A "Green" Route to Adipic Acid: Direct Oxidation of Cyclohexenes with 30 Percent Hydrogen Peroxide

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Currently, the industrial production of adipic acid uses nitric acid oxidation of cyclohexanol or a cyclohexanol/cyclohexanone mixture. The nitrous oxide emission from this process measurably contributes to global warming and ozone depletion. Therefore, the development of an adipic acid production process that is less damaging to the environment is an important subject in chemical research. Cyclohexene can now be oxidized directly to colorless crystalline adipic acid with aqueous 30 percent hydrogen peroxide under organic solvent- and halide-free conditions, which could provide an ideal solution to this serious problem.

Adipic acid is an important chemical, whose production is necessary for the manufacture of nylon-6,6, which is used in carpet fibers, upholstery, tire reinforcements, auto parts, apparel, and other products. Most industrial processes of adipic acid production use nitric acid oxidation of cyclohexanol, cyclohexanone, or both, which are accessible from benzene (*1*). The worldwide industrial adipic acid production of up to 2.2 million metric tons per year (*1, 2*) relies on a refined technology that minimizes the emission of nitrous oxide (N_2O) (*3*), an inevitable stoichiometric waste (*2*) that is commonly thought to cause global warming and ozone depletion (*4*) as well as acid rain and smog. Despite the efficient recovery or recycling of N_2O, ~400,000 metric tons are still emitted each year, which corresponds to 5 to 8% of the worldwide anthropogenic emission of N_2O. Therefore, the development of environmentally conscious practical procedures for the oxidation of six-carbon feedstocks is highly desirable, particularly for the medium- to large-scale synthesis of adipic acid and its derivatives (*5*).

Aqueous H_2O_2 is an ideal clean oxidant if the oxidation reaction is achieved with a H_2O_2 concentration of <60%. The use, storage, and transportation of higher concentrations of H_2O_2 are not desirable for safety reasons (*6*). We recently developed practical oxidation methods with aqueous 30% H_2O_2 in the presence of small amounts of Na_2WO_4 and $[CH_3(n\text{-}C_8H_{17})_3N]HSO_4$ as a phase-transfer catalyst (PTC) (*7, 8*). This aqueous, organic biphasic reaction enables the high-yield epoxidation of olefins, either terminal or internal (*7*), as well as the oxidation of primary and secondary alcohols (*8*) under conditions that are entirely free of organic solvents and halides. The high catalytic efficiency can be obtained only by using a quaternary ammonium hydrogensulfate rather than conventional chlorides as the PTC. Because the oxidation employs acidic conditions (*9*), certain epoxides undergo hydrolytic ring cleavage readily. This effect may be a problem for some epoxide syntheses, but it provides an opportunity for the direct conversion of olefins to carboxylic acids. Here, we describe a practical method to oxidize cyclohexenes to crystalline adipic acid and its derivatives.

When a mixture of cyclohexene (**1**, Fig. 1) (*10*), 30% H_2O_2, $Na_2WO_4 \cdot 2H_2O$, and $[CH_3(n\text{-}C_8H_{17})_3N]HSO_4$ as the PTC (the olefin:W:PTC molar ratio is 100:1:1) was stirred in air at 1000 rpm and at a temperature of 75° to 90°C for 8 hours, adipic acid (**2**) was formed in 93% yield [as determined by gas chromatographic (GC) analysis]. The collection of the crystalline product by filtration followed by drying in air produced colorless, analytically pure **2** in 90% yield. The oxidation of 100 g of **1** produced 161 g of crystalline **2**. The aqueous phase of the reaction mixture can be reused with a renewed PTC and 30% H_2O_2 to produce **2** in 78% yield (*11*). This catalytic system does not induce the unproductive decomposition of H_2O_2 to any great extent and enables the economic use of the oxidant, namely, 4.0 to 4.4 mol of H_2O_2 per 1 mol of **1** for four oxidation steps. With 60% H_2O_2, the product yield was decreased to some extent. The efficiency of this halide-free, biphasic oxidation procedure compares well with the efficiency of earlier methods that used 35% H_2O_2 and $(N\text{-}n\text{-}C_{16}H_{33}\text{pyridinum})_3(PW_{12}O_{40})$ or H_2WO_4 in *tert*-butyl alcohol (*12*) or with the efficiency of other patented procedures that used either 40% H_2O_2 and $[CH_3(n\text{-}C_8H_{17})_3N]_3PO_4[W(O)(O_2)_2]_4$ in 1,2-dichloroethane (*13*) or 60% H_2O_2 and H_2WO_4 (*14*).

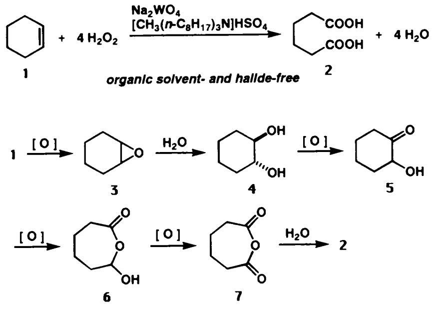

Fig. 1. The reaction pathway for the direct oxidation of cyclohexene to adipic acid with aqueous H_2O_2.

