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Co(II) Catalyzed Solvent Free Auto-Oxidation of Methylbenzenes to Substituted Benzoic Acids Under Phase Transfer Conditions

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Abstract A novel methodology for the solvent free auto-oxidation of methylbenzenes under mild conditions is disclosed. The new scheme is based on a combination of metallic salt (cobalt chloride) and a quaternary ammonium phase transfer catalyst (didecyldimethylammonium bromide) which together form a complex soluble catalyst in the organic phase. Major reaction parameters are studied and optimized and the procedure is applied for the conversion of several substituted toluenes to the corresponding benzoic acids in excellent isolated yields.

Keywords Solvent free oxidation · Auto-oxidation · Substituted benzoic acid · Didecyldimethylammonium bromide · Cobalt chloride · Phase transfer catalysis

1 Introduction

The standard protocol for the catalytic auto-oxidation of methylbenzenes to benzoic acids (e.g. *p*-xylene to terephthalic acid) and numerous other hydrocarbons is based on the combination of *cobalt (II)* and bromide salts as catalysts and on acetic acid as solvent. The prominent Mid-Century (MC) process, developed by Amoco, incorporates co-catalysis by manganese and, at times, zirconium salts as well [1, 2]. Acetic acid is an excellent media for the above process due to the high solubility of the substrate and catalysts and relatively low solubility of the products (thus allowing simple recrystallization and separation of the produced terephthalic acid). It was advocated that the role of acetic acid is not merely as solvent and that it directly participates in the catalytic cycle by providing methyl radicals via decarboxylation which function as chain carriers [1, 2]. Unfortunately, the latter decomposition which is desirable in small quantities becomes a setback example at high temperature, where large portions of the solvent decompose. It was estimated that more than 11% of the annual global production of acetic acid is consumed in the MC terephthalic acid process [1, 2]. Another obvious disadvantage is the highly corrosive nature of the bromide–acetic acid mixtures. The benefits of solvent free methods are thus obvious.

Up to now, preparation of aromatic acids from methylbenzenes via auto-oxidation in non-acidic solvent and/or solvent free systems has rarely been reported. A water/xylene two phase system [3] further improved in the presence of lipophilic quaternary ammonium salts as phase transfer agents was advised by Hronec et al. [4–6] as an alternative to the typical MC procedure. Ishii et al. [7] reported the catalytic oxidation of alkyl benzenes with molecular oxygen using *N*-hydroxy-phthalimide (NHPI) combined with $Co(OAc)_2$ in acetonitrile or, preferably, acetic acid. However, low conversions were reported in oxidation of substrates with electron-attracting groups. Based on the above report, the oxidation of *p*-chlorotoluene yielded only 40% of *p*-chlorobenzoic acid. In a study by Zhang et al. [8] the oxidation of substituted toluenes with molecular oxygen in number of organic solvents were carried out with merely 2% yield of acid. In 1998, Clark et al. reported a new heterogeneous catalyst namely a chemically modified mesoporous silica gel containing

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immobilized chromium ions which was applied for the auto-oxidation of alkyl aromatics at atmospheric pressure in the absence of solvent. Unfortunately, the yields for the corresponding acids are very low even at high temperature and prolonged reaction time [9].

The direct oxidation of substituted toluenes to substituted benzoic acids was studied by Yang et al. [10] using oxygen at one atmosphere in non-acidic solvents such as dichlorobenzene, chlorobenzene and bromobenzene using $Co(C_{18}H_{35}O_2)_2/NH_4Br$ or $Co(OAc)_2/NaBr/AcOH$ as catalysts in the presence of a radical initiator, AIBN. These authors claimed satisfactory yields (up to 96%) of acid for number of substituted toluenes. Recently, Halligudi et al. [11] reported the aerial oxidation of substituted methylbenzenes to oxygenated products using Co/Mn/Br-catalyst system in water–dioxane medium in pressure range of 14–56 bars at 110–150 °C. These authors used the combination of salts of $Co(OAc)_2$, $Mn(OAc)_2$ and NaBr with high bromide concentrations and realized high conversions but low selectivity to the acid and the main products were alcohols and aldehydes.

