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# Efficient imine synthesis from oxidative coupling of alcohols and amines under air atmosphere catalysed by Zn-doped Al<sub>2</sub>O<sub>3</sub> supported Au nanoparticles



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#### ABSTRACT

Direct oxidative coupling of alcohols and amines is regarded as an effective and green approach for imine synthesis under mild conditions. In this work, Zn-doped  $\gamma$ -Al<sub>2</sub>O<sub>3</sub> supported Au nanoparticles was demonstrated as highly active and selective heterogeneous catalyst for a series of imine productions with good to excellent yields, from alcohols and amines via direct oxidative coupling under air atmosphere without extra base additives. Various physicochemical techniques, including ICP-MS, XRD, N<sub>2</sub> physisorption, TEM, XPS and CO<sub>2</sub>-/NH<sub>3</sub>-TPD, were used to study the properties of the catalysts. Well-dispersed Au<sup>0</sup> nanoparticles with a mean size of ca. 2.9 nm were found highly effective in activating alcohols in the presence of reactive amines. The amount of Zn<sup>2+</sup> dopant and the calcination temperature of support during catalyst preparation showed crucial impact on tuning the intrinsic activity for oxidation of benzyl alcohol to benzaldehyde (i.e., the rate-determining step for the model reaction), which was disclosed to be related with the active surface oxygen species and the acidic-basic property of support. The 0.4% Au/Zn<sub>0.02</sub>Al<sub>2</sub>O<sub>3</sub> catalyst calcined at 400 °C exhibited the highest TOF (39.1 h<sup>-1</sup>) at 60 °C based on a >99% yield to benzylideneaniline among all the ever-reported Au-based catalysts. Moreover, this catalysts could afford 98% yield to benzylideneaniline at only 30 °C and work effectively for the gram-scale synthesis. It also showed considerable stability after five consecutive recycling.

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# 1. Introduction

Imines stand as a class of important N-containing organic intermediates and have been extensively used in manufacture of pharmaceuticals, bioactive compounds and agrochemicals [1–8]. Traditional synthesis of imines relies on the condensation of carbonyl compounds with amines. But such a process is usually assisted with acid medium, leading to several environmental issues due to use of hazardous regents and/or formation of toxic by-products. On light of that, alternative methodologies have been dedicated to direct synthesis of imines mainly through oxidation of secondary amines [9–11], dimerization of primary amines [12–14], and other approaches [15–17]. Nonetheless, those approaches often receive criticisms from a lack of selectivity, resulting consequently in complexity and high cost for extra separation and purification. Among others, direct coupling of alcohols and amines under oxidative conditions is regarded as a very ideal strategy toward imine synthesis owning to its friendly environmental impact, high atom economy and fast response [18–23]. Moreover, this green and practical method allows transforming a wide spectrum of reactive, low-cost and easily available alcohols to diverse imines at lower temperature and pressure but with only water formed as the by-product.

During the last decade, a few supported Pd [24,25], Pt [26] and Ru [27,28] catalysts have been reported for direct oxidative coupling of alcohols and amines due to the high reactivity of noblemetal nanoparticles in activating alcohols. Nevertheless, most of those catalytic systems have to work effectively in pure O<sub>2</sub> atmosphere and at high temperatures. And moreover, excessive base additives are most often required. Therefore, from the point view of high atom economy and positive environmental impact, it is of



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**Scheme 1.** Schematic illustration of the reaction pathway of oxidative coupling of benzyl alcohol and aniline.

importance to develop new noble metal based catalysts and technologies for coupling alcohols with amines under oxidative conditions.

As described in Scheme 1, it has been well illustrated for the model reaction that coupling benzyl alcohol with aniline undergoes a tandem reaction pathway [18–23], in which oxidation of alcohol to aldehyde is a slow and catalysed step (i.e., identified as the rate-determining step), while the subsequent condensation of aldehyde with amine is a fast and sometimes uncatalysed step. In such a context, design and fabrication of active sites to selectively oxidize alcohols to aldehydes remains no doubt critical for obtaining high yield to imines. As expected, the catalyst property would be decisive not only for conversion of alcohols but also selectivity to imines.

Supported Au nanoparticles have been widely recognised as promising catalysts for diverse mild and efficient selective aerobic oxidations in liquid phase [29–34]. As Au-based catalysts can offer better resistance to water and oxygen, it is generally accepted that Au catalysts are more selective and stable for aerobic oxidation of many different alcohols rather than the conventional Pd and Pt oxidation catalysts [35–38]. To the best of our knowledge, there are only a few Au-based catalysts reported for oxidative coupling of alcohol and amine, as summarised in Table 1. All the catalysts showed quite satisfying selectivity (95-99%) to benzylideneaniline but rather different conversion of benzyl alcohol. Au/HAP presented the optimal performance among the monometallic Au catalysts at mild temperatures using O<sub>2</sub> as oxidant [39]. A high TOF  $(33.0 h^{-1})$  with 99% yield to benzylideneaniline was reported. It was demonstrated that a delicate cooperation between metallic Au and the acidic-basic sites of the HAP surface may play a key role in determining the efficiency and compatibility of the Au/HAP catalyst for not only the rate-determining alcohol oxidation but also for the subsequent condensation step of the tandem reaction. Among the bimetallic Au-Pd catalysts, Au-Pd@ZrO2 exhibited the optimal performance via a one-pot, two-step process for tandem imine synthesis followed by the benzyl alcohol oxidation, affording a comparable TOF (35.2  $h^{-1}$ ) but with a lower yield (94%) to imine [40]. It was disclosed that the superior catalytic properties of alloy NP catalyst was because the surface of alloy NPs showed higher charge heterogeneity than that of pure metal NPs. However, it can be concluded that most of those Au catalysts still suffer from addition of base additives, insufficient conversion of alcohol and uncertainty in reusability. Hence those above would further hamper the green footprint of imine production. Furthermore, the reaction pathway and plausible reaction mechanism remain unclear in the point view of molecular catalysis.

