₅
- (13) R = C₄H₉



(12)

Oxidized product

Table 3.11 The oxidation of selected alkylbenzenes catalyzed by chromium(III) stearate.

Entry	Substrate	Product	% Yield of Product
1	Toluene (1)	Benzoic acid (8)	12
2	Ethylbenzene (2)	Acetophenone (9)	95
3	Propylbenzene (3)	Propiophenone (10)	92
4	<i>n</i> -butylbenzene (4)	Butyrophenone (11)	76
5	<i>sec</i> -butylbenzene (5)	3-phenylbutan-2-one (12)	40
6	<i>tert</i> -butylbenzene (6)	none	none
7	<i>n</i> -pentylbenzene (7)	Valerophenone (13)	80

Reaction condition : substrate (5.0 mmol), chromium(III) stearate (0.2 mmol), TBHP (9.0 mmol) and isooctane 5 mL at 70°C for 24 h

Table 3.11 reveals that ethylbenzene (2), propylbenzene (3), *n*-butylbenzene(4) and *n*-pentylbenzene (7) could be converted to the desired carbonyl compounds in high yield. When *sec*-butylbenzene (5) was used as a substrate, it provided only low conversion to give 3-phenylbutan-2-one (12). This may be explained by high steric hindrance at benzylic position. In addition, the attempt to oxidize toluene (1) afforded benzoic acid as a desired product in low yield. This was because the primary radical generated as an intermediate in this reaction had lower stability than secondary radical in other alkylbenzenes selected. Furthermore, the C-H bond energy of toluene was high thus not favor for the reaction to take place. *Tert*-butylbenzene (6) had no hydrogen at benzylic position to be abstracted; therefore, no oxidation could be taken place.

The selectivity of radical process could be ordered as tertiary C-H bond was more prevailed to attack over secondary and primary C-H bonds, respectively. Free radical formed on benzylic carbon would then proceed with oxygen in the oxidation process. Because of secondary radicals are more susceptible to attack than primary ones then the oxidation of toluene should be more difficult to proceed than other alkylbenzenes.

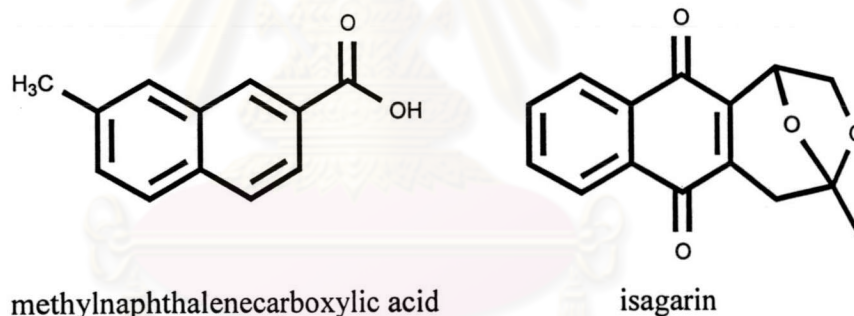
Cited in literature, the oxidation of ethylbenzene using air in a batch reactor with dichromate/alumina catalyst at 130°C for 24 hr was studied. The acetophenone and

benzoic acid were received with 3A molecular seive as dehydrant in moderate yield (53% yield).²¹

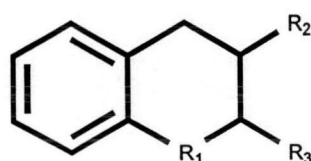
To summarize, the oxidation of alkylbenzene employing this developed oxidation reaction could be achieved. Steric hindrance at the benzylic position rendered the possibility for the oxidation to take place. The yields of desired carbonyl compounds obtained by this methodology were comparable and in some cases more prevailed than those in reported processes.¹⁰

3.3.2 Oxidation of tetralin, 1,2,3,4-tetrahydroquinoline and xanthene.

The aim of the present study was to extend the scope of the oxidation of benzylic methylene compounds. Many industrially required chemicals or bioactive compounds contained the α -carbonyl functional group to the aromatic moiety. Methyl-naphthalene carboxylate³⁴, palmarumycin⁴⁰, deoxycompresserin⁴¹⁻⁴², diepoxin³³ and isagarin³² are among those selected examples.

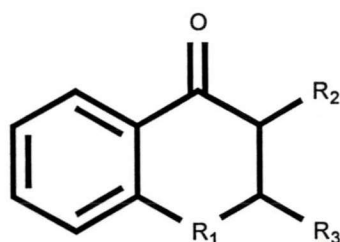


In this study, tetralin (14), 1,2,3,4-tetrahydroquinoline (16) and xanthene (18) were selected as chemical models and the results of the oxidation of these substrates are presented in Table 3.12.



- (14) $R_1 = \text{CH}_2$, R_2 and $R_3 = \text{H}$
 (16) $R_1 = \text{NH}$, R_2 and $R_3 = \text{H}$
 (18) $R_1 = \text{O}$, $R_2 + R_3 = \text{C}_6\text{H}_6$

Substrate



- (15) $R_1 = \text{CH}_2$, R_2 and $R_3 = \text{H}$
 (20) $R_1 = \text{NH}$, R_2 and $R_3 = \text{H}$
 (21) $R_1 = \text{O}$, $R_2 + R_3 = \text{C}_6\text{H}_6$

Oxidized products (Carbonyl compounds)

Table 3.12 The oxidation of tetralin, 1,2,3,4-tetrahydroquinoline and xanthene catalyzed by chromium(III) stearate.

Entry	Substrate	Product	% yield of Product
1	Tetralin (14)	α -Tetralone (15)	40 ^a
2	α -Tetralone (15)	2,3-Dihydro-[1,4]-naphthoquinone (19)	99 ^b
3	1,2,3,4-Tetrahydroquinoline (16)	-	-
4	1-(3,4-Dihydro-2H-quinolin-1-yl)-2,2-dimethyl-propan-one (17)	2,3-Dihydroquinolin-1-one (20)	74 ^b
5	Xanthene (18)	Xanthone (21)	94 ^b

Reaction condition : substrate (5.0 mmol), chromium(III) stearate (0.2 mmol) isooctane (5 mL), TBHP (9.0 mmol) at 70 °C for 24 h.

^aYield determined by gas chromatography. ^bIsolated yield.

Table 3.14 exhibits that tetralin (14) could be converted to α -tetralone (15) in poor yield. This derived product, α -tetralone (15) was confirmed its identity by conducting *co*-TLC with authentic α -tetralone. Comparing this obtained result with that

reported recently, the use of $\text{Cr}(\text{OAc})_3$ as a catalyst with molecular oxygen also produced only low yield of α -tetralone (33%).¹²

The attempt to gain higher yield of the desired carbonyl compound was tried with the addition of 18 mmol of TBHP instead of using 9 mmol in general procedure. Unfortunately, the yield of α -tetralone was lessened, only 23% was observed. The systematic study on the effect of the amount of oxidant was therefore set up and the results are displayed as shown in Fig 3.8.

