

Chemistry Europe

European Chemical

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Chemistry A European Journal



Accepted Article

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Authors: Shipeng Wu, Yinghao Wang, Qiue Cao, Qihua Zhao, and Wenhao Fang

This manuscript has been accepted after peer review and appears as an Accepted Article online prior to editing, proofing, and formal publication of the final Version of Record (VoR). This work is currently citable by using the Digital Object Identifier (DOI) given below. The VoR will be published online in Early View as soon as possible and may be different to this Accepted Article as a result of editing. Readers should obtain the VoR from the journal website shown below when it is published to ensure accuracy of information. The authors are responsible for the content of this Accepted Article.

To be cited as: Chem. Eur. J. 10.1002/chem.202003915

Link to VoR: https://doi.org/10.1002/chem.202003915



Efficient Imine Formation *via* Oxidative Coupling at Low Temperature Catalyzed by High-Surface-Area Mesoporous CeO₂ with an Exceptional Redox Property

Shipeng Wu,^[a] Yinghao Wang,^[a] Qiue Cao,^[ab] Qihua Zhao,^[a] and Wenhao Fang^{[ab}*[]]

^[a] S. Wu, Y. Wang, Prof. Q. Cao, Prof. Q. Zhao, Dr. W. Fang
 School of Chemical Science and Technology, Key Laboratory of Medicinal Chemistry for
 Natural Resource - Ministry of Education, Functional Molecules Analysis and
 Biotransformation Key Laboratory of Universities in Yunnan Province, Yunnan University, 2
 North Cuihu Road, 650091 Kunming, China
 Email: wenhao.fang@ynu.edu.cn

^[b] Prof. Q. Cao, Dr. W. Fang

National Demonstration Center for Experimental Chemistry and Chemical Engineering Education, Yunnan University, 650091 Kunming, China

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Abstract

A high-surface-area mesoporous CeO_2 (hsmCeO₂) is prepared by a facile organic template-induced homogeneous precipitation method and shows excellent catalytic activity in imine synthesis in absence of base from primary alcohols and amines in air atmosphere at low temperature. In comparison, an ordinary CeO₂ and *hsm*CeO₂ after different thermal treatments are also investigated. XRD, N₂ physisorption, UV-Raman, H₂-TPR, O₂-TPD, EPR and XPS are used to mainly unravel their structural and redox properties. hsmCeO₂ calcined at 400 °C shows the highest specific surface area (158 m² g⁻¹), the highest fraction of surface coordinatively unsaturated Ce³⁺ ions (18.2%), and the highest concentration of reactive oxygen vacancies $(2.4 \times 10^{15} \text{ spins g}^{-1})$. In the model reaction of oxidative coupling of benzyl alcohol and aniline, such an exceptional redox property of the *hsm*CeO₂ catalyst can boost benzylideneaniline formation (2.75 and 5.55 mmol $g_{ceria}^{-1} h^{-1}$) based on a > 99% yield at 60 °C and 80 °C respectively in air with no base additives. It can also work effectively at room temperature of 30 °C, as well as for the gram-grade synthesis. This is one of the best results among all the ceria benchmark catalysts in literature. Moreover, the hsmCeO₂ catalyst displays a wide scope towards primary alcohols and amines with good to excellent yield of imines. The influence of reaction parameters, the reusability of catalyst, and the reaction mechanism are investigated.

Keywords

ceria catalyst; high surface area; imine synthesis; oxidative coupling; oxygen vacancy

Introduction

The fluorite-type ceria (CeO₂) has been widely used as heterogeneous catalyst for various reactions by taking advantages of its oxygen storage and/or oxygen diffusion properties.^[1] The release and uptake of oxygen by ceria enable the redox reactions and the formation of reactive oxygen

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vacancies (V ö) due to the easily reversible redox cycle between Ce³⁺ and Ce⁴⁺ ions, which has been shown to be important for catalytic activity.^[2] Ceria also exhibits good stability owing to its firm fluorite structure. Therefore, the unique surface properties of ceria, i.e., abundant oxygen vacancy and strong oxophilicity, can give rise to an enhancement of adsorption and activation of molecular O₂ and oxygen-containing organic compounds. However, such redox property of ceria is barely used in catalysis at low temperature for organic reactions,^[3] even though oxygen vacancies on ceria are demonstrated to be mobile at room temperature.^[4] In order to enhance the surface redox ability of ceria, various strategies have been used, such as controlling morphologies,^[5] modulating crystal planes,^[6] changing cerium precursors,^[7] doping metals,^[8] and treating with plasma atmospheres.^[9] It is well known for solid catalysts that high surface area usually contain more reactive sites. Thus, preparing high-surface-area ceria can be probably a straighter and simpler way to enrich surface Ce³⁺ ions and oxygen vacancy on ceria, but this remains much challenging. To the best of our knowledge, very few attempts have been successful till date.^[10]