Phase transfer catalysis is a well established methodology that has transformed the synthetic potential of multiphase reactions such as liquid/liquid and liquid/solid systems [12–15]. Solid–liquid phase-transfer reactions, where the function of the catalyst is to transfer anions from a solid crystalline salt into the organic phase, are usually considered to be transfer controlled under all conditions, [16, 17] although some exceptions are known. Some years ago we studied the ruthenium catalyzed oxidation of 1-phenyl ethanol to acetophenone using didecyldimethylammonium bromide $(DDAB)/H_2O_2$/dichloroethane system and found unusual PTC mechanism which differed from the classical extraction and interfacial mechanism often encountered in PTC oxidations [18]. Recently, we explored the DDAB as universal, robust and highly potent phase transfer catalyst for various organic transformations [19–21]. We have now realized that solid liquid extraction of *Cobalt (II) chloride* by anion exchange with lipophilic ammonium bromide salts in organic solvent generates a very potent auto-oxidation catalyst for methylbenzenes (Eq. 1).

$$Q^+Br^-_{(org)} + CoCl_{2\,(s)} \leftrightharpoons Q^+CoCl_2Br^-_{(org)} \tag{1}$$

2 Experimental

2.1 Materials

A 80% aqueous solution of DDAB was purchased from Alfa Aesar and all other chemicals were procured from Sigma–Aldrich and used without further purification.

2.2 Typical Procedure

A mixture of $CoCl_2 \cdot 6H_2O$ (0.374 mmol, 1 mol%, 0.089 g), DDAB (0.187 mmol, 0.5 mol% 0.095 g) and *p-tert*-butyl toluene (37.4 mmol, 5.55 g) was stirred for 20 min at 120 °C to completely dissolve the catalyst. Oxygen was passed through the solution at the rate of 200 ml/min STP for 3 h maintaining the temperature, 120 °C. Samples were withdrawn from the reaction mixture at regular intervals and analyzed by a gas chromatograph (HP 5890) equipped with a flame ionization detector and a capillary column (5% diphenyl, 95% dimethylpolysiloxane gum, 0.25 mm thickness and 30 m long). After completion of the reaction, the reaction mixture (which solidifies) was cooled to room temperature and washed with water (25 ml × 4) to remove the DDAB and $CoCl_2$ catalysts and solid product vacuum dried for 5 h. The solid product (6.2 g, 93% yield) of practically pure *p-tert*-butyl benzoic acid (93% yield) was positively identified by GC/MS (HP-G1800B) analysis, melting point (163–164 °C) and had 1H NMR fitting.

2.3 Identification Data for the Compounds Given in Table 2

Entry 1 (*p-tert*-butylbenzoic acid): melting point (165 °C); 1H NMR ($CDCl_3$) $\delta = 1.34$ (S, 9H), 7.47 (D, 2H), 8.01 (D, 2H), 10.01 (S, 1H).

Entry 2 (*o*-toluic acid): melting point (106 °C); 1H NMR ($CDCl_3$) $\delta = 2.64$ (S, 3H), 7.24 (D, 1H), 7.25 (T, 1H), 7.32 (T, 1H), 8.0 (D, 1H), 11.74 (S, 1H).

Entry 3 (*p*-toluic acid): melting point (179 °C); 1H NMR (DMSO-d_6) $\delta = 2.38$ (S, 3H), 7.39 (D, 2H), 7.86 (D, 2H), 12.79 (S, 1H).

Entry 4 (3,5-dimethylbenzoic acid): melting point (170 °C); 1H NMR ($CDCl_3$) $\delta = 2.36$ (S, 6H), 7.24 (S, 1H), 7.75 (S, 2H), 12.7 (S, 1H).

Entry 5 (4-chlorobenzoic acid): melting point (241 °C); 1H NMR (DMSO-d_6) $\delta = 5$ (S, 1H), 7.59 (D, 2H), 17.99 (D, 2H).

Entry 6 (2-chlorobenzoic acid): melting point (142 °C); 1H NMR (DMSO-d_6) $\delta = 7.44$ (T, 1H), 7.55 (T, 1H), 7.56 (D, 1H), 7.80 (D, 1H), 13.43 (S, 1H).

Entry 7 (4-bromobenzoic acid): melting point (245 °C); 1H NMR (DMSO-d_6) $\delta = 7.72$ (D, 2H), 7.88 (D, 2H), 13.20 (S, 1H).

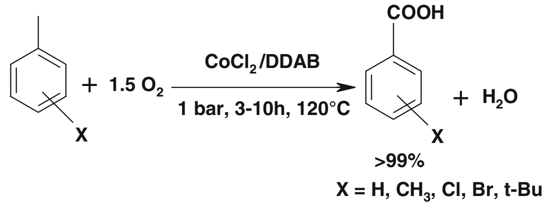
Entry 8 (2,4-dichlorobenzoic acid): melting point (158 °C); 1H NMR ($CDCl_3$) $\delta = 7.53$ (D, 1H), 7.72 (S, 1H), 7.85 (D, 1H), 13.52 (S, 1H).

2.4 Catalyst Regeneration

Regeneration of the combination catalyst was done by the simple separation procedure using an organic and aqueous phases. The metal chloride and the phase transfer agent were brought to aqueous phase, which was evaporated to dryness and recovered the catalyst without any loss of activity.