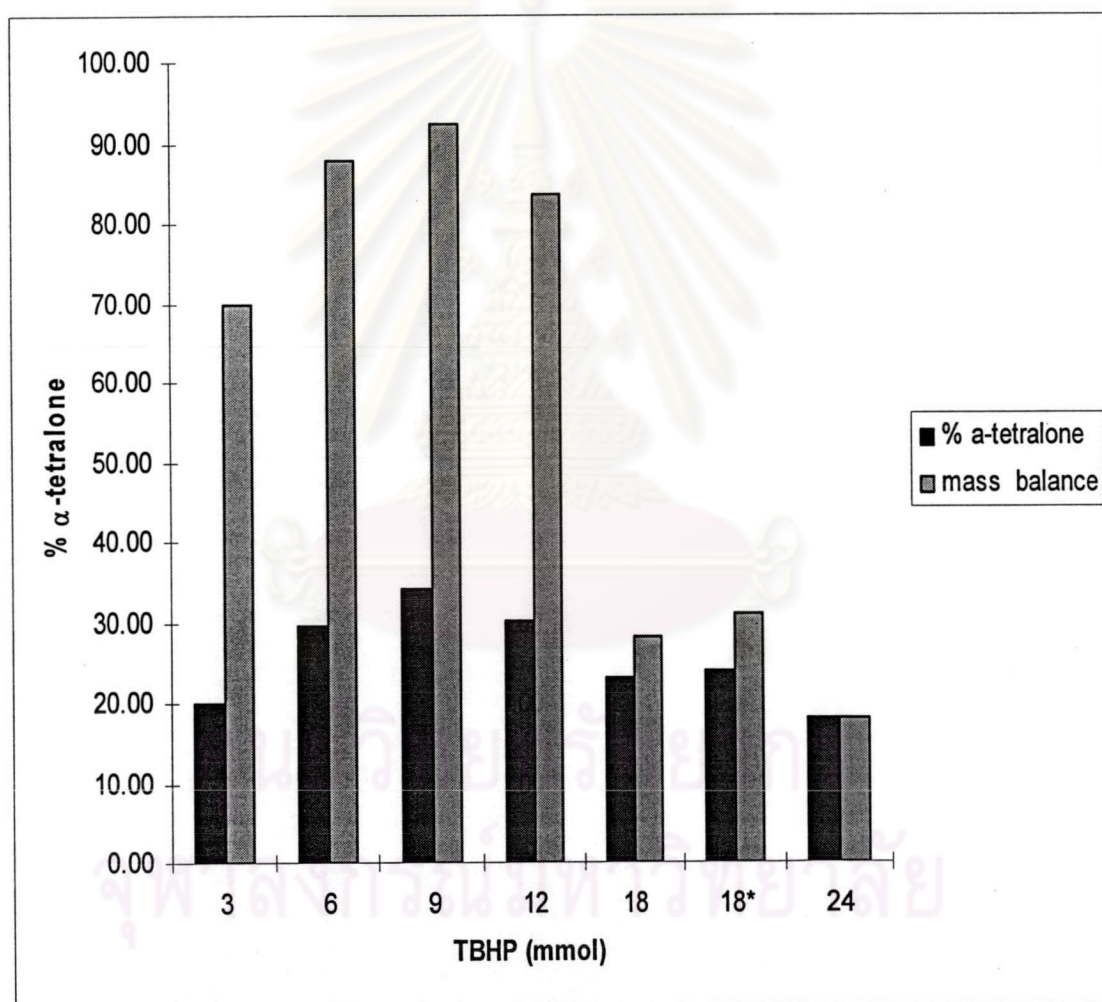


Fig 3.8 The effect of the amount of TBHP in tetralin oxidation.

* Two portions of 9 mmol of TBHP were consecutively added (at time 0 and 9 h).

It was observed that tetralin could be converted to α -tetralone in poor yield with 9 mmol of TBHP. Some was overoxidized to 2,3-dihydro-1,4-naphthoquinone with 18 mmol of TBHP. In the case of excess TBHP, for example, 18 and 24 mmol of TBHP, it was found that the mass balance of the reaction was to recede and overoxidation reaction was found in place of α -tetralone in these system. One way to avoid the overoxidation was the use of excess amount to tetralin. The separate experiment was performed employing tetralin 50 mmol and TBHP 18 mmol. Only mono-oxidized product, α -tetralone was attained in moderate yield (64% yield based on TBHP) with good mass balance under the optimized condition.

Another set of experiments was also attempted by prolonging the reaction time. The results clearly revealed that the longer the reaction proceeded, the less amount of α -tetralone received. This observation called for the study on the kinetic of product formation and the results are presented as shown in Fig 3.9.

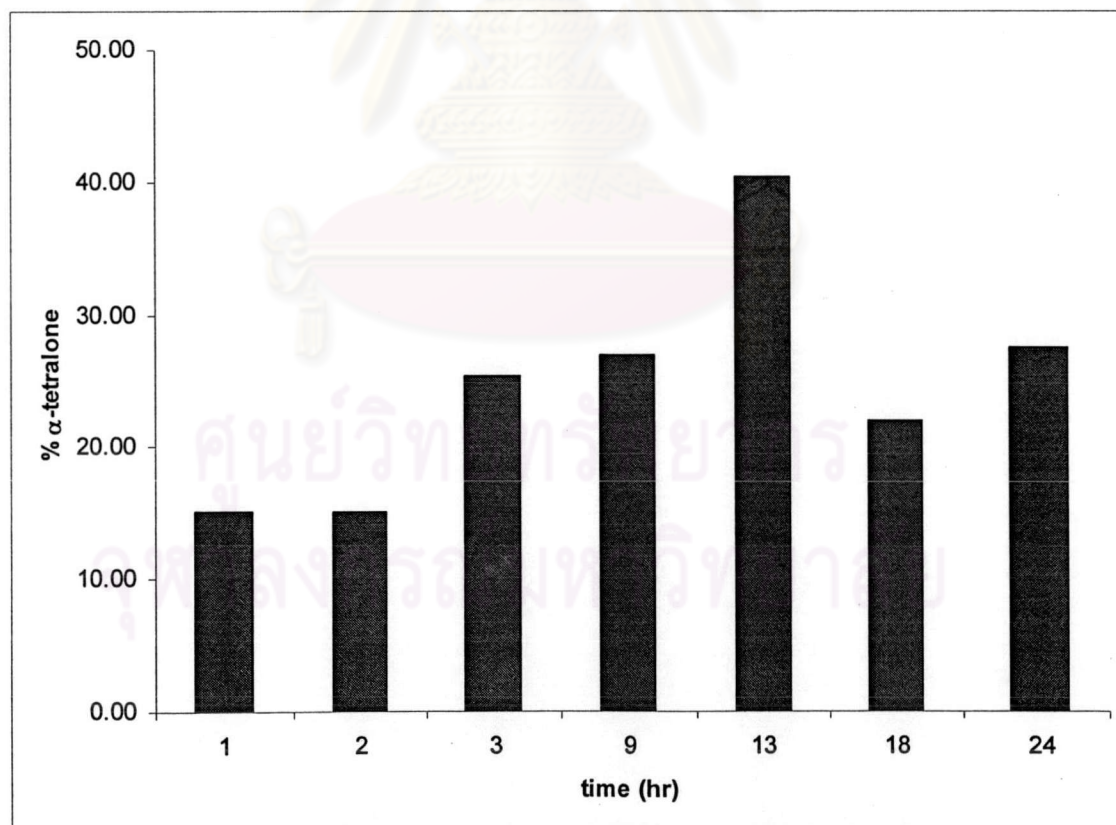
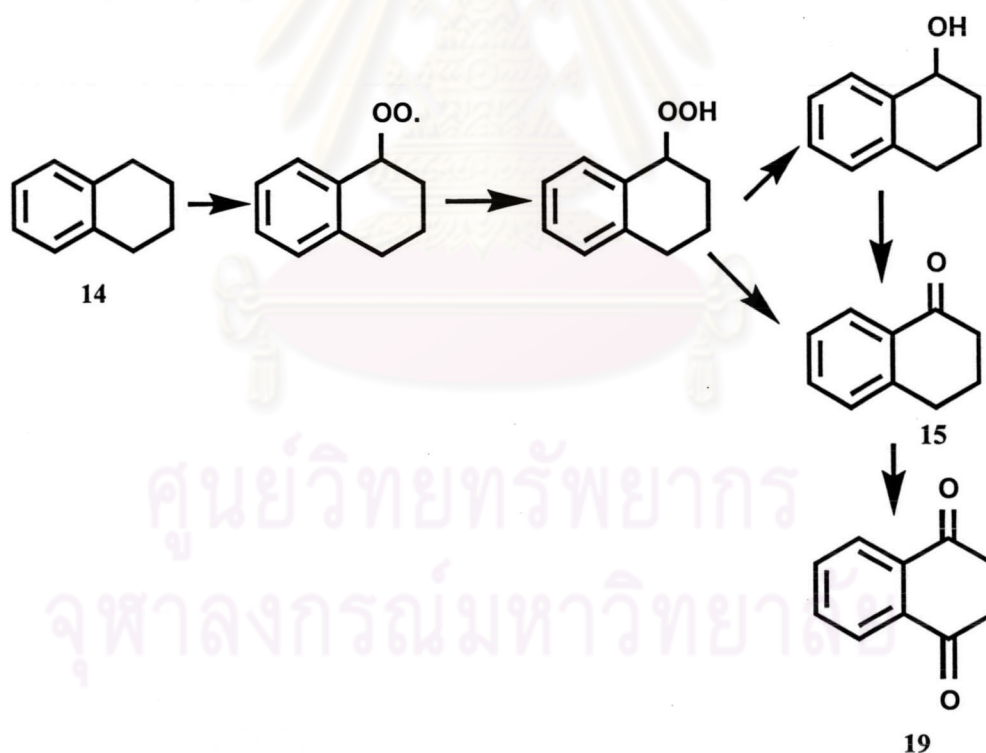