Imines as a major class of nitrogen-containing organic intermediates are widely used in the fields of agriculture, biology, chemistry and pharmacy.^[11] Among various chemical syntheses of imines, the direct coupling of alcohol and amine is regard to be the most promising route.^[12] Because alcohols are usually cheap and readily available and the byproduct of this reaction is water and/or hydrogen. These are in line with the principle of sustainable chemistry. However, how to effectively activate C–H bond in an alcohol and simultaneously stabilize C=N bond in an imine under mild reaction conditions is rather difficult. Metal oxides (Mg, Al, Mn, Fe, Co and Cu) as inexpensive heterogeneous catalysts are highly desirable to oxidative coupling of alcohol and amine, by making full use of their acidic-basic and/or redox properties to activate alcohol and O₂.^[13]

Interestingly, ceria catalysts have been recently explored for imine synthesis on the model

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reaction of oxidative coupling of benzyl alcohol and aniline.^[3, 6-7, 10b, 14]. M. Tamura *et al.* first reported the use of redox property of CeO₂ for this reaction at low temperatures of 30 °C and 60 °C but with moderate to high yields of benzylideneaniline (75% and 96%) in air atmosphere.^[3a] They recently demonstrated in a continuous work on the reaction mechanism that the reactive lattice oxygen (O_{latt.}) species were mobile ones at the redox sites of CeO₂, and the high mobility of O_{latt.} was responsible for the high activity in the reaction.^[14a] Z. Zhang *et al.* investigated the effect of CeO₂ crystal planes and disclosed the (110) plane to be the best among the (110), (100) and (111) planes due to its strongest redox ability and highest concentration of oxygen vacancy. 97% yield of imine was obtained under O₂ atmosphere at 60 $^{\circ}$ C.^[6] L. Geng *et al.* discovered CeO₂ nanorods anchored on mesoporous carbon (CeO₂/MC) as an efficient catalyst, i.e., > 99% yield at 80 °C in O₂. atmosphere. The high activity was dependent on the abundant surface Ce³⁺ ions and the suitable interaction between CeO₂ nanorods and MC support, but unsupported CeO₂ nanorods could only afford 77.6% yield.^[14b] J. Zhang et al. compared three different inorganic cerium precursors for preparation of CeO₂ catalyst and cerium nitrate was found to be the optimal choice probably related with the highest proportion of oxygen vacancy on the prepared CeO₂^[7] H. Zhang *et al.* elucidated the effect of five morphologies for ceria catalysts on their behaviors in the model reaction. The amorphous CeO₂-5 catalyst prepared by precipitation at room temperature can achieve \geq 99% yield of imine in air atmosphere at 30 °C and 60 °C. The higher acidic sites, specific surface area and proportion of surface oxygen were demonstrated to be responsible for its high activity.^[3b] Recently, they reported a CeO₂-P_{fa}-7 catalyst derived from Ce-based organometallic precursor (Ce-MOFs) induced mesoporous CeO₂, giving 92% yield of imine at 60 $\,^{\circ}$ C in air. The catalytic activity was ascribed to the defect-enriched CeO₂ with high specific surface area.^[10b] Y. Long *et at.* developed mesoporous hollow CeO₂ microspheres (mh-CeO₂) catalyst by a novel protective roasting strategy.

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This mh-CeO₂ catalyst showed superior activity (98% yield at 60 $^{\circ}$ C in air) due to its super high specific surface area and mesoporous hollow structure.^[14c] Nonetheless, the reported catalytic systems still have some obvious shortcomings, such as unsatisfying conversion or selectivity, difficulty in reuse of catalysts, complicated morphology-controlled synthesis, and requirement of pure O₂. Moreover, the deep understanding of the reaction mechanism of ceria catalysis at low temperature still remains unclear.

Herein, a high-surface-area mesoporous CeO₂ (*hsm*CeO₂) catalyst was successfully prepared by a facile organic template-induced homogeneous precipitation method. The cheap surfactant hexadecyltrimethylammonium bromide was used as a soft template. This catalyst showed exceptional redox property which can significantly boost imine synthesis from the direct oxidative coupling of alcohol and amine at low temperature in air atmosphere. The catalyst efficiency in form of productivity toward imine ranked among the top for ever-reported ceria catalysts in literature. The influence of preparation method (i.e., organic temperate and calcination temperature) and reaction parameters (i.e., reaction temperature and time, amine/alcohol ratio, reusability and scaling-up test) on the redox property of the *hsm*CeO₂ catalyst was investigated. The structure-activity relationship by combining the catalytic kinetic results and the role of Ce³⁺ ions and oxygen vacancy in CeO₂ was elucidated, which allowed openly discussing the reaction mechanism of CeO₂ catalysis in molecular level.

Results and Discussion

Comprehensive characterizations of hsmCeO₂

The structures of CeO₂ and *hsm*CeO₂-T are analyzed by XRD and N₂ physisorption. As shown in Figure 1a, both CeO₂ and *hsm*CeO₂ present the characteristic pattern due to the cubic CeO₂ phase (JCPDS #43-1002). The diffraction peaks corresponding to the (111), (200), (220), (311), (222),

(400), (311), (420) and (422) planes of CeO₂ are well resolved. The mean crystal size of *hsm*CeO₂ is calculated to be of about 9.8 nm, which is smaller than that of the ordinary CeO₂ (11.9 nm, Table 1). As shown in Figure 1b, when the temperature of thermal treatment increases from 120 °C to 600 °C, the crystal structure of *hsm*CeO₂ remains stable, but as expected the crystallinity and the grain size gently increase (Table 1).