Herein, in this work we develop for the first time Zn-doped  $\gamma$ -Al<sub>2</sub>O<sub>3</sub> supported Au nanoparticles (Au/Zn<sub>X</sub>Al<sub>2</sub>O<sub>3</sub>), which is a new supported Au catalyst for imine synthesis through direct oxidative coupling of alcohol and amine. The Au/Zn<sub>X</sub>Al<sub>2</sub>O<sub>3</sub> catalyst shows superior activity, selectivity, stability and scope towards imine productions by using very mild temperature and oxidant, offering a highest TOF ever reported for Au-based catalysts in literature. We will demonstrate the role of Au nanoparticles, the unique effect of Zn-doping and calcination conditions on support, investigate reaction parameters and reusability, and finally elucidate the structure-activity relationship of the Au/Zn<sub>X</sub>Al<sub>2</sub>O<sub>3</sub> catalysts.

# 2. Experimental

#### 2.1. Catalyst preparation

Zn-doped Al<sub>2</sub>O<sub>3</sub> donated as Zn<sub>x</sub>Al<sub>2</sub>O<sub>3</sub> (x = 0.01, 0.02 and 0.04, i.e., Zn/Al ratio in mol.) was prepared by co-precipitation method. A mixed solution of Zn(NO<sub>3</sub>)<sub>2</sub>·6H<sub>2</sub>O and Al(NO<sub>3</sub>)<sub>3</sub>·9H<sub>2</sub>O was dissolved in deionized water, and then co-precipitated by dropwise addition of NH<sub>4</sub>OH solution (28 wt%) under stirring (600 rmp) till pH value of the mixture reached 9. The obtained slurry was stirred at room temperature for 2 h. The solids were recovered by filtration and washed by excessive deionized water when the filtrate presented a neutral pH value. Finally, the solids were oven-dried at 110 °C for 12 h followed by a calcination at (T = 300, 400, 500, 650 and 800 °C, with a ramp of 2 °C/min) under air flow for 5 h. Al<sub>2</sub>O<sub>3</sub> and ZnO were also prepared by this protocol.

Supported Au nanocatalysts with a loading of 0.4 wt% were prepared by immobilization of the PVA-stabilized colloidal Au nanoparticles onto various supports. Typically, a poly(vinyl alcohol) (MW = 10,000) aqueous solution was added into a HAuCl<sub>4</sub> solution (PVA/Au = 1.2/1, in w/w) under stirring. After 15 min, a suspension of powdery support was added and the mixture was vigorously stirred at room temperature for 15 min. Then a freshly made NaBH<sub>4</sub> solution (NaBH<sub>4</sub>/Au = 4/1, in w/w) was slowly introduced into the mixture to yield a dark-purple colloidal solution. After it was stirred for another 2 h, the solid catalyst was recovered by filtration and washed repeatedly with excessive hot deionized water (90 °C) to remove PVA and with excessive deionized water to remove Na<sup>+</sup> and Cl<sup>-</sup> ions. Finally, the resultant Au nanocatalyst was dried in vacuum at 50 °C for 24 h.

## 2.2. Catalytic reaction

Oxidative coupling of alcohols and amines was performed in a WP-TEC-1020HC parallel reactor provided by WATTCAS<sup>™</sup> (WAT-TECS LAB EQUIPMENT CO., LTD.). In a typical protocol, 0.5 mmol benzyl alcohol, 0.75 mmol aniline, 5 mL toluene and 40 mg catalyst were added successively. And then the reaction mixture was

Table 1

Summary of supported Au-based catalysts for benzylideneaniline synthesis from oxidative coupling of benzyl alcohol and aniline.

Reference	Catalyst	T (°C)	Oxidant (1 bar)	Base	Time (h)	Conv. (%)	Yield (%)	$TOF(h^{-1})$	Reuse times	Stability
[39]	Au/HAP	60	02	None	3	99	>99	33.0	5	Yes
[41]	Au/TiO <sub>2</sub>	20	02	KOCH <sub>3</sub>	24	7	7	14.4	Not done	Unknown
[42]	Au/ZrO <sub>2</sub>	60	02	KOCH <sub>3</sub>	24	32	32	0.9	Not done	Unknown
[43]	AuPd <sub>4</sub> /resin	40	02	NaOH	12	80	80	2.2 <sup>b</sup>	6	No
[44]	PICB-Au/Pd	60	02	NaOH	12	74	70	3.9 <sup>b</sup>	Not done	Unknown
[40]	Au-Pd@ZrO2ª	40	Air	None	8	94	94	35.2 <sup>b</sup>	3	Yes
This work	$Au/Zn_{0.02}Al_2O_3$	60	Air	None	8	99	>99	39.1	5	Yes

<sup>a</sup> Two stepped reaction of oxidation of benzyl alcohol to benzaldehyde (7 h) and condensation of benzaldehyde with aniline (1 h).