Fig 3.9 The kinetic study of tetralin oxidation catalyzed by Cr(III) stearate.

It was observed that the best yield of α -tetralone was attained when the reaction proceeded around 13 hours (40% yield with mass balance 87%). Leaving the reaction mixture for 24 hours gave the lower yield of α -tetralone (28%) with poor mass balance of 40%. The qualitative analysis of the reaction crude product revealed another interesting spot on TLC besides α -tetralone at R_f 0.54 (hexane-ethyl acetate (7:1) as a solvent system). This compound was later characterized by spectroscopic method as the overoxidized product of α -tetralone, namely 2,3-dihydro-1,4-naphthoquinone.

It therefore could be understood at this point that under this particular reaction condition, the product derived from tetralin oxidation proceeded the overoxidation reaction. The formation of intermediate and the final products was summarized as depicted in Scheme 3.1 in the similar fashion to that postulated in the literature.¹² The details of mechanistic pathway of this oxidation reaction will be discussed later.



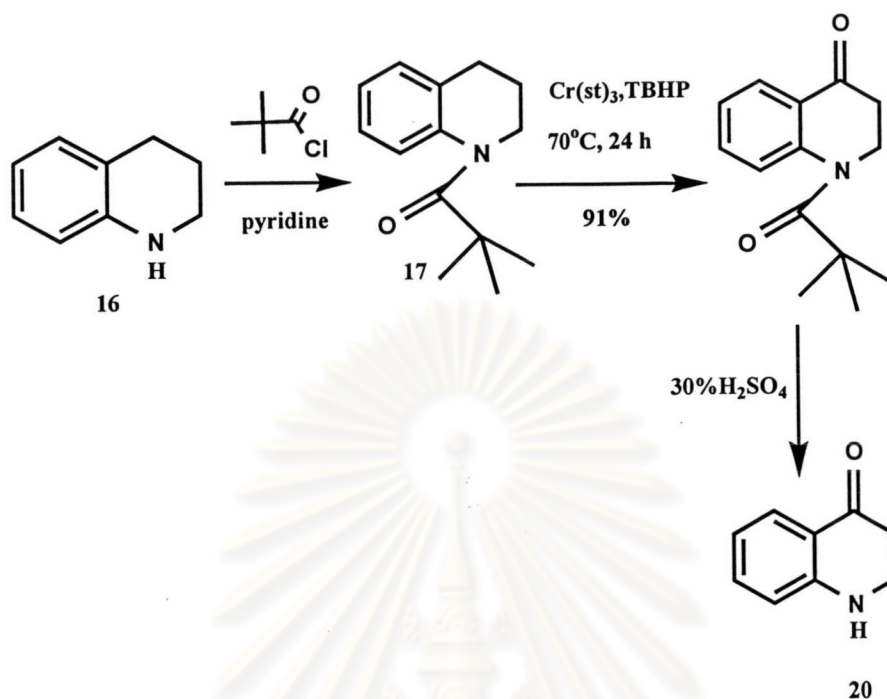
Scheme 3.1 The formation of intermediate and end products derived from tetralin oxidation

Further study was involved the oxidation of α -tetralone (**15**). When α -tetralone (**15**) was subjected to this oxidation system, it provided intriguing results. To illustrate this, 2,3-dihydro-1,4-naphthoquinone (**19**) was obtained as a sole isolated product in a quantitative yield. This obtained product was confirmed its structure by IR and NMR spectroscopy. The IR spectrum of this compound revealed the absorption band of C-H stretching of aromatic group at 3064 cm^{-1} and 1670 cm^{-1} for typical C=O stretching of quinone.⁴³ The ^1H NMR (CDCl_3) spectrum exhibited the important signals of methylene protons at δ 2.20 ppm (s, 4H) and aromatic protons could be detected around δ 7.52-8.08 ppm.

This result provided an alternative route to prepare naphthoquinone derivatives in excellent yield. Nevertheless, the attempt to oxidize 1,2,3,4-tetrahydroquinoline (**16**), the next substrate under this optimized condition was not successful. This may be because the oxidation of *N*-atom, possibly to *N*-oxide^{24,44-46} was prevailed over the benzylic methylene oxidation.

To overcome this bottleneck, the easily oxidized portion was protected as an amide of pivalic acid as 1-(3,4-dihydro-2H-quinolin-1-yl)-2,2-dimethyl-propan-1-one (**17**) employing the methodology described in the literature.⁴⁷ The oxidation of the protected molecule (**17**) under the normal condition was conducted. The oxidized product, namely 1-(2,2-dimethyl-propionyl)-2,3-dihydro-1H-quinolin-4-one was obtained in high yield (91% isolated yield). After deprotection with 30% H_2SO_4 , the desired product as 2,3-dihydro-1H-quinolin-4-one (**20**) was achieved in 61% overall yield based on the starting material, 1,2,3,4-tetrahydroquinoline.

To summarize the route to synthesize 2,3-dihydro-1H-quinolin-4-one (**20**), three steps for this transformation were required as depicted in Scheme 3.2.



Scheme 3.2 The synthesis of 2,3-dihydro-1H-quinolin-4-one employing this developed methodology

All synthesized compounds are characterized their identities by IR and $^1\text{H-NMR}$ spectrophotometer as described in Chapter II.