A minimum pathway from **1** to **2** is shown in Fig. 1. The transformation is achieved through multiple steps involving three kinds of oxidative reactions (olefin epoxidation, two alcohol oxidations, and Baeyer-Villiger oxidation) and hydrolyses. The efficiency of this adipic acid synthesis is based on factors including a ready epoxidation of cyclic olefins, a rapid hydrolytic ring opening of the strained bicyclic epoxide **3**, a facile dehydrogenation of a secondary alcohol **4** and hemiacylal **6** [all of which are characteristics of the present oxidation procedure (*7, 8*)], a high migratory propensity of a hydroxy-bearing alkyl group in the Baeyer-Villiger oxidation of the α-hydroxy ketone **5** (*15, 16*), and a ready crystallization of **2** from aqueous solution. The intermediates **3** to **5** were detected by GC analysis of reaction aliquots, and separate experiments showed that these compounds were smoothly converted to **2** under comparable oxidation conditions. Many steps in Fig. 1 are facilitated by acidic conditions.

Consistent with this mechanistic scheme, the overall yield of this one-pot, six-step conversion is highly dependent on the ring size and substitution patterns of the olefinic substrates. Examples of carboxylic acids derived from cyclic olefins are shown in Fig. 2. This procedure is equally applicable to the oxidation of substituted cyclohexenes. Thus, the reaction of cyclohexene-4,5-dicarboxylic anhydride (100 g) with 30% H_2O_2 (328 g) in the presence of a W catalyst and a PTC followed by the concentration of the reaction mixture produced crystalline *meso*-1,2,3,4-butanetet-

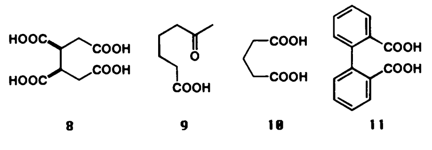

Fig. 2. Examples of carboxylic acids derived from cyclic olefins.

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racarboxylic acid (**8**) (141 g) directly in 91% yield, which is an important intermediate for synthetic resins and flexibilizers. Cyclohexene-*cis*-4,5-dicarboxylic acid was also convertible to **8** in 96% yield (*17*). Under standard conditions, 1-methylcyclohexene was converted to 6-oxoheptanoic acid (**9**) in 59% yield. Oxidation of cyclopentene (100 g) with 30% H_2O_2 (736 g), $Na_2WO_4 \cdot 2H_2O$ (4.84 g), and $[CH_3(n\text{-}C_8H_{17})_3N]HSO_4$ (6.84 g) at 70° to 90°C for 13 hours produced crystalline glutaric acid (**10**) (175 g) in 90% yield. Oxidative cleavage of the C(9)–C(10) bond of phenanthrene with the aid of (aminomethyl)phosphonic acid (*7*) produced 2,2′-biphenyldicarboxylic acid (**11**) in 41% yield. Cyclooctene and 1-octene produced suberic acid and heptanoic acid in only 9 and 36% yield, respectively, because the initially formed epoxides are resistant to hydrolytic cleavage.

This solvent- and halide-free oxidation of cyclohexene and cyclopentene is clean, safe, and reproducible, with conditions that are less corrosive than those of the nitric acid oxidation. No operational problems are foreseen for a large-scale version of this "green" process, and technical refinement should further increase the synthetic efficiency. The worldwide chemical industry is directing extensive efforts toward the efficient production of H_2O_2 as a clean, selective oxidant (*18*). Thus, this environmentally conscious, non–nitric acid route to adipic acids will be attractive only if the cost of H_2O_2 is considerably reduced or if the regulations regarding N_2O emission become more stringent.

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Onset of Catalytic Activity of Gold Clusters on Titania with the Appearance of Nonmetallic Properties

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Gold clusters ranging in diameter from 1 to 6 nanometers have been prepared on single crystalline surfaces of titania in ultrahigh vacuum to investigate the unusual size dependence of the low-temperature catalytic oxidation of carbon monoxide. Scanning tunneling microscopy/spectroscopy (STM/STS) and elevated pressure reaction kinetics measurements show that the structure sensitivity of this reaction on gold clusters supported on titania is related to a quantum size effect with respect to the thickness of the gold islands; islands with two layers of gold are most effective for catalyzing the oxidation of carbon monoxide. These results suggest that supported clusters, in general, may have unusual catalytic properties as one dimension of the cluster becomes smaller than three atomic spacings.

An atomic-level understanding of structure-activity relations in surface-catalyzed reactions is one of the most important goals of surface science studies related to heterogeneous catalysis. Planar model catalysts (*1–3*) consisting of metal clusters supported on thin (2.0 to 10 nm) oxide films simulate the critical features of most practical high surface area metal catalysts, yet are tractable for a wide range of surface analytical probes. The oxide films (SiO_2, Al_2O_3, TiO_2, MgO) used are thin enough to be suitably conductive for use with various electron spectroscopies in-

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