

Osmium Tetroxide Anchored to Porous Resins Bearing Residual Vinyl Groups: A Highly Active and Recyclable Solid for Asymmetric Dihydroxylation of Olefins

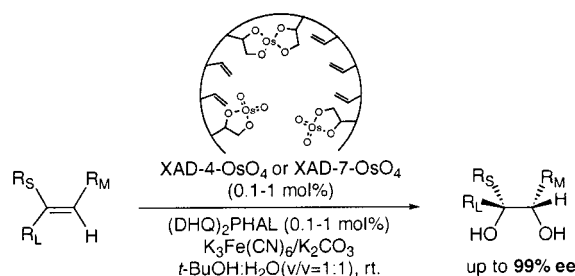
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ABSTRACT



OsO₄ was simply immobilized onto resins such as Amberlite XAD-4 or XAD-7 bearing residual vinyl groups. The resulting osmylated resins are air-stable, nonvolatile, and much easier to handle than their homogeneous counterpart (OsO₄). Moreover, the resin-bound OsO₄ exhibited excellent catalytic activity in the asymmetric dihydroxylation of olefins and was easily recovered and reused in five consecutive reactions without any significant decrease in product yield. Turnover time, however, was significantly increased for the fourth and fifth reactions.

During the past decade, a number of powerful catalytic asymmetric reactions have emerged as a result of the growing need to develop more efficient and practical synthetic methods for biologically active compounds.¹ Although a number of homogeneous chiral catalysts have gained wide acceptance in terms of efficiency and selectivity, the contribution of asymmetric catalysis in the overall production of chiral chemicals is much lower than originally expected. One of the major drawbacks of homogeneous catalysis is the need to separate relatively expensive catalysts from the reaction mixture at the end of the process. One of the most

promising solutions to this problem seems to be the immobilization of the soluble catalysts to an insoluble matrix,² ideally without any reduction of catalytic performance (activity and selectivity, etc.) with respect to the homogeneous phase.

The Os-catalyzed asymmetric dihydroxylation (AD) of olefins provides one of the most elegant methods for the synthesis of chiral vicinal diols.³ Although the AD reaction can be applied to the synthesis of chiral drugs, natural products, fine chemicals, etc., the high cost of osmium and the chiral ligands as well as the high toxicity and volatility of the osmium component have made large-scale industrial

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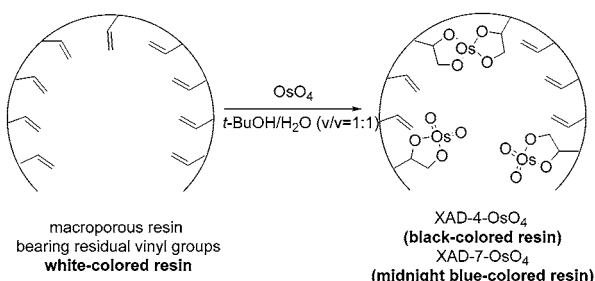
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applications with these reagents difficult. To explore the possibility of repetitive use of both catalytic components, several attempts to immobilize this catalytic system have been made.^{4–6} Early attempts to immobilize OsO₄ on solid-supported alkaloid ligands failed due to severe osmium leaching.⁴ Recently, Kobayashi reported that microencapsulated OsO₄ in a polymer matrix can be used as a recyclable catalyst.⁵ However, high loading (5 mol %) of osmium is needed to achieve a reasonable reaction rate. Very recently, another approach to immobilize K₂OsO₄·2H₂O has been achieved using an ion-exchange technique on various solid supports.⁶ Although recycling experiments using 1 mol % of this type of immobilized osmium catalyst have been successfully performed for five consecutive reactions, the amount of catalyst is still too large compared to that needed in homogeneous AD reactions. In homogeneous cases, 0.2 mol % osmium is enough to complete most of the reactions.

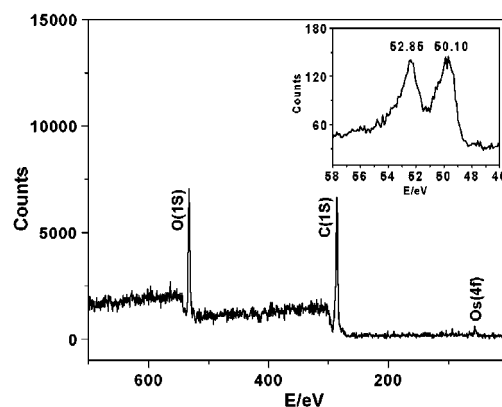
In searching for a more efficient heterogeneous catalytic system for AD reactions, we considered that OsO₄ might be simply immobilized onto nonionic porous resins such as Amberlite XAD-4 (polystyrene-based) and XAD-7 (polyacrylate-based). Synthetic nonionic adsorbents such as XAD-4 and XAD-7 are essentially highly cross-linked macroporous resins bearing residual vinyl groups (from 0.20 to over 0.40 mol of vinyl groups per mole of polymer repeating units).⁷ Thus, our idea was that OsO₄ might be simply anchored to residual vinyl groups within pores of the resins by osmylation (Scheme 1) and freed from the solid