To verify the structure of target molecule, the IR spectrum (Fig 3.10) clearly revealed the absorption band of N-H stretching at 3460 cm^{-1} , aromatic C-H stretching at $2852\text{-}3064\text{ cm}^{-1}$ and the peak ascribed for C=O stretching in quinoline could be detected at 1670 cm^{-1} .⁴³ The $^1\text{H-NMR}$ (CDCl_3) spectrum (Fig 3.11) provided good agreement with the IR information. The signal appeared at δ 2.78 (t, $J = 6.80\text{ Hz}$, 2H) was the methylene protons adjacent to carbonyl group. Two triplet proton signals visualized at δ 4.22 ($J = 6.00\text{ Hz}$) were in good agreement with those located close to nitrogen atom. Four aromatic protons could be detected around δ 7.21.

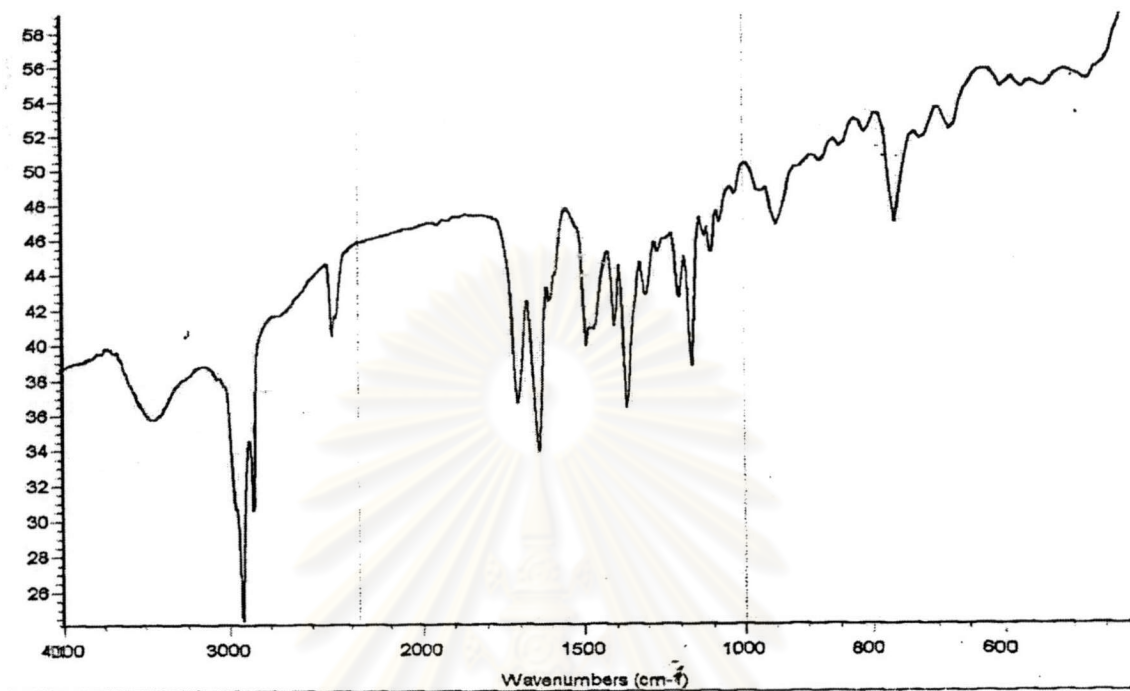


Fig 3.10 The IR spectrum of 2,3-dihydro-1H-quinolin-4-one.

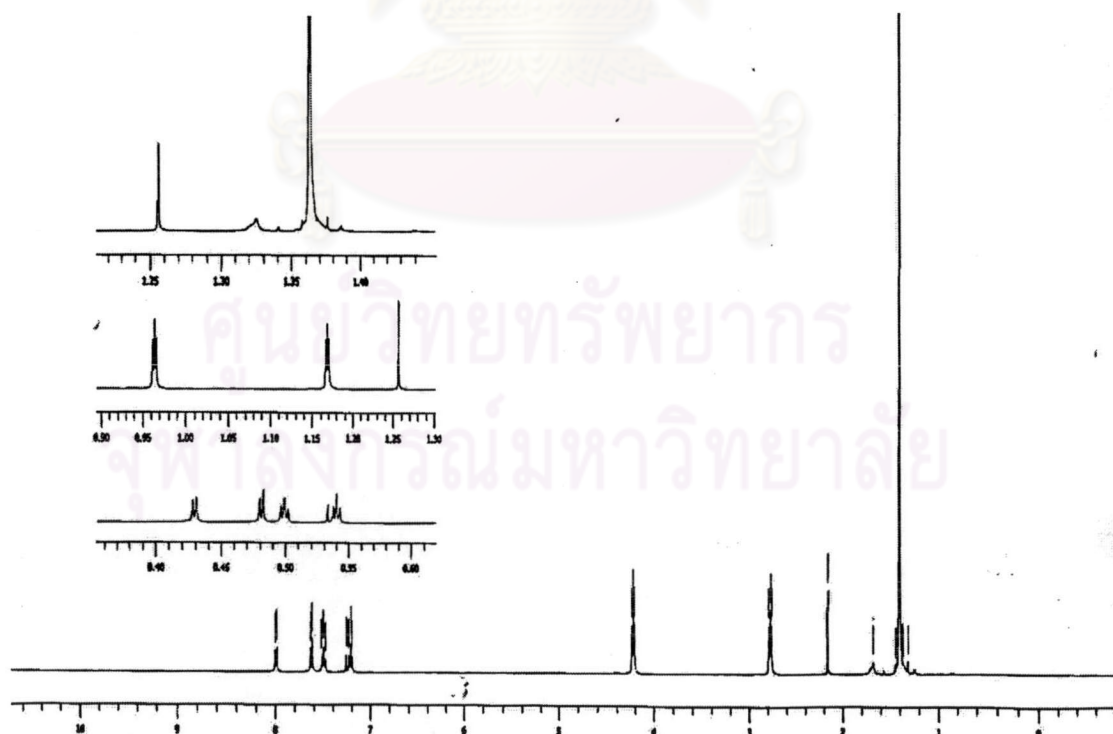
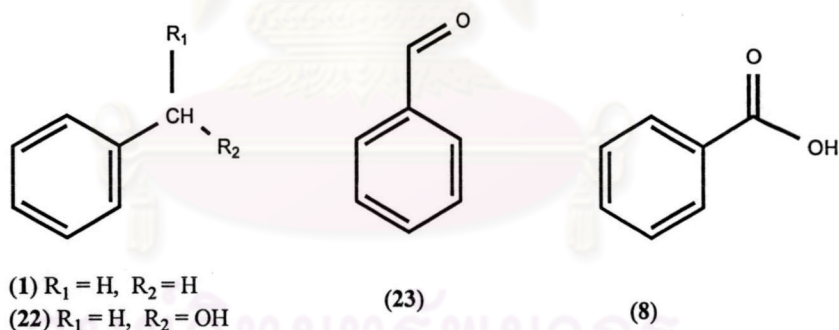


Fig 3.11 The ^1H NMR spectrum of 2,3-dihydro-1H-quinolin-4-one.

Another excellent example for the utilization of this developed system was the oxidation of xanthene (**18**) to xanthone (**21**). The oxidation could be carried out straight forward to gain xanthone (**21**) 94% yield. The identification by spectroscopic data was found to be in good agreement with authentic sample. To illustrate this, the IR spectrum of this compound exhibited the absorption band of C-H stretching at 3053 cm^{-1} and strong absorption band at $1602\text{-}1658\text{ cm}^{-1}$ due to the conjugated C=O stretching. The $^1\text{H-NMR}$ spectrum revealed only the aromatic protons detected in the range of $\delta\ 7.35\text{-}8.34$.