<sup>b</sup> Based on the total amount of Au and Pd.

stirred (900 rpm) at 60 °C under air (1 atm) for 8 h. The tube was immediately cooled in ice water and the reaction mixture was analysed using a Thermo Scientific TRACE 1310 gas chromatograph (GC) equipped with a flame ionization detector (FID) and a TR-5 column (30 m  $\times$  0.32 mm  $\times$  0.25  $\mu m$  ). The quantification was carried out using the external standard method. A series of toluene solutions in different concentrations of benzyl alcohol, benzaldehyde or benzylideneaniline were used as external standard, respectively. Each reaction was at least repeated twice to guarantee a reproducible result. The conversion of benzyl alcohol, the selectivity to alkylamines and the yield of imine were calculated, on the basis of a carbon balance. For the reusability test, the catalyst was separated by centrifugation (8000 rpm for 10 min), washed three times in turn with ethanol (100 mL) and water (100 mL), dried at 50 °C for 24 h under vacuum, and was used for the next run.

#### 2.3. Characterization methods

The textural property of support materials was studied by N<sub>2</sub> adsorption-desorption at 77 K using BET and BJH methods on a Micromeritics TriStar II 3020 Surface-Area and Porosimetry analyzer. The metal loadings for Au, Zn and Al were precisely measured by inductively coupled plasma mass spectrometry (ICP-MS) on an Agilent 7500a apparatus. X-ray diffraction (XRD) was conducted using a Rigaku TTR III Diffractometer provided with Cu K $\alpha$  radiation ( $\lambda$  = 1.5418 Å) and a beam voltage of 40 kV. The patterns were registered in the  $2\theta$  domain (5–90°) with a measured step of 0.02° and a time integration of 0.2 s. X-ray photoelectron spectroscopy (XPS) was performed under ultra-high vacuum on a Thermo Scientific Escalab 250Xi system provided with Al Ka radiation. The binding energy shift due to the surface charging was adjusted using a reference to the C 1s line at 284.6 eV. CO<sub>2</sub> and NH<sub>3</sub> temperature-programmed desorption (TPD) was carried out on a Micromeritics Autochem II Chemisorption analyzer. 50 mg sample loaded in a quartz reactor was pre-treated with He at 200 °C for 1 h. After cooling to 50 °C, CO<sub>2</sub> or NH<sub>3</sub> adsorption was performed by switching He to a 10% CO<sub>2</sub>/NH<sub>3</sub>-90% He (in vol.) mixed gas and then maintaining for 1 h. The gas-phase CO<sub>2</sub>/NH<sub>3</sub> was purged by He at the same temperature. TPD was then performed in He flow by raising the temperature to 800 °C at a rate of 10 °C/min. The desorbed CO2 or NH3 was detected on a ThermoStar GSD 301 T2 mass spectrometer. Transmission electron

Table 2 Oxidativ

Oxidative coupling of benzyl	alcohol and aniline ov	ver Al <sub>2</sub> O <sub>2</sub> - ZnO- and	Zn <sub>v</sub> Al <sub>2</sub> O <sub>2</sub> -supported	Au catalysts
Oxidative coupling of benzyl		7CI 711203-, 2110- allu	Zng/n203-supported	Au catalysts.

OH + $OH$ + $O$ (Eq. 1)							
	1	2	3	4			
Entry	Catalyst	Conv. 1 (%)	Select. <b>3</b> (%)	Select. 4 (%)	Yield <b>3</b> (%)		
1	$Au/Al_2O_3$	6	99	1	5		
2	Au/ZnO	12	99	1	11		
3	$Au/Zn_{0.01}Al_2O_3$	42	>99	<1	41		
4	$Au/Zn_{0.02}Al_2O_3$	73	>99	<1	72		
5	$Au/Zn_{0.04}Al_2O_3$	14	>99	<1	13		
6	$Au-Zn_{0.02}/Al_2O_3$	30	>99	<1	29		
7	$Au/Zn_{0.02}Al_2O_3^a$	100	>99	<1	>99		
8	$Au/Zn_{0.02}Al_2O_3^b$	100	97	3	97		
9	$Au/Zn_{0.02}Al_2O_3^{c}$	97	93	7	90		
10	$Au/Zn_{0.02}Al_2O_3{}^d$	33	>99	<1	32		

Reaction conditions: benzyl alcohol, 0.5 mmol; aniline, 0.75 mmol; catalyst, 40 mg; toluene, 5 mL; air, 1 atm; temperature, 60 °C; time, 8 h. <sup>a</sup> Catalyst, 80 mg.

<sup>b</sup> Benzyl alcohol, 0.5 mmol; aniline, 0.625 mmol.

<sup>c</sup> Benzyl alcohol, 0.5 mmol; aniline, 0.5 mmol.

<sup>d</sup> Ar, 1 atm.

microscopy (TEM) was conducted on a Philips-FEITECNAI F30 field emission electron microscope with an acceleration voltage of 300 kV.

# 3. Results and discussion

# 3.1. Importance of $Au^0$ nanoparticles and $Zn^{2+}$ doping

*N*-benzylideneaniline is selected as a model imine from direct oxidative coupling of benzyl alcohol and aniline (Eq. 1), and a series of supported Au catalysts are evaluated (Table 2). The supports were lab-made and calcined under air flow at 400 °C. Au/Al<sub>2</sub>O<sub>3</sub> and Au/ZnO give 6% and 12% conversion of alcohol, respectively. While selectivity of imine is found at 99% over both catalysts with aldehyde formed as the sole by-product. Adding a small amount of Zn in Al<sub>2</sub>O<sub>3</sub> support (Zn/Al, 0.01–0.04 in mol.) brings about significant increase of alcohol conversion and excellent retention of imine selectivity (>99%). The Au/Zn<sub>0.02</sub>Al<sub>2</sub>O<sub>3</sub> catalyst shows the optimal yield at 73% to benzylideneaniline at 60 °C under air atmosphere. To be noted, the bare supports are found inactive to imine synthesis (Table S1), showing that Au nanoparticles are essential and work as the active sites. Interestingly, adding the same amount of Zn (0.02 mol.%) to Au rather than Al<sub>2</sub>O<sub>3</sub> leads to a much lower alcohol conversion (30%). This clearly confirms that the enhancement on catalytic activity can be only realized by incorporating a suitable Zn to Al<sub>2</sub>O<sub>3</sub>, probably associated with the unique materials property.