3 Results and Discussion

In a typical example, a mixture of 89 mg (0.374 mmol) cobalt chloride hexahydrate and 76 mg (0.187 mmol) of DDAB in 5.54 g (37.4 mmol) of *p-tert*-butyltoluene (TBT) was stirred in a 20 ml test tube for 30 min until complete dissolution was observed. Maintaining the mixture at 120 °C, oxygen was passed through the solution at a rate of 200 ml/min for 3 h. After cooling, GC analysis of the product confirmed complete conversion of TBT with >99% selectivity to the corresponding benzoic acid (Eq. 2).



(2)

GC analyses of samples withdrawn from the above reaction mixture in the course of the process yielded the profile presented in Fig. 1. It is apparent that the reaction is consecutive in nature with the intermediate formation of *p-tert*-butylbenzaldehyde which reaches a maximum after 30 min. Traces of *p-tert*-butylbenzyl alcohol could also be detected. No other intermediates were observed in the mixture at any time during the reaction.

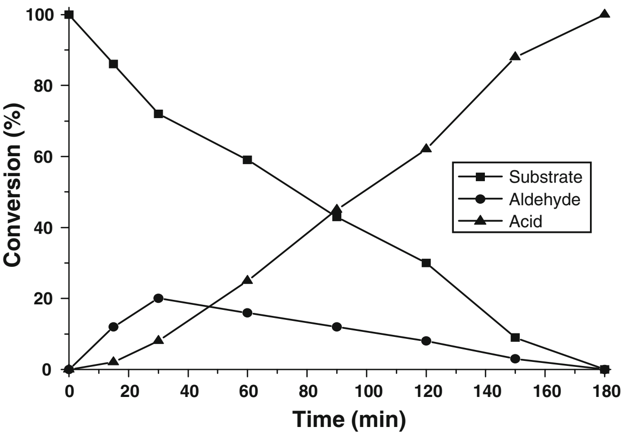


Fig. 1 Typical kinetic profile of reaction. Experimental conditions: *p-tert*-butyl toluene (37.4 mmol); $CoCl_2{\cdot}6H_2O$ (1 mol%, 0.374 mmol); DDAB (0.5 mol %, 0.187 mmol); O_2 (200 ml/min); temperature (120 °C)

Some experimental parameters were assessed for their effect on the reaction progress. Results are summarized in Table 1. Entries 1–5 examine the effect of PTC (DDAB) concentration while keeping all other reaction conditions constant. The results show that increasing the PTC

Table 1 Reaction parameters optimization studies in oxidation of *p-tert*-butyl toluene to *p-tert*-butylbenzoic acid as a model reaction

Entry	Optimization parameter	Acid conversion (%)[a]	Aldehyde conversion (%)[a]
PTC concentration (DDAB, mol%)[b]			
1	0	0	0
2	0.1	47	7
3	0.5	62	8
4	1.0	25	8
5	2.0	0	0
Catalyst concentration ($CoCl_2{\cdot}6H_2O$, mol%)[c]			
6	0	0	0
7	0.2	60	2
8	0.5	60	6
9	1.0	62	8
10	2.0	61	13
Reaction temperature (°C)[d]			
11	80	0	0
12	100	33	14
13	120	64	12
14	130	62	8
PTC structure effect[e]			
15	DDAB	62	8
16	TOAB	32	18
17	THAB	27	19
18	Aliquat 336	25	7
Oxygen flow rate (ml/l)[f]			
19	30	32	12
20	50	40	12
21	100	51	11
22	200	62	8

[a] Conversions based on GC with area minimization

[b] Reaction conditions: *p-tert*-butyl toluene (37.4 mmol); $CoCl_2.6H_2O$ (1 mol%, 0.374 mmol); O_2 (200 ml/min); time (2 h); temperature (130 °C)

[c] Reaction conditions: *p-tert*-butyl toluene (37.4 mmol); DDAB/$CoCl_2{\cdot}6H_2O$ (1:2); O_2 (200 ml/min); time (2 h); temperature (130 °C)

[d] Reaction conditions: *p-tert*-butyl toluene (37.4 mmol); DDAB (0.5 mol%, 0.187 mmol); $CoCl_2 \cdot 6H_2O$ (1.0 mol%, 0.374 mmol); O_2 (200 ml/min); time (2 h)

[e] Reaction conditions: *p-tert*-butyl toluene (37.4 mmol); PTC (0.5 mol%, 0.187 mmol); $CoCl_2{\cdot}6H_2O$ (1.0 mol%, 0.374 mmol); O_2 (200 ml/min); time (2 h); temperature (130 °C)

[f] Reaction conditions: *p-tert*-butyl toluene (37.4 mmol); DDAB (0.5 mol%, 0.187 mmol); $CoCl_2{\cdot}6H_2O$ (1.0 mol%, 0.374 mmol); time (2 h); temperature (130 °C)

concentration from 0 to 0.5 mol% increased the reaction rate and the acid conversion from 0 to 62% but did not affect much the aldehyde conversion. Further increase of the concentration of PTC showed the inverse correlation with reaction rate decreased with DDAB concentration was increased above 0.5 mol% relative to the substrate. The reaction came to a stall at 1 mol% of DDAB. We attribute this effect to the known property of quaternary ammonium salts as radical inhibitors [22].