3.3.3 Oxidation of toluene, benzyl alcohol and benzaldehyde.

Benzoic acid was another fine chemical with many applications.²² It could be used as an agricultural foodstuff, preservative and an organic synthesis intermediate. To utilize this developed system for the preparation of benzoic acid, three substrates namely toluene, benzyl alcohol and benzaldehyde were selected. The results of the oxidation of these substrates are illustrated in Table 3.13.



Substrate

Oxidized product

Table 3.13 The oxidation of toluene, benzyl alcohol and benzaldehyde in the presence of chromium(III) stearate

Entry	Substrate	Product	% Isolated yield
1	Toluene (1)	Benzoic acid (8)	12
2	Benzyl alcohol (22)	Benzoic acid (8)	91
3	Benzaldehyde (23)	Benzoic acid (8)	85

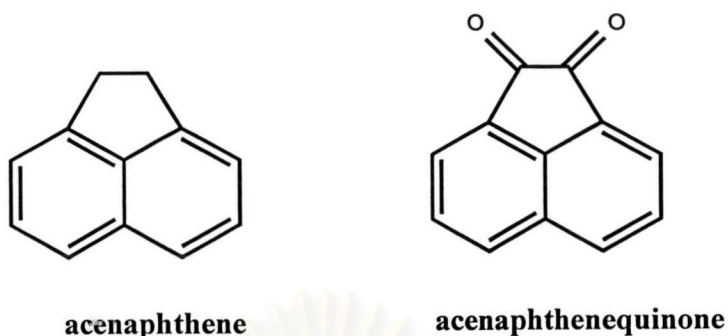
Reaction conditions : substrate (5.0 mmol), chromium(III) stearate (0.2 mmol), TBHP (9.0 mmol), isooctane 5 mL at 70 °C for 24 h.

From the above results, it was observed that the oxidation of benzyl alcohol could be accomplished with the high yield of benzoic acid (91%) under mild conditions. The desired product was easily separable from the reaction mixture by filtration and recrystallization with hot water. The oxidation performing with benzaldehyde (23) as a substrate yielded 85% of benzoic acid (entry 3). However, with toluene (1) the oxidation under this condition still gave poor yield of the desired product (12%, entry 1).

Therefore, this developed system could be another alternative for the preparation of benzoic acid and its derivatives. In fact, the oxidation of benzyl alcohol to the corresponding benzoic acid in high yield was another interesting topic since many benzoic acid derivatives fine chemicals were obtained from the oxidation of the corresponding benzyl alcohols. For instance, the 3-hydroxybenzoic acid, obtained by the oxidation of 3-hydroxymethylphenol.²⁹

3.3.4 Oxidation of acenaphthene

Acenaphthene has been known as one component in hazardous polycyclic aromatic hydrocarbons (PAHs) found in petroleum residues, in the incomplete burning process of various materials such as coal, oil, gas and garbage, cigarette smoke, automobiles and wood preservatives. The most environmental concern point of view was trying to eliminate this compound or transform it to another less toxic forms such as oxidized compound by chemical reaction or by treatment with microorganisms.



With the aim to utilize this developed oxidation in various aspects, the oxidation of acenaphthene was conducted. It was found that under the optimal conditions, acenaphthene could be converted to acenaphthenequinone in high yield (90% isolated yield). The isolated product was confirmed its identity by spectroscopic data. The IR spectrum exhibited the absorption band of C-H stretching at 3033 cm^{-1} and strong absorption band at 1710 cm^{-1} due to the conjugated C=O stretching. The $^1\text{H-NMR}$ spectrum (CDCl_3) revealed only the aromatic protons detected in the range of $\delta\ 7.52\text{-}8.02$.

Thus, this developed chromium(III) catalytic system was another usefully appropriate choice to use to eliminate acenaphthene in natural environment, considering based upon the ease of handling and low cost of operation. Moreover, the oxidized products, acenaphthenequinone in this particular case could be used for many applications such as insecticides and in dye industry.

3.3.5 Oxidation of ethers and esters

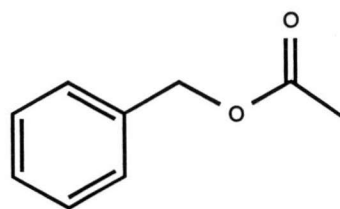
The oxidation of oxygen containing organic compounds in the class of ether was manipulated utilizing this catalytic system. Typical results are listed in Table 3.14.

NMR spectrum (CDCl_3) revealed the methyl protons detected at δ 1.29 (s, 3H) ppm and the aromatic protons observed in the range of δ 7.46-8.10 ppm.

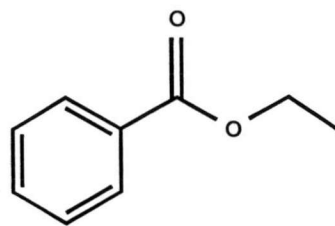
The IR spectrum of hexanoyl benzoate exhibited the absorption band of C-H stretching at 3440 cm^{-1} and strong absorption band at 1760 cm^{-1} due to the conjugated C=O stretching of anhydride. The $^1\text{H-NMR}$ spectrum (CDCl_3) revealed methyl protons at δ 1.00 (t, $J = 6.80\text{ Hz}$, 3H), methylene protons at δ 1.29 (qin, $J = 13.60\text{ Hz}$, 2H), δ 1.34-1.38 (m, 2H) and δ 1.57 (qin, $J = 14.40\text{ Hz}$, 2H) ppm. The methylene protons near adjacent to the carbonyl group at δ 2.16 (t, $J = 1.20\text{ Hz}$, 2H) and aromatic protons visualized in the range of δ 7.46-7.95.

Normally, unsymmetrical aromatic anhydride was gained by the reaction of carboxylic acids or metal carboxylates with acyl halides. Whilst investigating the Friedel-Crafts reactions, Zeavin *et al.* found that benzoyl chloride could be reacted with benzoic acid derivatives in the presence of pyridine to produce unsymmetrical aromatics anhydrides in good to excellent yields.³⁶ Nevertheless, the preparation of unsymmetrical anhydride from unsymmetrical ether has not been reported in the literature.³⁶ This reaction was presumably taken place at the benzylic position prior to subsequent oxidation reaction occurred at the other position next to oxygen atom. To verify this hypothesis two substrates, namely benzyl acetate (30) and ethyl benzoate (31) were subjected to the oxidation reaction. The results are presented as illustrated in Table 3.15.