Figure 1. XRD patterns of (a) CeO_2 and $hsmCeO_2$, (b) $hsmCeO_2$ after different thermal treatments.

For the microstructure, all the *hsm*CeO₂-T compounds, as well as CeO₂, present a unique type IV isothermal curve and an obvious H2 hysteresis loop at a relative pressure of 0.4–0.9 (Figure 2), which is indicative of mesoporous structure. Furthermore, the pore size distributions confirm the relatively uniform mesoporous structures of the series ceria. As listed in Table 1, as the thermal treatment temperature increases from 120 °C to 600 °C, the specific surface areas and the pore volumes of *hsm*CeO₂-T first quickly rise and then dramatically fall, while the pore sizes slightly decrease. The S_{BET} and V_P of *hsm*CeO₂-400 reach the highest values of 158 m² g⁻¹ and 0.18 cm³ g⁻¹ respectively, which are much larger than those of CeO₂ (87 m² g⁻¹ and 0.14 cm³ g⁻¹). This reveals the successful preparation of mesoporous CeO₂ with high specific surface by the organic template-induced homogeneous precipitation method. And moreover, the calcination temperature is found to strongly affect the textural property.



Figure 2. N₂ adsorption-desorption isotherms and the corresponding pore size distribution of (a, b)

CeO_2 and $hsmCeO_2$, (c	c, d) $hsmCeO_2$	after different thermal	treatments
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$d_{\rm crystal} [\rm nm]^{a)}$	$S_{\rm BET} [m^2 g^{-1}]$	$V_{\rm P} [{\rm cm}^3{\rm g}^{-1}]$	$D_{\rm P} [{\rm nm}]$
11.9	87	0.14	6.2
9.3	63	0.10	6.3
9.6	135	0.16	4.7
9.8	158	0.18	4.8
10.0	98	0.13	4.8
10.4	48	0.08	5.6
	d _{crystal} [nm] ^{a)} 11.9 9.3 9.6 9.8 10.0 10.4	$\begin{array}{c c} d_{\rm crystal} [\rm nm]^{a)} & S_{\rm BET} [\rm m^2 g^{-1}] \\ \hline 11.9 & 87 \\ 9.3 & 63 \\ 9.6 & 135 \\ 9.6 & 135 \\ 9.8 & 158 \\ 10.0 & 98 \\ 10.4 & 48 \\ \end{array}$	$d_{\text{crystal}} [\text{nm}]^{a}$ $S_{\text{BET}} [\text{m}^2 \text{g}^{-1}]$ $V_{\text{P}} [\text{cm}^3 \text{g}^{-1}]$ 11.9870.149.3630.109.61350.169.81580.1810.0980.1310.4480.08

Table 1. The mean crystal size and the textural parameter	eters of CeO ₂ and <i>hsm</i> CeO ₂ -T
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^{a)} Calculated by the Scherrer equation from the (111) plane of CeO_2 .

The redox properties of CeO₂ and *hsm*CeO₂ (calcined at 400 °C as default) are comprehensively analyzed by UV-Raman, H₂-TPR, O₂-TPD, EPR and XPS. The resonance Raman effect is very sensitive to detect defects on the surface of ceria. As displayed in Figure S1, both CeO₂ and *hsm*CeO₂ show a strong band at about 460 cm⁻¹, which is characteristic of F_{2g} band of fluorite nanocrystalline ceria.^[15] In comparison with CeO₂, the F_{2g} band of *hsm*CeO₂ shifts to a lower frequency (465 cm⁻¹ vs 460 cm⁻¹) and becomes broader, which can be caused by the smaller

particle size of hsmCeO₂,^[16] in consistent with XRD analysis. This phenomenon has been also attributed to the presence of higher lattice distortion and oxygen vacancy (V ö) in ceria.^[17] Besides, the secondary bands due to the nanostructured ceria are also observed at about 260 cm⁻¹ and 330 cm⁻¹.^[16] Notably, the band at 600 cm⁻¹ is characteristic of local vibration of oxygen vacancy on Ce³⁺–V ö complex in ceria lattice,^[17] and a stronger intensity is obtained for *hsm*CeO₂. Raman results imply on the surface of *hsm*CeO₂ that there is a higher amount of oxygen vacancies attached to the coordinatively unsaturated Ce³⁺ ions.