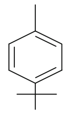
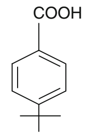
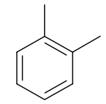
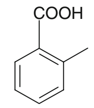
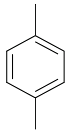
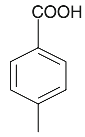
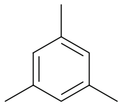
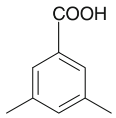
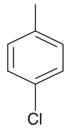
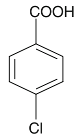
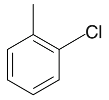
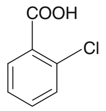
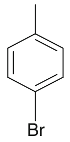
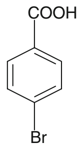
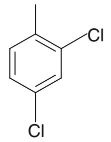
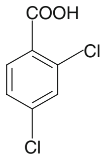
With regard to the $CoCl_2$ concentration the results (Entries 6–10) indicate that the oxidation reaction did not occur in the absence of metal catalyst. Increasing the concentration of the metal did not affect the reaction rate. On the other hand, it is seen that increasing the metal concentration increased the intermediate aldehyde yield. This is an interesting phenomenon that can be utilized in the syntheses of benzaldehydes.

The influence of temperature on the oxidation of *p-tert*-butyl toluene was studied by varying the temperature from 80 to 130 °C (Entries 11–14). From the results it is seen that the maximum oxidation rate was observed at 120 °C. The auto-oxidation process (Eq. 2) is characterized by a short induction period (see Fig. 1). We have noticed that increasing the temperature decreased the induction time until it totally disappears above 130 °C. This study further showed the integrated first order rate law. The calculated activation energy for this particular reaction was 2.349 kcal/mol. As shown in Fig. 1, complete conversion is obtained after 3 h with 100% selectivity for the acid using minimum catalyst concentration (0.1 mol%) that yielded turn over frequency (TOF) of 0.092 s^{-1}.

The effect of different PTC structures has been studied by four different quaternary ammonium salts and the results are shown in Table 1 (Entries 15–18). The symmetrical quaternary salts tetraoctylammonium bromide (TOAB) and tetrahexylammonium bromide (THAB) exhibited about half the reaction rate achieved by DDAB under identical conditions. The low performance of Aliquat 336 can be attributed to the absence of bromide anion. The reactivity of chloride radical towards the hydrogen abstraction is low relative to bromide radical [22]. In the past we have ascribed the unique performance of DDAB in metal catalyzed phase transfer reactions to the formation of distinctive vesicular structures within the organic phase which maintain the metal catalyst in a particular unique assembly [18].

The dependence of oxidation rate on oxygen flow rate was investigated in the range of 30–200 ml/min (Entry 19–22). Based on these results we concluded that increasing the oxygen flow rate increased the oxidation rate. While decreasing the flow rate below 50 ml/min affected the induction time to increase. This can indicate that the effective concentration of oxygen is critical for initiating the reaction and the overall rate. The very low activation

Table 2 Synthesis of substituted benzoic acids using DDAB as PTC and $CoCl_2$ as catalyst[a]

Entry	Substrate	Time (h)	Temperature (°C)	Product	Yield (%)[b]
1		3	130		99
2		5	110		98
3		4	110		96
4		4	115		95
5		7	130		98
6		10	130		97
7		15	130		95
8		8	130		97

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[a] Reaction conditions: substrate (37.4 mmol); DDAB (0.5 mol%, 0.187 mmol); $CoCl_2{\cdot}6H_2O$ (1 mol%, 0.374 mmol); O_2 (200 ml/min)

[b] Isolated yields

energy measured (2.349 kcal/mol) clearly suggest a gas/liquid mass transfer controlled process.

Employing the optimized reaction conditions, we studied the $CoCl_2$/DDAB catalyzed solvent free oxidation of eight different substituted toluenes to benzoic acids and realized complete conversions and >95% isolated yields in all the examples studied (Table 2). In the cases of *ortho*- and *para*- xylenes only one methyl group was oxidized under our conditions producing the corresponding toluic acids (Entries 2–3) similar behaviour was observed with mesitylene (Entry 4). Longer reaction time was required for the halogen substituted toluenes (Entries 5–8).

4 Conclusions

In conclusion, a practical solvent free oxidation of substituted methylbenzenes has been developed using combination of DDAB as a phase transfer agent and $CoCl_2$ as metal oxidation catalyst.

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