To optimise conversion of benzyl alcohol, the catalyst mass is increased. As shown in Table S2, conversion gradually goes up with increasing catalyst mass from 40 mg to 80 mg. A total conversion is obtained when the catalyst mass is doubled to 80 mg. This suggests the difficulty in activating benzyl alcohol by using metal catalysts. In addition, the reactant composition, i.e., the ratio of benzyl alcohol to aniline is believed to affect the yield of imine. Though the stoichiometry of alcohol to amine for oxidative coupling reaction is of 1 as used in some work [23,39], different stoichiometry are also employed, i.e., alcohol/amine molar ratio is of 1.5 [4,25] or 0.5 [18,19]. Given that, the amount of aniline is reduced to 1.25 and 1.0 equiv. to investigate the influence. As shown in Table 2, the decrease in the amount of aniline leads mainly to lowering selectivity of imine, as well as conversion of benzyl alcohol. In return, selectivity of benzaldehyde is increased. This implies a promotion effect on yield to imine by an excessive use of aniline in the

Table 3						
Oxidative coupling of benzyl alcohol and aniline over $Zn_{0.02}Al_2O_3$ -supported noble metal catalysts.						

Entry	Catalyst	Conv. 1 (%)	Select. 3 (%)	Select. 4 (%)	Formation rate $3 (g g h^{-1})^{\mathbf{b}}$
1	Au/Zn <sub>0.01</sub> Al <sub>2</sub> O <sub>3</sub>	100	>99	<1	35.0
2	$Pd/Zn_{0.02}Al_2O_3$	55	92	0 <sup>a</sup>	17.9
3	$Ru/Zn_{0.02}Al_2O_3$	34	99	<1	11.9
4	$Pt/Zn_{0.02}Al_2O_3$	2	99	<1	<1

Reaction conditions: benzyl alcohol, 0.5 mmol; aniline, 0.75 mmol; catalyst, 80 mg; toluene, 5 mL; air, 1 atm; temperature, 60 °C; time, 8 h.

<sup>a</sup> 8% selectivity to benzylaniline.

<sup>b</sup> Based on the amount of noble metals.

present catalytic system, as supported by literature [20–22]. Thereafter, some other noble metals (i.e., typical oxidation catalysts) including Pd, Ru, Pt are loaded onto the optimal  $Zn_{0.02}Al_2O_3$  support with the same metal loading (0.4 wt%) and further tested for benzylideneaniline formation. As summarised in Table 3, Au/Zn<sub>0.02</sub>Al<sub>2</sub>O<sub>3</sub> shows the best catalytic performance with >99% yield to imine. Supported Ru and Pt could offer excellent selectivity of imine but alcohol conversion is found much lower, i.e., 34% and 2%, respectively. To be noted, Pd/Zn<sub>0.02</sub>Al<sub>2</sub>O<sub>3</sub> may afford a moderate alcohol conversion at 55% but yield the secondary amine (i.e., 8% selectivity to benzylaniline) as by-product, in agreement with Pd-based catalysts [25,45]. A highest formation rate of benzylideneaniline (35.0 g g h<sup>-1</sup>) can be obtained over the Au/Zn<sub>0.02</sub>Al<sub>2</sub>O<sub>3</sub> catalyst taking into account the efficiency of active metal toward imine formation, among different noble metals catalysts.

To understand the superior catalytic performances of the Au/ Zn<sub>X</sub>Al<sub>2</sub>O<sub>3</sub> catalysts, some preliminary information on their composition and structure are analysed by ICP-MS, XRD and N<sub>2</sub> physisorption. As listed in Table 4, Au is effectively loaded by adsorption method onto different supports. ICP-MS shows the precise Au loadings nearly the same as the theoretical values (0.4 wt %). And a very small amount of Zn is confirmed to be successfully added to Al<sub>2</sub>O<sub>3</sub> by co-precipitation method. Al<sub>2</sub>O<sub>3</sub> and ZnO present typical diffraction peaks due to  $\gamma$ -Al<sub>2</sub>O<sub>3</sub> (JCPDS #29-0063) and hexagonal ZnO (JCPDS #36-1451), respectively (Fig. 1). While Zndoped Al<sub>2</sub>O<sub>3</sub> display patterns identical to  $\gamma$ -Al<sub>2</sub>O<sub>3</sub> without presence of ZnO phase, probably due to the quite low loading of Zn. The incorporation of ZnO into Al<sub>2</sub>O<sub>3</sub> is confirmed by the shift of Al<sub>2</sub>O<sub>3</sub> peaks to lower  $2\theta$  values, which is caused by the doping of Zn ions in lattice (atomic radius: Zn, 0.74 Å > Al, 0.54 Å), resulting in an expansion of the mean size of Al<sub>2</sub>O<sub>3</sub> crystals (Table 4) [46,47]. As shown in Fig. 2, both Al<sub>2</sub>O<sub>3</sub> and Zn<sub>x</sub>Al<sub>2</sub>O<sub>3</sub> supports exhibit distinctive type-IV isothermal profiles with an obvious H<sub>2</sub> hysteresis loop located at a relative pressure of 0.4–0.9. This is indicative of mesoporous materials. Moreover, pore size distribution obtained from BJH isotherms confirms the relatively uniform mesoporous structure that can be attributed to accumulation of oxide nanoparticles [48]. Then, high specific surface areas between 259 and  $304 \text{ m}^2/\text{g}$ are obtained (Table 4), and Zn<sub>X</sub>Al<sub>2</sub>O<sub>3</sub> oxides show relevant values with respect to Al<sub>2</sub>O<sub>3</sub>, suggesting the influence of Zn doping in a small amount. The BET surface area of Zn<sub>x</sub>Al<sub>2</sub>O generally decreases compared to Al<sub>2</sub>O<sub>3</sub>. This can be associated with large lattice distortions generated from incorporation of Zn. The Zn<sub>0.02</sub>Al<sub>2</sub>O<sub>3</sub> oxide displays a relatively higher surface area probably due to the relatively low crystallinity and abundant crystal defects of the Zn—Al—O solid solution. It is usually believed that such morphology could probably provide more reactive sites and be benefit to effectively dispersing active Au nanoparticles [35]. ZnO displays a type-III isotherm and a low specific surface area (5 m<sup>2</sup>/g).