Combined H₂-TPR and O₂-TPD are used to further investigate the redox properties of CeO₂ and hsmCeO₂. As reported in Figure 3a, hsmCeO₂ shows three reduction peaks that can be respectively attributed to the reduction of weakly adsorbed physical and/or chemical oxygen species (O_{ads}), Ce⁴⁺ to Ce³⁺ on surface and Ce⁴⁺ to Ce³⁺ in bulk,^[3b] from low to high temperatures. However, CeO₂ shows only two peaks related to the reduction of ceria. Notably, the reduction temperatures of Ce^{4+} to Ce^{3+} from surface and bulk for *hsm*CeO₂ are found to be lower than those of CeO₂ (i.e., 495) °C vs 512 °C, 749 °C vs 770 °C). In addition, hsmCeO₂ presents a higher total consumption of H₂ (about 1.5 folds) and the fraction of surface consumption of H₂ out of the total is measured to be 64% (Table S2), i.e., about 2 folds over CeO₂. These results clearly show an enhanced surface reducibility of *hsm*CeO₂. Moreover, As shown in Figure 3b, three types of oxygen species can be identified, which can be assigned to physically adsorbed and weakly chemisorbed oxygen species (O_{ads}) on ceria surface (≤ 180 °C), surface reactive oxygen species $(O_{surf}, i.e., O_2^-, O_2^{2-} and O^-)$ originated from oxygen vacancy (180–550 °C), and lattice oxygen species ($O_{latt.} \ge 550$ °C),^[18] respectively. Notably, the desorption intensity of O_{surf.} species on hsmCeO₂ is stronger. This phenomenon reveals the presence of abundant reactive O_{surf.} species on CeO₂ and hsmCeO₂ and an enhanced oxygen mobility of O_{surf.} for hsmCeO₂, which is well consistent with Raman and TPR

results.



Figure 3. (a) H₂-TPR and (b) O₂-TPD profiles of CeO₂ and *hsm*CeO₂.

EPR is regarded to be powerful to identify and measure oxygen vacancy (V ö) in ceria-based materials. Thereby, a deep determination of oxygen vacancy in CeO₂ and *hsm*CeO₂ is carried out. A signal at about 3515 G (Figure 4a) is obtained and the free electron factor *g* is of 2.003 (Figure 4b), which confirm the existence of oxygen vacancies in CeO₂ and *hsm*CeO₂.^[19] The EPR spectrum of *hsm*CeO₂ grows more intense, which can be indicative of a higher amount of oxygen vacancy. The quantitative analysis evidences that *hsm*CeO₂ contains obviously higher concentration of oxygen vacancy compared to CeO₂ (2.4×10^{15} *vs* 1.7×10^{15} , spins g⁻¹).



Figure 4. EPR spectra of CeO₂ and *hsm*CeO₂.

Following that, the surface features of CeO_2 and $hsmCeO_2$ are further analyzed by XPS. Particularly, $hsmCeO_2$ -600 with unusual structural and textural information is compared so as to unravel the influence of calcination temperature on its redox property. As shown in Figure 5, the Ce 3d spectra registered on different ceria can be resolved into three spin-orbits doublets Ce $3d_{3/2}$ -Ce $3d_{5/2}$, respectively. The binding energy (BE) at about 885.3 eV (v_1) and 903.9 eV (u_1) are attributed to Ce³⁺ species, while the other peaks are assigned to Ce⁴⁺ species.^[3a] The O 1s spectra can be resolved into two peaks. The peak at a lower BE of about 529.2 eV is characteristic of O_{latt}. species (O^{2^-}), while the peak at a higher BE of about 530.7 eV can be attributed to the reactive O_{surf}. species ($O_2^{-^-}$ and O^-) that are mainly associated with the active oxygen vacancy.^[20] As listed in Table S2, the BE values of different valence states for Ce and O show barely variations regardless of the use of organic template or the calcination temperature. However, the quantitative analysis reveals that the optimal *hsm*CeO₂ calcined at 400 °C shows the highest proportions of Ce³⁺ species (18.2%) and O_{surf}. species (36.2%), followed by CeO₂ and *hsm*CeO₂-600. This implies that the template-induced precipitation method is beneficial to create more active coordinatively unsaturated Ce³⁺ species and O_{surf}, species on the surface of ceria and the calcination at higher temperature (\geq 500 °C) would inhibit those desirable reactive sites. These data are in good agreement with TPR results.



Figure 5 Deconvoluted XPS spectra for Ce 3d and O 1s core levels of CeO₂, *hsm*CeO₂-400 and *hsm*CeO₂-600.

Oxidative coupling of benzyl alcohol and aniline

The oxidative coupling of benzyl alcohol and aniline is selected as a model reaction for evaluating

the prepared ceria catalysts. As reported in Table 2, the ordinary CeO₂ catalyst (entry 1) shows 70% conversion of benzyl alcohol and > 99% selectivity of benzylideneaniline with benzaldehyde (< 1%) as the only byproduct. The dried and calcined *hsm*CeO₂ catalysts (entries 2–6) maintain the excellent selectivity of imine but demonstrate different conversions of benzyl alcohol. On the catalysts thermally treated between 120 °C and 600 °C, conversion of benzyl alcohol increases from 58% to 99% and then decreases to 36%, and productivity of imine also follows the similar tendency from 1.59 mmol g⁻¹ h⁻¹ up to 2.75 mmol g⁻¹ h⁻¹ and then down to 1.00 mmol g⁻¹ h⁻¹. The optimum result is obtained on the *hsm*CeO₂-400 catalyst. Therefore, a volcano-like curve can be plotted between the thermal treatment temperature and the activity of *hsm*CeO₂-T catalysts. The *hsm*CeO₂ catalyst (calcined at 400 °C as default) shows about 1.5 folds of productivity toward imine over CeO₂. These catalytic results are found to be consistent with the specific surface areas of the series ceria catalysts and can be probably related with their redox properties.

