Clean Synthesis of 3,3′,5,5′-Tetra-*tert*-butyl-4,4′-diphenoquinone from the Oxidative Coupling of 2,6-Di-*tert*-butylphenol Catalyzed by Alkali-promoted Cu–Mg–Al Hydrotalcites in the Presence of Molecular Oxygen

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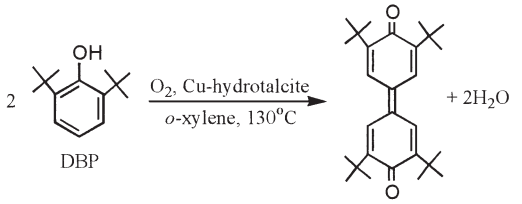
2,6-Di-*tert*-butylphenol is selectively transformed to 3,3′,5,5′-tetra-*tert*-butyl-4,4′-diphenoquinone in the presence of molecular oxygen using alkali-promoted Cu–Mg–Al hydrotalcites as recyclable heterogeneous catalysts.

3,3′,5,5′-Tetra-*tert*-butyl-4,4′-diphenoquinone (TBDPQ) is a valuable raw material for highly functionalized photosensitizers.[1] TBDPQ can be conventionally synthesized by the liquid-phase oxidative coupling of 2,6-di-*tert*-butylphenol (DBP) using stoichiometric inorganic oxidants,[2] that produces copious amounts of wastes. With ever-growing environmental issues of chemical processes,[3] much attention has been paid to the use of molecular oxygen as a "green" oxidant to achieve transformation of DBP to TBDPQ in the presence of metal catalysts.[4,5] Typical examples are copper(II)-amine complexes coupled with a strong base such as KOH. Tsuruya et al. tried to heterogenize the Cu complex catalysts on the surface of poly(4-vinylpyridine)[6] and mesoporous silicate MCM-41 for the liquid-phase oxidation of DBP in the presence of potassium compounds.[7] However, the oxidation by both catalysts needs a chlorinated solvent of $CHCl_3$. Moreover, the TBDPQ yield resulted in only 40%, where the Cu/MCM-41 catalyst could not be reused.[7]

Our approach to developing a highly efficient and recyclable heterogeneous catalyst in the TBDPQ synthesis is incorporation of Cu^{II} species into inorganic base crystals as macroligands. Hydrotalcites, consisted of a positively charged Brucite-layer and interlayer of $CO_3{}^{2-}$ species,[8] have surface base sites.[9] Further, Mg and/or Al cations, composing the Brucite-layer, can be replaced with various metal cations as the catalytically active centers.[10] We report here a clean and simple synthesis of TBDPQ from the oxidative coupling of DBP under an O_2 atmosphere using an alkali-promoted Cu-exchanged hydrotalcite, which acts as a recyclable heterogeneous catalyst (eq. 1).



DBP

TBDPQ

(1)

The hydrotalcite was prepared according to the modified method in the literature.[8] A representative procedure is for K/Cu–Mg–Al–CO_3. A mixture of $CuCl_2{\cdot}2H_2O$ (12.9 mmol), $MgCl_2{\cdot}6H_2O$ (129.6 mmol), and $AlCl_3{\cdot}H_2O$ (43.2 mmol) was dissolved in 120 mL of distilled water. A 120 mL of an aqueous solution of Na_2CO_3 (0.224 mol) and NaOH (0.39 mol) was slowly added to the above solution, and then the resultant mixture was heated at 65 °C for 18 h with vigorous stirring. The obtained slurry was filtered, and washed with distilled water and drying at 100 °C for 15 h to give 12.0 g of Cu–Mg–Al–CO_3. A 2.0 g of the Cu-hydrotalcite was soaked in 1 M aqueous KOH solution (20 mL) for 2 h, followed by filtration, washing, and drying afforded a gray powder of K/Cu–Mg–Al–CO_3 sample. The hydrotalcite structure of the gray powder was confirmed by its XRD pattern, and the basal spacing was 7.9 Å. [Anal. Calcd for $K_{0.14}Mg_{4.89}Al_{1.0}Cu_{0.5}(OH)_{12.9}0.49CO_3{\cdot}nH_2O$ (n = 5): K, 1.1; Mg, 22.8; Al, 5.2; Cu, 6.1. Found: K, 1.08; Mg, 22.7; Al, 5.2; Cu, 6.2 wt%.] A typical example for the oxidation of DBP is as follows. Into a reaction vessel were placed DBP (1.24 g, 6 mmol), K/Cu–Mg–Al–CO_3 (1.20 g, Cu: 1.2 mmol), and *o*-xylene (15 mL). The heterogeneous mixture was then stirred at 130 °C under an O_2 atmosphere. After 10 h, the hydrotalcite was separated by filtration. LC analysis of the filtrate[11] showed a quantitative yield of TBDPQ. Column chromatography of the filtrate on silica, followed by recrystallization from ethanol gave 1.18 g of TBDPQ (96% yield). The isolated hydrotalcite was washed with methanol, and soaked in 20 mL of 1 M aqueous KOH solution. After filtration, the solid was washed with water and dried at 100 °C, which could be reused keeping its activity and selectivity for the above oxidative coupling reaction; the yields of TBDPQ in the first and second recycle experiments were over 94%, respectively.