To further rationalise the role of Au nanoparticles and Zn doping, XPS, TEM, and CO<sub>2</sub>-/NH<sub>3</sub>-TPD are carried out. Metallic Au<sup>0</sup> species are identified on surface of all the catalysts (Fig. S1, Table 5) [29,30]. This confirms that Au nanoparticles in metallic state are catalytic active sites. The surface Au loadings from XPS (ca. 0.35 wt%) are slightly lower than the bulk values from ICP-MS (Table 4). Then, typical  $Zn^{2+}$  (Fig. 3) and  $Al^{3+}$  species (Fig. S1) are clearly observed [49], revealing co-presence of ZnO and Al<sub>2</sub>O<sub>3</sub> on catalyst surface. And moreover, ZnO is found segregated onto the surface (Table 4). In addition, the best Au/Zn<sub>0.02</sub>Al<sub>2</sub>O<sub>3</sub> catalyst exhibits a lower B.E. for the Au 4f7/2 peak, which is indicative of the strong interaction between Au nanoparticles and the Zn<sub>0.02</sub>Al<sub>2</sub>O<sub>3</sub> support due to the electron transfer from support to active metal. The O 1s peak can be deconvoluted into two bands (Fig. 3). The band at a lower B.E. of ca. 530.6 eV is characteristic of lattice O<sup>2-</sup> species (i.e.,  $O_{\alpha}$  species) in Al<sub>2</sub>O<sub>3</sub> or doped-Al oxides [50], while the band at a higher B.E. of ca. 532.1 eV can be attributed to the surface oxygen species (i.e.,  $O_{B}$  species) mainly due to OH<sup>-</sup>,  $O^{2-}$ and/or O<sup>-</sup> ions [51]. To be noted, the B.E. of O 1s peak for Au/ZnO is found lower but in consistent with the data from typical ZnO in literature [52]. The  $O_{B}$  species are most often associated with active oxygen vacancy sites, and have been shown as highly active species for oxidative coupling of benzyl alcohol and aniline [21,22,25]. A volcano-like relationship can be correlated in this work between conversion of benzyl alcohol and the proportion of  $O_{\beta}$  species on surface of the Au/Zn<sub>x</sub>Al<sub>2</sub>O<sub>3</sub> catalysts. An optimal conversion is obtained on  $Au/Zn_{0.02}Al_2O_3$  due to its highest proportion of active  $O_{\beta}$  species.

For this representative catalyst, TEM analysis shows small and uniform Au nanoparticles highly dispersed on the support that displays a typical thin-layered morphology due to doped  $Al_2O_3$ (Fig. 4-a) [53]. The size of Au nanoparticles is found narrowly distributed and the mean particle size is measured of  $2.9 \pm 0.2$  nm. HRTEM image (Fig. 4-b) reveals an interplanar spacing (0.234 nm) identical to the (1 1 1) plane of Au. A geometric morphology of truncated cubo-octahedral may be recognised. As a matter of fact, such small and highly-dispersed Au nanoparticles

#### Table 4

Composition and textural property of the Au/Zn<sub>x</sub>Al<sub>2</sub>O<sub>3</sub> catalysts.

Entry	Catalyst	Au loading	(wt.%)	Zn/Al mola	r ratio	d,Al <sub>2</sub> O <sub>3</sub> (nm) <sup>a</sup>	$S_{\rm BET} (m^2/g)^{\rm b}$	$V_{\rm P}  ({\rm cm}^3/{\rm g})^{\rm b}$	$D_{\rm P} ({\rm nm})^{\rm b}$
		ICP-MS	XPS	ICP-MS	XPS				
1	Au/Al <sub>2</sub> O <sub>3</sub>	0.39	0.34	_	_	4.2	298	0.49	5.3
2	$Au/Zn_{0.01}Al_2O_3$	0.40	0.35	0.01	0.02	5.0	259	0.31	4.2
3	Au/Zn <sub>0.02</sub> Al <sub>2</sub> O <sub>3</sub>	0.40	0.36	0.02	0.03	5.2	304	0.27	3.7
4	Au/Zn <sub>0.04</sub> Al <sub>2</sub> O <sub>3</sub>	0.39	0.34	0.04	0.05	6.0	281	0.31	4.2
5	Au/ZnO	0.36	0.33	-	_	_	5	0.02	19.6

<sup>a</sup> Mean crystal size of Al<sub>2</sub>O<sub>3</sub> calculated by Scherrer equation from the (4 4 0) plane of XRD patterns.

<sup>b</sup> Data obtained from the bare supports.