Reaction parameters including the molar ratio of aniline to benzyl alcohol, the reaction temperature and the scale-up test are further investigated on the *hsm*CeO₂ catalyst. As reported in entries 4, 7 and 8, decreasing the ratio from 1.5/1 to 1/1 brings about a decline in both conversion of benzyl alcohol (99% to 85%) and selectivity of imine (99% to 91%), while selectivity of benzaldehyde increases (1% to 9%). This shows that properly excessive aniline is necessary to promote the oxidative coupling reaction, which has been observed on other CeO₂-based catalysts and may be related with the weak basicity of aniline to facilitate selective oxidation of benzyl alcohol to benzaldehyde.^[14c, 21] Interestingly, the *hsm*CeO₂ catalyst can work at room temperature of 30 °C (entry 9). An excellent yield (98%) to imine can be obtained by simply extending the reaction time to 24 h. In addition, a higher reaction temperature at 80 °C enables to greatly improve the productivity of imine up to 5.55 mmol g⁻¹ h⁻¹ (entry 10), which is two folds of that obtained at

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60 °C and is also the highest activity ever reported for ceria catalysts in literature. Furthermore, the hsmCeO₂ catalyst shows a superior performance in the scale-up test (entry 11). A gram-grade production of imine (1.79 g) with an excellent yield (99%) can be obtained at 60 °C after 12 h.

For heterogeneous catalysis, the stability and reusability of a catalyst is important for potential practical applications. The used hsmCeO₂ catalyst after the post-treatment (see experimental details) is evaluated in the consecutive oxidative coupling reactions under the same conditions. As shown in Figure S2, the hsmCeO₂ catalyst remains a stable yield of imine (99%) after five cycles, showing the same activity as the fresh catalyst dose. However, sometimes the possible saturation of catalytic activity may exist under the optimized conditions. To exclude that interference, conversion of benzyl alcohol in the kinetic controlled region (i.e., the initial stage after 1 h) is further examined. To one's satisfaction, the hsmCeO₂ catalyst demonstrates a considerable stability and reusability.

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Entry	Catalyst	Conv. 1 [%]	Select. 3 [%]	Select. 4 [%]	CB [%]	Prod. 3 [mmol $g^{-1} h^{-1}$]
1	CeO ₂	70	> 99	< 1	99.8	1.91
2	hsmCeO ₂ -120	58	> 99	< 1	99.6	1.59
3	hsmCeO ₂ -300	82	> 99	< 1	99.9	2.26
4	hsmCeO ₂ -400	99	> 99	< 1	99.8	2.75
5	hsmCeO ₂ -500	73	> 99	< 1	100	2.00
6	hsmCeO ₂ -600	36	> 99	< 1	99.7	1.00
7	<i>hsm</i> CeO ₂ ^{a)}	98	97	3	99.9	2.64
8	<i>hsm</i> CeO ₂ ^{b)}	85	91	9	99.9	2.14
9	$hsmCeO_2^{c)}$	99	99	1	100	0.46
10	$hsmCeO_2^{d}$	100	> 99	< 1	99.8	5.55
11	$hsmCeO_2^{e}$	99	> 99	< 1	99.7	0.91

 Table 2. Oxidative coupling of benzyl alcohol and aniline over CeO₂ and *hsm*CeO₂-T catalysts

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OH NH₂ Catal.

Reaction conditions: benzyl alcohol, 1 mmol; aniline, 1.5 mmol; catalyst, 90 mg; toluene, 5 mL; air, 1 atm; temperature, 60 °C; time, 4 h. Carbon balance (CB) is reported.

^{a)} Aniline, 1.25 mmol.

^{b)} Aniline, 1 mmol.

^{c)} Temperature, 30 °C; time, 24 h.

^{d)} Temperature, 80 °C; time, 2 h.

^{e)} Benzyl alcohol, 10 mmol; aniline (1.08 g), aniline, 15 mmol (1.40 g); catalyst, 900 mg; toluene, 10 mL; time, 12 h.

Comparison with benchmark catalysts

The prepared hsmCeO₂ catalyst is compared with typical ceria catalysts that have been so far reported for oxidative coupling of benzyl alcohol and aniline. As summarized in Table 3, three ceria catalysts including hsmCeO₂ allow working in air atmosphere at room temperature of 30 $^{\circ}$ C (entries 1-3).^[3] Nonetheless, the CeO₂-5 catalyst deactivates (about 20% of yield) after four recycles even though it can afford the highest productivity of imine based on a 99% yield.^[3b] Though the hsmCeO₂ catalyst shows the second highest productivity of imine, the excellent yield (99%) is very well remained during catalyst reuse. Another CeO₂ catalyst produces a moderate yield of imine (75%) with benzaldehyde as byproduct.^[3a] In comparison with other ceria catalysts working at 60 °C (entries 4–10), the hsmCeO₂ catalyst also exhibits the second highest productivity of imine. Notably, the mh-CeO₂ and the CeO₂-P_{fa}-7 catalysts present very high productivity as well, but the mesoporous hollow CeO₂ microspheres^[14c] and the organometallic precursor induced defect-enriched mesoporous CeO₂ catalysts^[10b] have to be prepared by complex and well-defined methods, and the exceptional productivity of imine largely depends on the unique morphologies of ceria. On other ceria catalysts, much lower productivities of imine are obtained. Moreover, a low to moderate formation of benzaldehyde is still detected and pure O_2 is necessarily needed.^[6, 14b] Working at a higher temperature of 80 °C, the hsmCeO₂ catalyst can offer an excellent productivity of imine in a fast response (entries 11 and 12). Therefore, the hsmCeO₂ catalyst prepared in this work by a simple template-induced homogeneous precipitation method is one of the best among all the ever-reported ceria catalysts in terms of activity and stability.