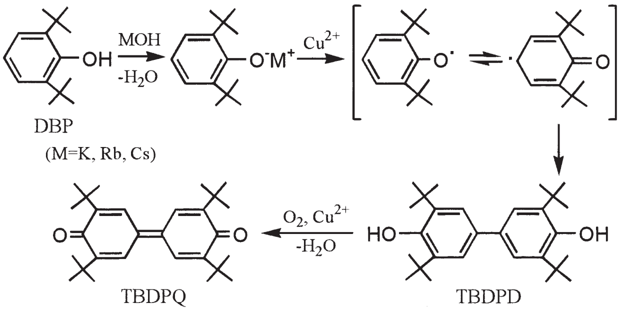
The oxidation of DBP was carried out using various hydrotalcites under an O_2 atmosphere, which is summarized in Table 1. Generally, major products under the above conditions were TBDPQ and 3,3′,5,5′-tetra-*tert*-butyl-4,4′-biphenyldiol (TBDPD) (Scheme 1). Notably, the Cu–Mg–Al–CO_3 hydrotalcites combined with K, Cs, and Rb cations were found to be highly active catalysts for the oxidative coupling of DBP to TBDPQ (entries 1, 4, and 5). These catalysts were more effective than the corresponding Cu-free Mg–Al–CO_3 hydrotalcites (entries 10–12). In the case of the alkali-free Cu–Mg–Al–CO_3 hydrotalcite, the yield of TBDPQ was quite low (entry 9). Further, the oxidations in the second and third runs using the spent K/Cu–Mg–Al–CO_3 catalyst gave similar TBDPQ yields (entries 2 and 3).[12]

In the oxidation of DBP by the Cu catalyst, the role of KOH is generally considered to be deprotonation of DBP into a K-phenolate species, which is subsequently oxidized by Cu^{II} to afford radical intermediates of carbon–carbon coupling.[4a,7] A

Table 1. Aerobic oxidation of 2,6-di-*tert*-butylphenol (DBP) catalyzed by various hydrotalcites[a]

Entry	Catalyst	DBP conv./%[b]	Yield/%[b]	
			TBDPQ	TBDPD[c]
1	K/Cu–Mg–Al–CO_3	99	99(96)[d]	0
2	K/Cu–Mg–Al–CO_3[e]	98	95	3
3	K/Cu–Mg–Al–CO_3[f]	98	94	4
4	Cs/Cu–Mg–Al–CO_3	100	97	1
5	Rb/Cu–Mg–Al–CO_3	98	98	0
6	Rb/Cu–Mg–Al–CO_3[e]	98	92	4
7	Na/Cu–Mg–Al–CO_3	87	61	25
8	Li/Cu–Mg–Al–CO_3	79	52	26
9	Cu–Mg–Al–CO_3	21	7	13
10	K/Mg–Al–CO_3	28	6	22
11	Cs/Mg–Al–CO_3	9	7	2
12	Rb/Mg–Al–CO_3	9	7	2
13	Li/Mg–Al–CO_3	10	8	2
14	Na/Mg–Al–CO_3	16	5	11

[a] Reaction conditions: 2,6-di-*tert*-butylphenol (1.24 g, 6 mmol), catalyst (1.2 g), *o*-oxylene (15 mL), O_2 flow, 130 °C, 10 h. [b] Conversion and yield were detemined by LC using an internal standard method. [c] 3,3′,5,5′-tetra-*tert*-butyl-4,4′-biphenyldiol. [d] A value in parenthesis is an isolated yield. [e] Reuse-1. [f] Reuse-2.



Scheme 1.

resultant Cu^I is reoxidized to Cu^{II} by O_2. In a similar fashion, we propose a catalytic cycle of this DBP oxidation using the alkali-promoted Cu-hydrotalcite as shown in Scheme 1. DBP is facilely deprotonated by alkali hydroxides on the hydrotalcite surface, giving the phenolate species. The Cu^{II} species immobilized in the Brucite-layer efficiently oxidizes the phenolate anion, and also TBDPD into TBDPQ in the presence of O_2. The divalent Cu cations are incorporated into base hydrotalcites as a macroligand, therefore Cu^{II}-exchanged hydrotalcite acted as a recyclable catalyst.

In conclusion, we have found a clean synthesis of TBDPQ by the oxidative coupling of DBP using a Cu^{II}-exchanged hydrotalcite catalyst. This heterogeneous catalyst system has the following advantages: (1) use of O_2 as an ultimate oxidant, (2) nonpolluting and reusable catalyst, and (3) simple work-up procedures.

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12 A slight decrease in the yield of TBDPQ may be attributed to a loss of the ability of the immobilized Cu^{II} species to oxidize TBDPD.