Fig. 1. XRD patterns with a zoomed region for the (a)  $Al_2O_3$ , (b)  $Zn_{0.01}Al_2O_3$ , (c)  $Zn_{0.02}Al_2O_3$ , (d)  $Zn_{0.04}Al_2O_3$ , and (e) ZnO supports.



Fig. 2. N<sub>2</sub> adsorption/desorption isotherms and the corresponding pore size distribution for (a) Al<sub>2</sub>O<sub>3</sub>, (b) Zn<sub>0.01</sub>Al<sub>2</sub>O<sub>3</sub>, (c) Zn<sub>0.02</sub>Al<sub>2</sub>O<sub>3</sub>, (d) Zn<sub>0.04</sub>Al<sub>2</sub>O<sub>3</sub>, and (e) ZnO supports.

 Table 5

 XPS parameters of Au 4f<sub>7/2</sub>, Al 2p<sub>3/2</sub>, Zn 2p<sub>3/2</sub> and O 1 s lines for the Au/Zn<sub>x</sub>Al<sub>2</sub>O<sub>3</sub> catalysts.

Entry	Catalyst	Bonding energy	Bonding energy (eV)				
		Au 4f <sub>7/2</sub>	Al 2p <sub>3/2</sub>	Zn 2p <sub>3/2</sub>	O 1s $(O_{\alpha}, O_{\beta})$		
1	$Au/Al_2O_3$	83.5	74.3	-	530.6, 532.1	64.4	
2	$Au/Zn_{0.01}Al_2O_3$	83.6	74.5	1021.9	530.7, 532.2	65.5	
3	$Au/Zn_{0.02}Al_2O_3$	83.4	74.4	1021.8	530.6, 532.1	68.7	
4	$Au/Zn_{0.04}Al_2O_3$	83.6	74.4	1021.9	530.7, 532.2	56.5	
5	Au/ZnO	82.9	-	1020.9	529.7, 531.2	53.9	

bearing this morphology have been found highly efficient toward aerobic oxidation of simple-to-complex alcohols [4,38,54].

The acidic-basic properties of a series of supports are examined by NH<sub>3</sub>- and CO<sub>2</sub>-TPD. As displayed in Fig. 5, no apparent weak acidic or basic sites can be measured, which could be related with interactions between surface OH group and NH<sub>3</sub> or CO<sub>2</sub> probe molecule, respectively. Zn-doped Al<sub>2</sub>O<sub>3</sub> exhibits similar acidic and basic sites to those of Al<sub>2</sub>O<sub>3</sub>. The broad CO<sub>2</sub> desorption peak can be assigned to the contribution of the medium basic sites centred at ca. 350 °C due to the M<sup>n+</sup>– O<sup>2–</sup> pairs (M = Al<sup>3+</sup>or Zn<sup>2+</sup>) and the strong basic sites centred at ca. 440 °C due to the isolated  $O^{2-}$  ions [55]. While the broad NH<sub>3</sub> desorption peak located at ca. 350–750 °C can generally be attributed to the medium-tostrong Lewis acid sites related to Al<sup>3+</sup>or Zn<sup>2+</sup> cations [56]. With increasing the Zn<sup>2+</sup>dopant both CO<sub>2</sub>- and NH<sub>3</sub>-desorption peaks obviously become more intensive and shift to higher temperatures. This suggests that the strength and number of acidic or basic sites of Zn<sub>X</sub>Al<sub>2</sub>O<sub>3</sub> supports may be enhanced. The moderate-strength acidic and basic sites can be measured on the optimal Zn<sub>0.02</sub>Al<sub>2</sub>O<sub>3</sub> support (Table S3). As already demonstrated in literature for supported-Au catalysts, those supports bearing both acidic and basic sites in an appropriate strength play a crucial role in



 $\textbf{Fig. 3. O 1s and } Zn \ 2p \ XPS \ spectra \ of \ the \ (a) \ Au/Al_2O_3, \ (b) \ Au/Zn_{0.01}Al_2O_3, \ (c) \ Au/Zn_{0.02}Al_2O_3, \ (d) \ Au/Zn_{0.04}Al_2O_3, \ and \ (e) \ Au/ZnO \ catalysts.$ 



Fig. 4. (a) TEM image with insertion of size distribution of Au nanoparticles, and (b) HRTEM image of Au nanoparticles for the Au/Zn<sub>0.02</sub>Al<sub>2</sub>O<sub>3</sub> catalyst.



Fig. 5.  $CO_2$ -TPD and NH<sub>3</sub>-TPD profiles of the (a)  $Al_2O_3$ , (b)  $Zn_{0.01}Al_2O_3$ , (c)  $Zn_{0.02}Al_2O_3$ , (d)  $Zn_{0.04}Al_2O_3$ , and (e) ZnO supports.

activating the O—H bond in various alcohols [57–59]. Moreover, it was revealed that the acidic-basic sites of the hydroxyapatite surface may play an important role in determining the efficiency and compatibility of the Au/HAP catalyst for imine synthesis from alcohols and amines [39].