Table 3. Comparison of oxidative coupling of benzyl alcohol and aniline to benzylideneaniline over typical c	eria
catalysts	

Entry	Catalyst	Temp. [°C]	Oxidant [1 atm]	Time [h]	Yield [%]	Prod. $[mmol g^{-1} h^{-1}]$	Stab.	Ref.
1	CeO ₂ -5	30	air	36	≥99	0.55	no	[3b]
2	hsmCeO ₂	30	air	24	99	0.46	yes	This work
3	CeO ₂	30	air	48	75	0.31	n.d.	[3a]
4	mh-CeO ₂	60	air	12	98	4.04	yes	[14c]
5	hsmCeO ₂	60	air	4	99	2.75	yes	This work

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6	CeO ₂ -P _{fa} -7	60	air	8	93	2.30	no	[10b]
7	CeO ₂ -5	60	air	24	≥99	0.83	no	[3b]
8	CeO ₂	60	air	24	96	0.80	n.d.	[3a]
9	CeO ₂ /MC	60	O ₂	6	77	0.43	yes	[14b]
10	$CeO_2 rod$	60	O ₂	12	92	0.38	yes	[6]
11	CeO ₂ /MC	80	O ₂	2	99	1.65	yes	[14b]
12	hsmCeO ₂	80	air	2	> 99	5.55	yes	This work

Substrate scope

Table 4 reports the oxidative coupling of aniline with various primary alcohols over the hsmCeO₂ catalyst under the optimal reaction conditions. This catalyst exhibits good universality and activity in converting substituted benzyl alcohols bearing electron-donating (MeO, Me and tBu) or electron-withdrawing (NO₂ and Cl) substituents, and high conversions (\geq 94%) of alcohols and high yields (\geq 93%) of imines are obtained (**3a-3f**). Still, there are some minor differences in the conversion and yield, which may be related with the property and location of the substituents. The electrophilicity of benzylic carbon is reduced because the electron-donating groups can increase its electron density to reduce its reactivity with nucleophilic amines. The electron-withdrawing group is beneficial to remove hydrogen from the hydroxyl group. The deprotonated alcohol or alkoxide can be oxidized and dehydrogenize benzyl carbon to form carbonyl compounds and react with aniline immediately to form imines. In addition, the influence of substituent position (3b and 3c) and steric hindrance (3d) should not be neglected. Besides substituted benzyl alcohols, some other aliphatic alcohols, aromatic alcohols, and even alcohols containing heteroatoms are also examined (3g-3l). Cyclohexylmethanol and pyridin-4-methanol afford 93% (3g) and 91% (3h) yields to the desired imines, respectively. The activation of unbranched linear alcohol is rather difficult, but the oxidative coupling of aniline with 1-octanol over the hsmCeO₂ catalyst gives a satisfactory yield (77%) of the corresponding imine (3i) when reaction time is extended to 8 h. In addition, the hsmCeO₂ catalyst can activate several complex alcohols including 3,4-(methylenedioxy)benzyl alcohol, 2-naphthalenemethanol and 2-thiophenemethanol to offer a moderate to low yield of the

corresponding imines (3j-3l) at 60 °C in 8 h.



 Table 4. Oxidative coupling of aniline with different primary alcohols over the hsmCeO2 catalyst

Reaction conditions: alcohol, 1 mmol; aniline, 1.5 mmol; catalyst, 90 mg; toluene, 5 mL; air, 1 atm; temperature, 60 °C. Reaction time, conversion of alcohol and yield of imine were reported.

Table 5 reports the oxidative coupling of benzyl alcohol with various primary amines over the hsmCeO₂ catalyst under the optimal reaction conditions. Similarly, this catalyst demonstrates good universality and activity for the substituted anilines (**3m-3q**) and a high yield (\geq 93%) of desired imines are obtained. As expected, the nucleophilicity of aniline can be enhanced by both electron-withdrawing (Cl) and electron-donating (MeO and Me) groups. And the enhanced nucleophilicity can promote nucleophilic attack, although there are some minor differences due to the property and the location of substituents. In companion with aniline, the oxidative coupling of benzyl alcohol with benzyl amine is examined and a high yield (96%) of imine (**3r**) is obtained, which may be due to the high basicity of benzyl amine. Notably, the linear aliphatic octan-1-amine would afford a high desired imine production (**3s**, 94%) in 4 h, compared with the yield of **3i** (77%) in 8 h. This implies that converting an alcohol to the aldehyde can be probably the rate-limited step in the oxidative coupling reaction. *t*-Butylamine and cyclohexylamine afford a moderate yield to the

desired imines (**3t** and **3u**). In addition, pyridin-4-amine shows as expected a much lower yield to the imine **3v** (40%), which is maybe affected by the basicity of pyridine group. In summary, the *hsm*CeO₂ catalyst shows a wide scope and good to excellent activity for imine synthesis from the direct oxidative coupling of various primary alcohols and amines. The electronic effect of substituents, the nucleophilicity or electrophilicity of substrates, and even the acidic-basic properties of substrates and catalysts are worthy of a comprehensive study in future work.