Scheme 1. Preparation of Solid Osmium Catalyst

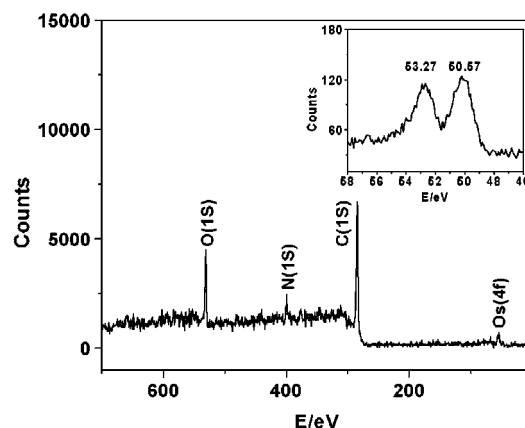


support in situ by an oxidant. After the desired reaction with alkene is complete, the OsO₄ is then taken up by other free vinyl groups on the solid support and thereby immobilized for reuse. Here we report our preliminary results.

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a: XAD-7-Os complex (before use)



b: XAD-7-Os complex (recovered after reaction)

Figure 1. XPS spectra of the XAD-7-Os complex (a, before use; b, recovered after reaction, entry 1 in Table 2).

The polymer-supported osmium catalysts were prepared as follows. Amberlite XAD-4 or XAD-7 (9.50 g)⁸ was added in *t*-BuOH/H₂O (v/v = 1:1, 95 mL) at room temperature, and to this mixture was added 0.98 wt % of aqueous solution of OsO₄ (95 mL). The reaction mixture was stirred for 4 h at room temperature. During the reaction of the resins with OsO₄, the solid turned black (XAD-4) or midnight blue

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(8) Resins were pretreated by Soxhlet extraction with methanol for several days, followed by drying under vacuum.

Table 1. Asymmetric Dihydroxylation Using Amberlite XAD-4 or XAD-7·OsO₄ Complex^a

entry	olefins	resin·OsO ₄ complex					
		XAD-4·OsO ₄			XAD-7·OsO ₄		
		time (h)	yield (%)	ee (%)	time (h)	yield (%)	ee (%)
1	styrene	0.5	92	95	1.5	97	95
2 ^b	styrene	2	91	93	3	98	93
3 ^c	styrene	5	91	93	6	96	92
4	<i>trans</i> -stilbene	8	94	>99	9	94	>99
5	β -methylstyrene	1.5	97	95	3.5	98	94
6	α -methylstyrene	0.5	96	89	2	97	88
7	methyl- <i>trans</i> -cinnamate	3.5	92	>99	4.5	92	>99
8	1-phenyl-1-cyclohexene	4.5	93	97	6	88	93

^a Unless otherwise noted, all reactions were carried out with the olefin (3 mmol), (DHQ)₂PHAL (1 mol %), Amberlite XAD-4·OsO₄ (1 mol %) or Amberlite XAD-7·OsO₄ (1 mol %), K₃Fe(CN)₆/K₂CO₃ (3 equiv), and CH₃SO₂NH₂ (1 equiv), and in *t*-BuOH/H₂O (v/v = 1:1, 15 mL) for 0.5–9 h. The ee was determined by chiral HPLC analysis. ^b (DHQ)₂PHAL (0.5 mol %), Amberlite XAD-4·OsO₄ (0.2 mol %) or Amberlite XAD-7·OsO₄ (0.2 mol %). ^c (DHQ)₂PHAL (0.25 mol %), Amberlite XAD-4·OsO₄ (0.1 mol %) or Amberlite XAD-7·OsO₄ (0.1 mol %).