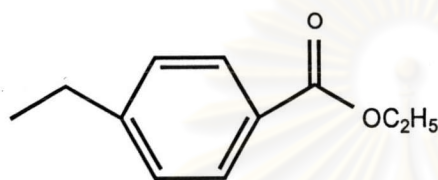
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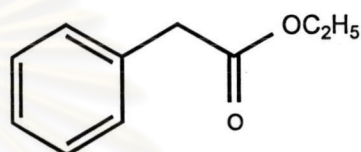
(30)



(31)

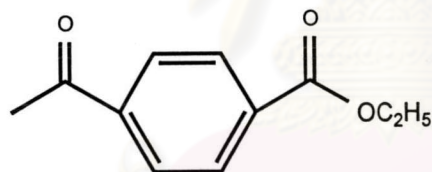


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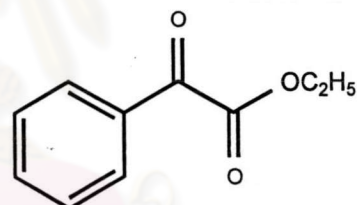


(33)

selected esters



(34)



(35)

oxidized products

ศูนย์วิทยทรัพยากร
จุฬาลงกรณ์มหาวิทยาลัย

Table 3.15 The oxidation of selected esters in the presence of chromium(III) stearate

Entry	Substrate	Product	% Isolated yield
1	Benzyl acetate (30)	Acetyl benzoate (29)	68
2	Ethyl benzoate (31)	Acetyl benzoate (29)	13
3	Ethyl 4-ethylbenzoate(32)	4-Acetylbenzoylacetate (34)	87
4	Ethyl phenylacetate (33)	Ethyl oxophenylacetate(35)	87
5	Ethyl phenylacetate (33)	Ethyl oxophenylacetate(35)	89*

Reaction conditions : substrate (5.0 mmol), TBHP (9 mmol), chromium(III) stearate (0.2 mmol) and isooctane 5 mL at 70°C for 24 h

*TBHP 18.0 mmol was used

The results presented in the above table manifestly displayed that the oxidation at benzylic position was more facile than alkyl part connecting to an oxygen atom with the isolated yield of 68% and 13% yield, respectively.

The comparative study using ethyl 4-ethylbenzoate, as that performed in literature was carried on. The oxidation of ethyl 4-ethylbenzoate under this developed reaction produced 4-acetylbenzoylacetate in the yield (87%) superior to that addressed in the literature (73%) using air oxidation in the presence of CrO₃ and CaCO₃.³⁷⁻³⁹

The derived isolated product was well-characterized by spectroscopy. The IR spectrum of 4-acetylbenzoylacetate exhibited the absorption band of C-H stretching at 2850-2990 cm⁻¹ and strong absorption band at 1680 cm⁻¹ due to the conjugated C=O stretching. The ¹H-NMR spectrum (CDCl₃) revealed the methyl protons at δ 1.41 (t, *J* = 6.80 Hz, 3H) and δ 2.64 (s, 3H) ppm. The methylene protons at δ 4.40 (q, *J* = 6.80 Hz, 2H) ppm and the aromatic protons were observed in the range of δ 7.80-8.12 ppm.

Considering for the application of this system, the importance of the production of keto acid and keto ester compounds mainly used in pharmaceutical industries was realized. Phenyl acetic acid or as its ester form, a commercially available compound could therefore possibly be value added to oxophenylacetic acid or its analogues ester

by this methodology. The direct benzylic oxidation of phenyl acetic acid did not give appreciable results. However, changing to the corresponding ethyl ester, the oxidation could fruitfully accomplish. Around 90% isolated product was gained. The oxidation by adding more TBHP to the system did not reveal any significantly difference in the yield of desired product. The IR spectrum (Fig 3.12) of ethyl oxophenylacetate obtained as the isolated product displayed the absorption band of C-H stretching at 2853-2912 cm^{-1} and strong absorption band at 1703 cm^{-1} due to the conjugated C=O stretching. The $^1\text{H-NMR}$ spectrum (CDCl_3 , Fig 3.13) revealed the ethyl protons at δ 1.46 (t, $J = 7.20$ Hz, 3H) and δ 4.49 (q, $J = 6.40$, 2H), methyl protons near carbonyl group at δ 2.64 (s, 3H), and the aromatic protons in the range of δ 7.55-8.05.

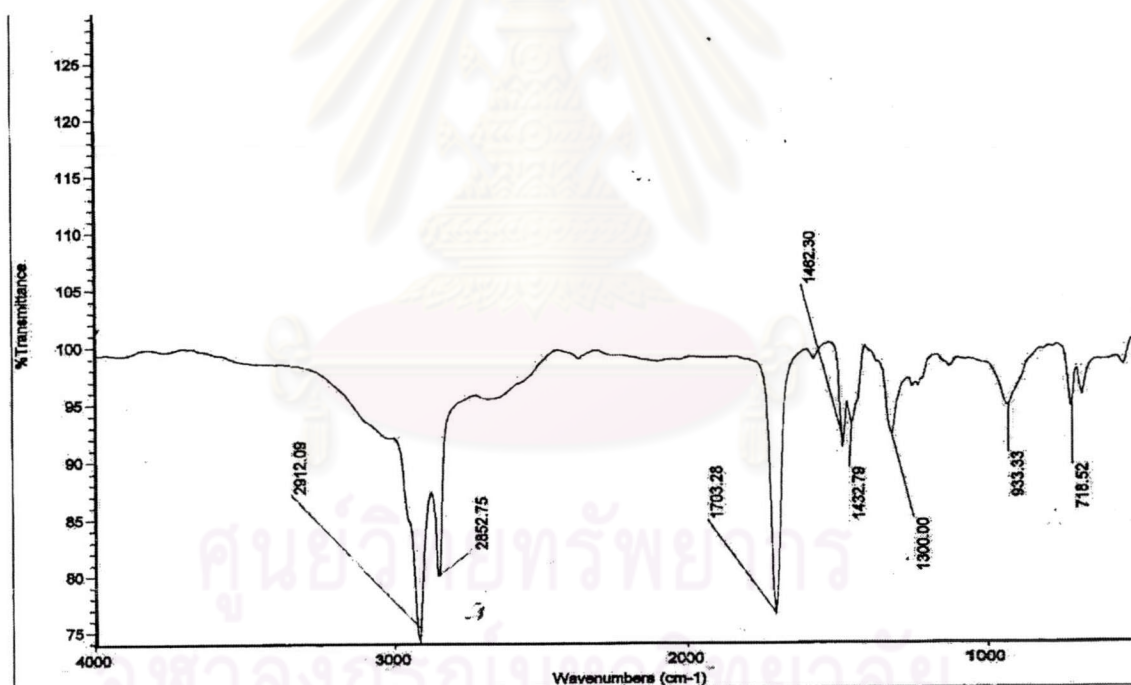


Fig 3.12 The IR spectrum of ethyl oxophenylacetate

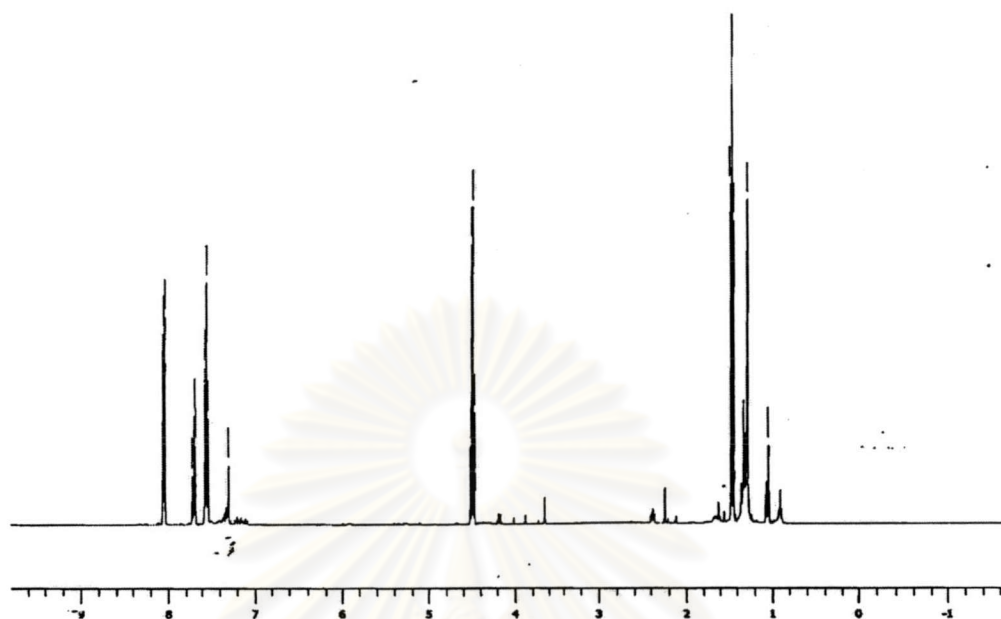


Fig 3.13 The ^1H -NMR spectrum of ethyl oxophenylacetate

Therefore, as presenting by various instances, this methodology become versatile for transformation of organic substrates to the more valuable oxidized products.