Table 5. Oxidative coupling of benzyl alcohol with different primary amines over the hsmCeO₂ catalyst



Reaction conditions: benzyl alcohol, 1 mmol; amine, 1.5 mmol; catalyst, 90 mg; toluene, 5 mL; air, 1atm; temperature, 60 °C. Reaction time, conversion of benzyl alcohol and yield of imine were reported.

Discussion on the structure-activity relation and the plausible mechanism

In order to understand the reaction pathway, the time-course performances of the hsmCeO₂ catalyst are investigated by a series of controlled experiments. As plotted Figure 6a, oxidative coupling of benzyl alcohol and aniline to benzylideneaniline shows a fast response. Conversion of alcohol and yield of imine almost linearly increase within 2 h and 1.5 h at 60 °C and 80 °C respectively, reaching 68% and 87%. > 99% yield of imine can be obtained at 4 h and 2 h, respectively. Meanwhile, only traces of benzaldehyde (select. < 1%) are detected in the whole reaction process.

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As plotted in Figure 6b, condensation of benzaldehyde and aniline to benzylideneaniline also proceeds very fast. Yield of imine reaches >99% in Ar or O₂ atmosphere at 60 °C within 2 h and at 80 °C within 1 h, respectively. Notably, the same tendencies and results are obtained in the absence of the hsmCeO₂ catalyst. This reveals that condensation of benzaldehyde and aniline over hsmCeO₂ is a non-catalytic process, which can be determined by the reaction temperature. This phenomenon has been also observed by other reports.^[12c, 22] As plotted in Figure 6c, aerobic oxidation of benzyl alcohol over the hsmCeO₂ catalyst proceeds gently. Conversion of benzyl alcohol gradually increases within 3 h and reaches about 55%. Selectivity of benzaldehyde is of 100%. This catalytic performance is stabilized by extending reaction time to 5 h. Thus a chemical equilibrium may be reached under the given reaction conditions. Interestingly, adding 1.5 equivalent of aniline into the reactor can give rise to a further oxidation of benzyl alcohol, and the conversion obviously increases up to 87% by extending reaction time to 8 h. Notably, benzylideneaniline (98% in select.) rather than benzaldehyde is found to be the dominant product. This result evidences that the presence of excessive aniline can promote aerobic oxidation of benzyl alcohol to benzaldehyde, which is consistent with the influence of the molar ratio of aniline to benzyl alcohol (Table 2). Once benzaldehyde is produced from benzyl alcohol, it can be immediately condensed with aniline to yield imine. This shows that benzaldehyde is an intermediate of the oxidative coupling reaction, and aerobic oxidation of benzyl alcohol to benzaldehyde is considered to be the rate-determining step, as proposed for CeO₂ catalysts.^[3, 14a] As plotted in Figure 6d, coupling benzyl alcohol and aniline can also proceed in Ar atmosphere over the hsmCeO₂ catalyst. But conversion of benzyl alcohol to benzaldehyde stops after 3 h in inert gas, the conversion stabilizes at 52% after 4 h. When Ar is replaced by air atmosphere, the oxidation process is initiated again and conversion of benzyl alcohol rapidly goes up to 85% within 1 h. This observation indicates that both molecular O2 and

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 $O_{surf.}$ species play important roles in the rate-determining step. $O_{surf.}$ species on the *hsm*CeO₂ catalyst can drive oxidation of benzyl alcohol in inert gas and are gradually consumed till a full depletion, then the reaction cannot proceed. When air is provided, molecular O₂ can be activated on the oxygen vacancy to generate O_{surf.} species that trigger the oxidation process.



Figure 6. (a) Time course for oxidative coupling of benzyl alcohol and aniline at different temperatures, (b) time course for condensation of benzaldehyde and aniline in Ar or O_2 with or without catalyst, (c) time course for aerobic oxidation of benzyl alcohol without or with addition of aniline, (d) time course for coupling of benzyl alcohol and aniline in Ar or air. Reaction conditions: benzyl alcohol, 1 mmol; benzaldehyde, 1 mmol; aniline, 1.5 mmol; the *hsm*CeO₂ catalyst, 90 mg; toluene, 5 mL; air or Ar, 1 atm; temperature, 60 °C unless specified.