## 3.2. Influence of calcination temperature on supports

The calcination temperature is usually important and decisive for the final structural, morphological, acidic-basic, redox and other properties of oxide materials. As shown in Table 6, the calcination temperature used for the Zn<sub>0.02</sub>Al<sub>2</sub>O<sub>3</sub> support has an effect mainly on conversion of benzyl alcohol. Between 300 °C and 800 °C a volcano-like tendency can be observed and the optimal conversion is obtained over the support calcined at 400 °C. To rationalise this effect, XRD, N<sub>2</sub> physisorption, CO<sub>2</sub>-/NH<sub>3</sub>-TPD, and XPS are conducted. When calcined at 300 °C the Zn<sub>0.02</sub>Al<sub>2</sub>O<sub>3</sub> support exhibits AlO(OH) phase (JCPDS #49-0133) due to the dried (at 110 °C) solid (Fig. S2). If calcined at higher than 400 °C only  $\gamma$ -Al<sub>2</sub>O<sub>3</sub> phase is observed. The mean size of Al<sub>2</sub>O<sub>3</sub> crystals slightly grows bigger with increasing calcination temperature (Table S4). A series of typical type-IV isotherms and the mesoporosity are well

## Table 6

Oxidative coupling of benzyl alcohol and aniline over Au nanoparticles l	loaded on the Zn <sub>0.02</sub> Al <sub>2</sub> O <sub>3</sub> supports calcined at different temperate	ires.
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Entry	T, Calcination (°C)	Conv. 1 (%)	Select. 3 (%)	Select. 4 (%)	Yield 3 (%)
1	300	62	>99	<1	61
2	400	73	>99	<1	72
3	500	67	>99	<1	66
4	650	59	99	1	58
5	800	52	99	1	51

Reaction conditions: benzyl alcohol, 0.5 mmol; aniline, 0.75 mmol; catalyst, Au/Zn<sub>0.02</sub>Al<sub>2</sub>O<sub>3</sub>, 40 mg; toluene, 5 mL; air, 1 atm; temperature, 60 °C; time, 8 h.



**Fig. 6.** (a) Time course and (b) kinetic curve for oxidative coupling of benzyl alcohol with aniline and aerobic oxidation of benzyl alcohol. (c) Time course for condensation of benzaldehyde and aniline in the presence of Ar with or without catalyst. (d) Time course for oxidative coupling of benzyl alcohol with aniline in the presence of Ar or air. Reaction conditions: benzyl alcohol, 0.5 mmol; aniline, 0.75 mmol; benzaldehyde, 0.5 mmol; Au/Zn<sub>0.02</sub>Al<sub>2</sub>O<sub>3</sub>, 80 mg; toluene, 5 mL; air, 1 atm; A, 1 atm; temperature, 60 °C.

maintained (Fig. S3), however, the specific surface areas obviously decrease from 304 m<sup>2</sup>/g to 145 m<sup>2</sup>/g due to the formation of highly crystalized oxides and the irregular distribution of pore size (Fig. S3, Table S4). Thus the reactive surface sites of the support would be reduced upon the higher calcination temperature. The number and strength of the basic sites of Zn<sub>0.02</sub>Al<sub>2</sub>O<sub>3</sub> are reinforced when increasing calcination temperature ( $300 \rightarrow 800 \ ^{\circ}C$ ), whereas the number of the acidic sites is found clearly declined even if the acid strength becomes slightly higher (Table S3, Fig. S4). Besides, the valence states of Au, Zn, Al and O are independent with the calcination temperature (Fig. S5, Table S5), despite the proportion of reactive surface  $O_{\beta}$  species descends when the support is calcined at higher temperatures. Therefore, it can be disclosed that calcination of the Zn<sub>x</sub>Al<sub>2</sub>O<sub>3</sub> supports is a crucial factor that may influence the catalytic performances mainly by modification on crystalline structure, acidity-basicity and surface oxygen species for the final catalysts.

## 3.3. Studies on reaction pathway and mechanism

To deeply understand the reaction pathway and the plausible reaction mechanism, the time-dependent performance of the  $Au/Zn_{0.02}Al_2O_3$  catalyst is measured for oxidative coupling of benzyl alcohol with aniline and aerobic oxidation of benzyl alcohol in the absence of aniline, respectively (Fig. 6-a). It can be clearly seen that the catalyst is highly selective to imine formation. Only traces of benzaldehyde (select. <0.5%) as by-product is formed during the oxidative coupling whole reaction. Conversion of benzyl alcohol increases linearly during the first 2 h and already approaches 50%. By further extending reaction time the increase of alcohol conversion becomes relatively gentle, reaching 100% after 8 h. Compared to aerobic oxidation of benzyl alcohol which needs 11 h to achieve a full conversion, the presence of aniline enables to facilitate conversion of benzyl alcohol by accelerating the initial rate, as clearly shown in Fig. 6-b and Table 7. At the same time, the catalytic oxidation of benzyl alcohol to benzaldehyde is an equilibrium or reversible reaction that can be promoted by the addition of aniline probably related with its weak basicity. The observation here is in agreement with the previous investigation on molar ratio of aniline to benzyl alcohol (Entry 7-9, Table 2). To be recalled, both oxidative coupling and aerobic oxidation cannot be driven by the Au-absent Zn<sub>X</sub>Al<sub>2</sub>O<sub>3</sub> oxides. And moreover, it is confirmed in this work that the condensation of benzaldehyde with aniline proceeds very fast, a stoichiometric yield (>99%) of benzylideneaniline can be obtained at 60 °C after 2 h in the presence of Ar (Fig. 6-c). To be mentioned, the yield of imine in absence of catalyst is found nearly the same as the value with catalyst under either O<sub>2</sub> or Ar. To further identify the role of the catalyst in condensation step, the reaction is performed with a higher temperature at  $80\ensuremath{\,^\circ C}$  under the same conditions. Interestingly, almost the same data during time course are also obtained whatever the presence

#### Table 7

Comparison on the initial conversion rates of benzyl alcohol in oxidative coupling with aniline and in aerobic oxidation over the  $Au/Zn_{0.02}Al_2O_3$  catalyst.