3.3.6 Oxidation of substituted ethylbenzene and its competitive study.

The oxidation of selected substituted ethylbenzenes under optimized condition was carried out. The results are presented as shown in Table 3.16.

Table 3.16 The oxidation of substituted ethylbenzene in the presence of $\text{Cr}(\text{st})_3$

Entry	Substrate	Product	% Yield
1	1-Bromo-2-ethylbenzene (36)	2-Bromoacetophenone (39)	57 ^a
2	1-ethyl-2-nitrobenzene (37)	2-Nitroacetophenone (40)	53 ^b
3	4-ethylbenzoic acid (38)	4-acetylbenzoicacid (41)	53 ^b

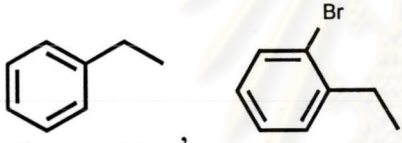
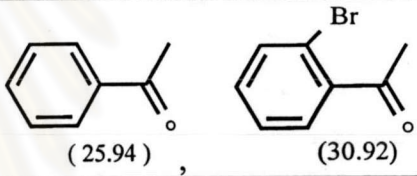
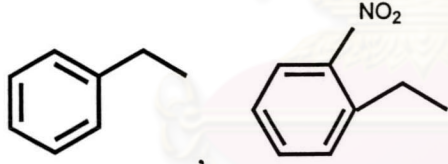
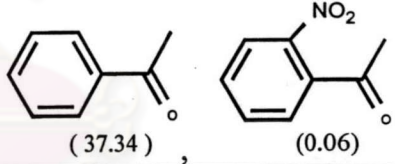
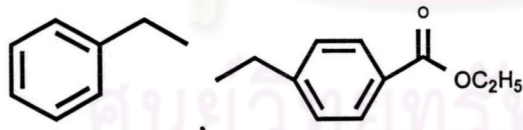
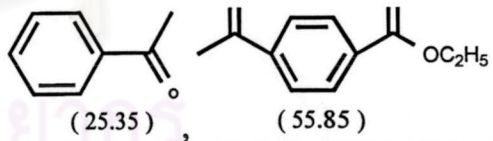
Reaction conditions : substrate (5.0 mmol), TBHP (9 mmol), chromium(III) stearate (0.2 mmol) and isooctane 5 mL at 70°C for 24 h.

^aYield determined by gas chromatography. ^bIsolated yield.

Substituted ethylbenzenes could transform to the corresponding carbonyl compounds in moderate yield under the standard conditions. Some starting materials were still left; the mass balance was still good. This implied that maybe more TBHP was needed for the oxidation of these substrates to obtain more desired products.

To observe the effect of substituents on the reactivity of this oxidation reaction the competitive studies between ethylbenzene and 1-bromo-2-ethylbenzene, ethylbenzene and 1-ethyl-2-nitrobenzene, ethylbenzene and ethyl-4-ethylbenzoate were investigated. The results are demonstrated in Table 3.17.

Table 3.17 Competitive studies on the oxidation of 1-bromo-2-ethylbenzene, 1-ethyl-2-nitrobenzene and ethyl-4-ethylbenzoate with ethylbenzene

Entry	Substrate	Product(s) (%)
1		 (25.94) , (30.92)
2		 (37.34) , (0.06)
3		 (25.35) , (55.85)

Reaction conditions : substrate (5.0 mmol each), chromium(III) stearate (0.2 mmol), TBHP (9 mmol), and isoctane 5 mL at 70°C for 24 h.

^aYield determined by gas chromatography. ^bIsolated yield

The relative reactivity compared with ethylbenzene was calculated and the results are presented as shown in Table 3.18.

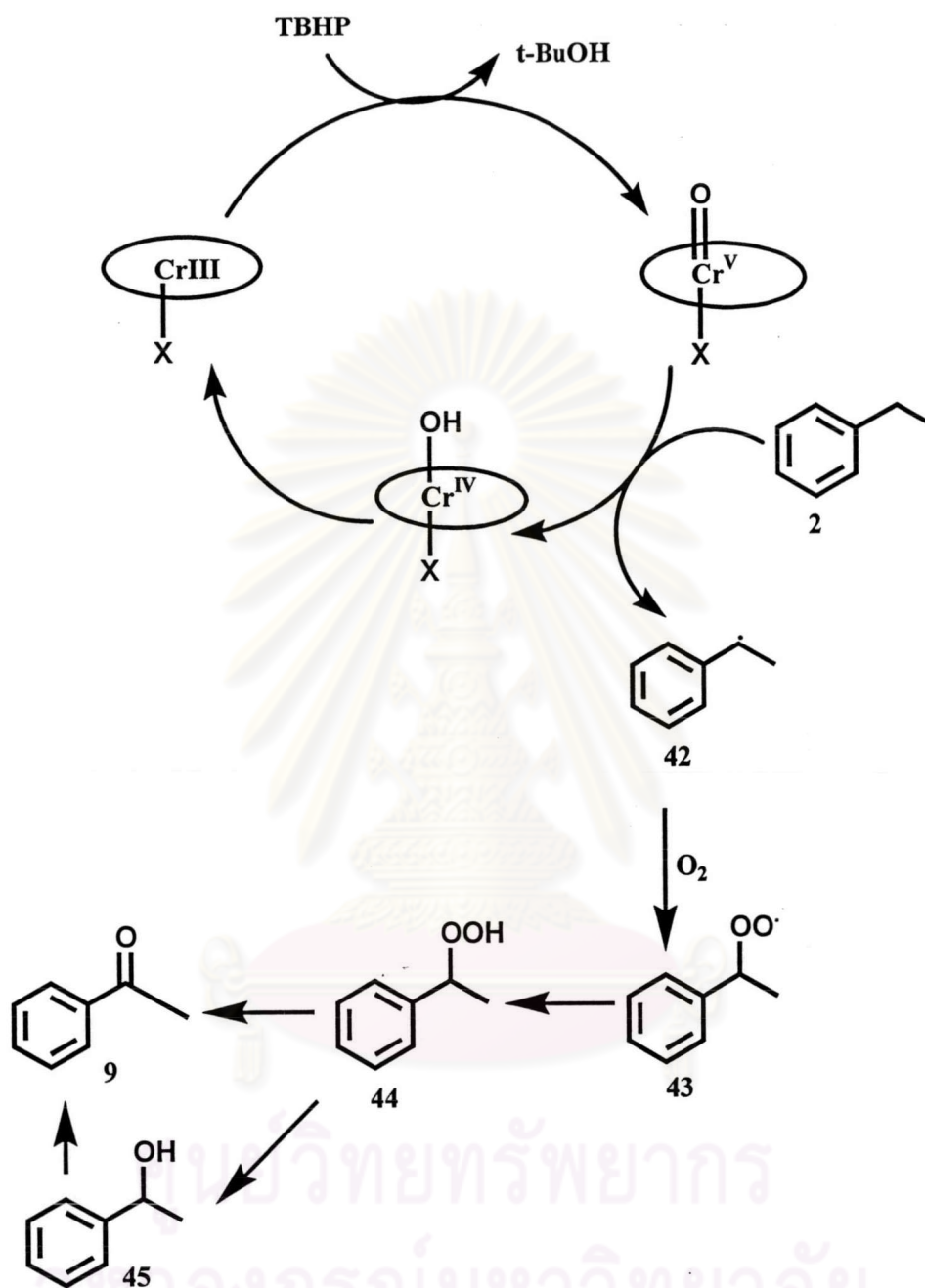
Table 3.18 The relative reactivity of various substituents towards the oxidation of substituted ethylbenzene