(XAD-7), while no color developed in the solution. The supported osmium catalyst was filtered, and the filtered resin was then washed with methanol several times and dried in vacuo for 48 h. UV analysis of the filtrate indicated that all OsO₄ used was anchored to the resins (~0.35 mmol of Os per gram of resin). No trace amounts of osmium could be found in filtrates. These results were revalidated by XRF (X-ray fluorescence) analysis of the osmylated resins. In the XPS (X-ray photoelectron spectroscopy) spectra of the resins, Os 4f_{7/2} lines appeared at ~53 eV and ~50 eV (inset of Figure 1). On the basis of these values, it is clear that the osmium tetroxide is reduced to Os(VI) monoglycolate and Os(IV) bisglycolate in the reaction with vinyl groups of resins.⁹

To investigate the catalytic performance of these immobilized catalysts, the AD of styrene was first carried out under the standard K₃Fe(CN)₆ conditions¹⁰ (K₃Fe(CN)₆ (3 equiv), K₂CO₃ (3 equiv), and CH₃SO₂NH₂ (1 equiv) in 1:1 *t*-BuOH/H₂O at room temperature) in the presence of the supported OsO₄ (1 mol %) and (DHQ)₂PHAL (1 mol %). The reaction using these immobilized catalysts was completed within 30 min (XAD-4·OsO₄) and 1.5 h (XAD-7·OsO₄), respectively, to give the desired diol in excellent yields and 95% ee (entry 1 in Table 1). Encouraged by this promising result, we moved to perform AD reaction of styrene with reduced amounts of both osmium and the ligand (entries 2 and 3 in Table 1). As shown in entry 3 in Table 1, even using 0.1 mol % catalyst, the reaction went very smoothly, affording the diol after 5–6 h in excellent yields and ees. On the basis of these results it can be assumed that osmium anchored to resins is highly exposed to the oxidant, and once oxidized, it became free to react with other more readily accessible alkenes and ligand in solution. After the oxidant and starting alkenes are consumed, the residual OsO₄ may form new bonds with less accessible resin-bound vinyl

groups. Our solid osmium catalysts were then applied to the oxidation of other olefins, and the results are summarized in Table 1.

In all cases, the desired diols were obtained in yields and enantioselectivities similar to those obtained in the homogeneous conditions.

Finally, the recyclability of the catalysts was also examined using 1.0 mol % XAD-4·Os. The black-colored resins were recovered by simple filtration after each reaction, which is not possible in a homogeneous process. The alkaloid ligand was also almost quantitatively recovered by simple acid/base extraction. XPS analysis of the recovered resins showed clearly that these recovered resins contain osmium species of +VI and +IV oxidation states (b of Figure 1). The recovered resins along with the replenished chiral ligand were subjected to further AD reactions of styrene. As shown in Table 2, the recovered catalyst could be recycled five times

Table 2. Asymmetric Dihydroxylation of Styrene with Recycled Amberlite XAD-4·OsO₄ or Amberlite XAD-7·OsO₄ Complexes^a

run	resin·OsO ₄ complex					
	XAD-4·OsO ₄ (1 mol %)			XAD-7·OsO ₄ (0.2 mol %)		
	time (h)	yield (%)	ee (%)	time (h)	yield (%)	ee (%)
1	2	93	95	4	98	93
2	2	92	95	6	94	93
3	2.5	90	95	15	73	91
4	6	88	95			
5	24	88	95			

^a Recycling experiments were carried out using 1 mol % XAD-4·OsO₄ or 0.2 mol % XAD-7·OsO₄.

without any significant loss of yields or enantioselectivity. Even in the recycle experiments using 0.2 mol % XAD-7·Os, the osmylated solid maintained its efficiency for nearly three cycles and, thus, the total turnover number (TON) was 1325 (Table 2). To the best of our knowledge, this is the

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highest total TON value ever reached in heterogeneous AD reactions. However, leaching of tiny amounts of OsO_4 into solution has been found, causing increased turnover time upon reuse.

In summary, we have developed a simple method of immobilizing OsO_4 . OsO_4 can be immobilized by mixing with a suspension of resins such as Amberlite XAD-4 or XAD-7 bearing vinyl groups. The resulting osmylated resins are air-stable, nonvolatile, and much easier to handle than their soluble counterpart (OsO_4). Moreover, the OsO_4 derived from these resins exhibited excellent catalytic performances in AD reactions of olefins, indicating little interference from the partially oxidized solid support. After reaction, the recovered osmylated resins could be reused several times without any significant loss of catalytic efficiency. Even in

the recycling experiments using 0.2 mol % XAD-7-Os, the osmylated resin maintained its efficiency for almost three cycles, and thus the total TON was 1325, which is the highest total TON value ever reached in heterogeneous AD reactions. Optimization studies on reaction conditions are currently in progress.

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Supporting Information Available: Experimental procedures and HPLC data of the products. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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