In order to elucidate the structure-activity relationship, the apparent activation energy (E_a) of oxidative coupling of benzyl alcohol and aniline by numerical regression assuming a valid

Arrhenius law is measured for the typical catalysts. Before that, the influence of mass transfer is investigated. As listed in Table S3, the default stirring rate (800 rpm) is found to be beyond the mass-transfer limited range. Thereby, all the reactions are conducted under chemical control and the mass transfer limitation can be excluded. The kinetic data in details can be found in Table S4. As displayed in Figure 7a, the hsmCeO₂ catalyst shows a much lower E_a of 39.2 kJ mol⁻¹, followed by the ordinary CeO₂ catalyst (55.4 kJ mol⁻¹) and the *hsm*CeO₂-600 catalyst (65.0 kJ mol⁻¹), which is well consistent with their catalytic performances (Table 2). Combined with the characterization results, the catalytic activities of these ceria catalysts can be related with their surface areas and specifically be greatly affected by their redox properties. Thereby, the productivity of imine is plotted against the proportion of surface Ce^{3+} ions and $O_{surf.}$ species and a good relationship can be established (Figure 7b). The productivity of imine is found to be closely related with the proportion of coordinatively unsaturated Ce^{3+} and reactive O_{surf} on ceria catalyst. The highest specific surface area of the $hsmCeO_2$ catalyst is beneficial to afford more surface Ce^{3+} ions and oxygen vacancies which can adsorb and activate O₂ to generate more reactive O_{surf.} species as the active sites for the oxidative coupling reaction.^[3b, 14c] However, CeO₂ and *hsm*CeO₂-600 catalysts with inadequate redox properties can only exhibit obviously lower catalytic activities.



Figure 7. (a) Arrhenius plot for conversion of benzyl alcohol. Reaction conditions: benzyl alcohol, 1 mmol; aniline, 1.5 mmol; catalyst, 90 mg; toluene, 5 mL; air, 1 atm; temperature, 60–80 °C; time,

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1 h. (b) The relationship between productivity of benzylideneaniline and the surface proportion of $O_{surf.}$ and Ce^{3+} species.

Therefore, as proposed in Scheme 1, a high concentration of oxygen vacancies (V ö) attached to the coordinatively unsaturated Ce^{3+} ions can be created in the *hsm*CeO₂ catalyst by using a template-induced homogenous precipitation method. The Ce^{3+} –V ö complex in ceria lattice is of great importance to the redox properties and the oxidation performances of ceria-based catalysts.^{[14a,} ^{23]} Besides, the higher proportion of Ce^{3+} ions in the *hsm*CeO₂ catalyst can correspond to the lower redox potential between Ce^{4+} and Ce^{3+} ions, which is characteristic of the catalyst with an enhanced mobility of chemisorbed oxygen.^[18b, 23] Oxygen vacancy is highly reactive to adsorb and activate molecular O_2 to generate $O_{surf.}$ species (O_2^-, O^-) that are usually called oxygen deficiency sites. $O_2^$ and O⁻ species are well known to be the highly reactive electrophilic radicals and can give rise to the promotion of oxidation reactions.^[24] The O_{surf.} species on *hsm*CeO₂ are proposed to be the active sites for oxidative coupling of benzyl alcohol and aniline, in agreement with other ceria-based catalytic systems.^[3b, 14a, 23] O_{surf.} species can efficiently convert benzyl alcohol to benzaldehyde, which is considered to be the rate-determining step. A high proportion of O_{surf} already exist in the hsmCeO₂ catalyst, and such active sites can be simultaneously created on oxygen vacancy by adsorption and activation of molecular O₂. Subsequently, aniline can react immediately with the produced benzaldehyde to rapidly yield benzylideneaniline via a non-catalytic step.





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over the *hsm*CeO₂ catalyst.

Conclusions

In conclusion, the *hsm*CeO₂ catalyst with exceptional redox property is reported for efficient oxidative coupling of primary alcohols and amines to imines in air atmosphere at low temperatures without base additives. This catalyst shows a good reusability, a wide substrate scope, and a potential scaling-up synthesis of imine. The template-induced homogeneous precipitation method allows creating a high surface area and a uniform mesoporous structure for CeO₂, on whose surface abundant oxygen vacancies attached to the coordinatively unsaturated Ce³⁺ ions are generated. It is demonstrated that molecular O₂ can be activated and transformed on oxygen vacancy to the highly reactive O_{surf.} species which can selectively convert benzyl alcohol to benzaldehyde, i.e., the proposed rate-determining step. The subsequent condensation of benzaldehyde with aniline to imine is a fast and uncatalyzed step. Compared to the ordinary CeO₂, the *hsm*CeO₂ catalyst bearing the optimal proportion of Ce³⁺ ions and oxygen vacancy can significantly boost the catalytic oxidation performance.

Experimental

The experimental details including chemicals, *hsm*CeO₂ preparation, characterization methods, and oxidative coupling reaction can be found in the supporting information.

Conflicts of interest

There is no conflict to declare.

Acknowledgements

This work was supported by National Natural Science Foundation of China (No. 21763031 and 22062025), National Special Funds of China (No. C176220100063), Yunnan Fundamental Research Projects (No. K264202007120), and Program for Excellent Young Talents of Yunnan University.

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Efficient Imine Formation via Oxidative Coupling at Low Temperature Catalyzed by

High-Surface-Area Mesoporous CeO_2 with an Exceptional Redox Property

Chem. Euro. J. Year, Volume, Page – Page

Shipeng Wu,^[a] Yinghao Wang,^[a] Qiue Cao,^[ab] Qihua Zhao,^[a] and Wenhao Fang^[ab*]

A high-surface-area mesoporous CeO₂ catalyst prepared by an organic template-induced

homogeneous precipitation method shows an exceptional redox property and can boost imine

formation via the direct oxidative coupling of primary alcohols and anilines in air atmosphere at

low temperature.



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