Substrate	Relative reactivity
1-ethyl-2-nitrobenzene	0.0
Ethylbenzene	1.0
1-Bromo-2-ethylbenzene	1.2
Ethyl 4-ethylbenzoate	2.2

Electronic effect displayed a major influence on the reactivity of the oxidation reaction. Bearing a withdrawing substituent such as $-\text{NO}_2$ group, the reactivity was dropped, compared with ethylbenzene with the relative reactivity of 0.002. The bromo substituent gave comparable amount of the corresponding carbonyl compound to a reference compound (ethylbenzene), while the ethyl ester group enhanced the oxidation taken place much better approximately twice. One of possible further studies regarding this topic was the structure reactivity relationship. This will provide informative clue for mechanistic study of the reaction.

3.4 Proposed mechanism for the oxidation of benzylic methylene compounds catalyzed by chromium(III) stearate.

The mechanism of the Cr(III) stearate oxidation of benzylic methylene compound employing TBHP as an oxidant was believed to occur *via* free radical pathway in the same fashion proposed in the literature¹⁹. Using ethylbenzene as a representative for benzylic methylene compounds, the proposed mechanism was shown in Scheme 3.1.



$\text{X} = \text{Carboxylate ligands}$

Scheme 3.1 Proposed mechanism for the ethylbenzene oxidation to acetophenone in the presence of $\text{Cr}(\text{st})_3$

The chromium(III) complex was transformed to the corresponding high valent (formally) $\text{Cr}^{\text{V}}=\text{O}$ species. This species was then abstracted benzylic hydrogen of ethylbenzene to form the corresponding benzylic radical (42) and $\text{Cr}^{\text{IV}}\text{X}(\text{OH})$. The generated benzylic radical was rapidly reacted with O_2 to give hydroperoxyl radical intermediate (43), subsequently transform to relatively not stable benzylic hydroperoxide (44). The decomposition of benzylic hydroperoxide (44) yielded acetophenone (9) and 1-phenyl ethanol (45). Under this reaction condition examined, 1-phenylethanol (45) was further oxidized to acetophenone (9) by $\text{Cr}(\text{st})_3$.

3.5 Preliminary study on the use of bi- and tricycatalysts in benzylic oxidation of ethylbenzene.

3.5.1 Effect of bicatalyst

With the attempt to reduce the amount of $\text{Cr}(\text{st})_3$ used and to observe the effect of other metal stearates coupled with $\text{Cr}(\text{st})_3$ as bicatalyst, the following experiments were manipulated. Two ratios (2:1) and (4:1) of $\text{Cr}(\text{st})_3$: other metal stearates were tested in the normal oxidation of ethylbenzene. The results are shown in Table 3.19.

Table 3.19 The effect of bicatalyst on ethylbenzene oxidation

Fraction		$\text{Co}(\text{st})_2$			$\text{Mn}(\text{st})_2$			$\text{Cu}(\text{st})_2$			$\text{Ni}(\text{st})_2$			$\text{Fe}(\text{st})_3$		
Cr	M	9	45	S	9	45	S	9	45	S	9	45	S	9	45	S
2	1	22	5	4	71	-	-	61	2	31	84	3	28	97	3	32
4	1	23	4	6	86	2	43	86	1	86	79	3	27	50	2	25

9: acetophenone, 45: 1-phenylethanol and S: On/ol ratio.

Reaction conditions : ethylbenzene (5.0 mmol), chromium(III) stearate + metal stearate (0.2 mmol), TBHP (9 mmol) and isooctane 5 mL at 70°C for 24 h.

The results revealed that the oxidation of ethylbenzene by bicatalyst gave relatively lower yield and selectivity compared with the system employing only $\text{Cr}(\text{st})_3$. Among the experiments conducted, the systems comprising of $\text{Cr}(\text{st})_3$ and $\text{Fe}(\text{st})_3$ (2:1),

yielded 97% yield of acetophenone. Other systems producing acetophenone more than 80% were Cr(st)₃ and Mn(st)₂ (4:1): 86% yield, Cr(st)₃ and Cu(st)₂ (4:1): 86% yield and Cr(st)₃ and Ni(st)₂ (2:1): 84% yield. Nevertheless, the yield of acetophenone was still less than normal yield derived from the standard reaction (95% yield).

From the above results, the decomposition mechanism of TBHP can also be considered to be as follow in scheme 3.1. The catalytic decomposition of TBHP by metal ions is thought to proceed via the formation of inner sphere and/or outer-sphere complexes of metals ion with TBHP. For the inner-sphere mechanism, the ligand attached to the metal ion must be replaced by the TBHP, *i.e.*, [ML₃Y] + ROOH to [ML(ROOH)] + Y. Such replacement is not required the formation of the outer-sphere complex. Accordingly, decomposition by the outer-sphere mechanism will depend mainly on the redox potential of the complex. On the other hand, decomposition by the inner-sphere mechanism appears to depend on the mobility of the ligands attached to the metal ion, as well as on the redox potential of metal ion.

In the oxidation of ethylbenzene catalyzed by six kinds of metal stearates, the reactivity order of these catalysts is Cr > Mn > Cu ≈ Fe > Ni > Co. This is in agreement with the orders of activities for the decomposition of benzylic hydroperoxide by these catalysts. Therefore, the order of TBHP selectivities and the oxidation rate are thought to arise from the differences in the decomposition rates of hydroperoxide produced in the ethylbenzene oxidation.¹² Thus, bicatalyst gave low yield of desired product than chromium(III) stearate.

3.5.2 Effect of tricatalyst

Tricatalyst systems were tested for the benzylic oxidation of ethylbenzene and the results are demonstrated in Table 3.20 using 1:1:1 ratio of Cr(st)₃ and other two metal stearates.

Table 3.20 The effect of tricatayst on ethylbenzene oxidation

M(st) _n	Mn(st) ₂	Cu(st) ₂	Co(st) ₂	Fe(st) ₃	Ni(st) ₂
Mn(st) ₂		51	20	33	74
Cu(st) ₂			20	47	47
Co(st) ₂				11	24
Fe(st) ₃					75

Reaction conditions : ethylbenzene (5.0 mmol), metal stearate (0.2 mmol), TBHP (9 mmol), and isooctane 5 mL at 70°C for 24 h.

The obtained data did not exhibit impressive results either in terms of %yield of acetophenone or selectivity (not shown) compared with the results derived from only Cr(st)₃ catalyst was utilized.

Eventhough bi- and tricataysts were claimed to provide a better result in certain reactions,¹² they were not appropriate for the catalytic reaction investigating in this study.

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