Entry	Catalyst	Initial conv. rate (mmol·g <sup>-1</sup> .·h <sup>-1</sup> ), with aniline	Initial conv. rate (mmol·g <sup>-1</sup> .h <sup>-1</sup> ), without aniline
1	$Au/Al_2O_3$	0.25	0.18
2	Au/Zn <sub>0.01</sub> Al <sub>2</sub> O <sub>3</sub>	0.98	0.83
3	Au/Zn <sub>0.02</sub> Al <sub>2</sub> O <sub>3</sub>	1.56	1.19
4	Au/Zn <sub>0.04</sub> Al <sub>2</sub> O <sub>3</sub>	0.53	0.43
5	Au/ZnO	0.36	0.29

Reaction conditions: benzyl alcohol, 0.5 mmol; aniline, 0.75 mmol;  $Au/Zn_{0.02}Al_2O_3$ , 80 mg; toluene, 5 mL; air, 1 atm; temperature, 60 °C; time, 1 h.

 $\begin{array}{c|c} & H & Air(O_2) \\ & H & Air(O_2) \\ & & V_0 \\ & & V_0 \\ & & & V_0 \\ \end{array}$ 

Scheme 2. Plausible reaction mechanism for oxidative coupling of benzyl alcohol and aniline catalysed by  $Au/Zn_XAl_2O_3$ .

of catalyst or not (Fig. 6-c). Moreover, >99% yield of benzylideneaniline can be achieved after only 1 h at 80 °C. This is in agreement with the previous reports [18,21]. Previously, S. Gao et al. verified the first order for bimolecular condensation of benzaldehyde and aniline in the homogeneous liquid phase in absence of catalyst [18]. Therefore, as soon as benzaldehyde is produced from benzyl alcohol, it can be immediately condensed with aniline to yield imine. Hence, the aerobic oxidation of benzyl alcohol to benzaldehyde can be considered as the rate-determining step for the direct coupling of benzyl alcohol with aniline. As expected, the initial conversion rates of benzyl alcohol over a series of Au/Zn<sub>x</sub>Al<sub>2</sub>O<sub>3</sub> catalysts depending on the Zn/Al molar ratio are in consistent with their performances for coupling alcohol and aniline (Fig. 6-b, Table 2). Metallic Au nanoparticles play a predominant role and allow significantly improving the yield of imine by accelerating the rate-determining step, because Au-based catalysts have been highly recognized for their superior behaviours for diverse mild and efficient selective aerobic oxidation of alcohols. On the other hand, molecular  $O_2$  and the surface  $O_\beta$  oxygen species play an important role in the rete-determining step. A time-online plot experiment shows that conversion of benzyl alcohol to benzaldehyde 'stops' under inert gas after 4 h (Fig. 6-d), i.e., conversion of benzyl alcohol stabilises at 33%, and then adding air into the reactor triggers the oxidation process and leads to an obvious increase in the conversion. This may confirm the contribution of the surface  $O_{B}$  species in the  $Zn_{x}Al_{2}O_{3}$  supports, because those reactive oxygen species could be progressively consumed and then, after full depletion, the reaction would probably stop. When fresh air is re-provided, O<sub>2</sub> could be dissociated at the vacancy site to generate active surface  $O_{\beta}$  species.

It is widely accepted that the OH group in benzyl alcohol is prone to adsorb onto the metallic Au nanoparticles to form a metal alkoxide intermediate [31,35], as shown in Scheme 2. Several computational studies demonstrated that the OH group or the formed alkoxide species can rapidly diffuse over the Au (111) plane, owing to the quite low energy barrier [60]. On the other hand, it is generally accepted that additional basic additives or basic sites could promote the activation of the O-H bond in alcohol [58,59]. Thus, it can be speculated that the basic sites (i.e.,  $M^{n+}-O^{2-}$  pairs as medium basic sites and  $O^{2-}$  ions as strong basic sites) from the Zn<sub>X</sub>Al<sub>2</sub>O<sub>3</sub> support should be benefit to activating the O-H bond to form the alkoxide intermediate. The subsequent formation of benzaldehyde, as well as the Au-H hydride species, via β-hydrogen elimination is the rate-controlled step and requires small Au nanoparticles in metallic state [37,58]. Hence the reactive surface  $O_{B}$  species may participate in the reaction by abstracting the  $\beta$ -H proton from the alkoxide intermediate, thus forming benzaldehyde. In addition, the strong interaction between Au<sup>0</sup> and Zn<sub>x</sub>Al<sub>2</sub>O<sub>3</sub> may lower the formation energy of oxygen vacancy and could further promote the catalytic activity at low temperatures. Moreover, the acidic sites on the Zn<sub>x</sub>Al<sub>2</sub>O<sub>3</sub> support might participate in the transformation of Au-H hydride which is believed to be oxidized by  $O_2$  to yield water [39]. The final step is the rapid

and uncatalysed condensation of the as-formed benzaldehyde with aniline to give benzylideneaniline. In this work, the optimal Au/Zn<sub>0.02</sub>Al<sub>2</sub>O<sub>3</sub> catalyst shows the highest specific surface area and proportion of reactive surface O<sub>β</sub> species, a moderate basicity and acidity, and also a strong interaction with highly dispersed metallic Au nanoparticles. These unique features could be responsible for the excellent catalytic performance for direct oxidative coupling of alcohol and amine.

# 3.4. Reusability, low-temperature test, scaling-up test and comparison study

The stability and reusability of a heterogeneous catalyst are important for sustainable chemistry. The used Au/Zn<sub>0.02</sub>Al<sub>2</sub>O<sub>3</sub> catalyst after the post-treatment (see Section 2) is tested for the recycling reactions under the same conditions. During a consecutive use of five cycles, as shown in Fig. 7, the catalyst still remains a very stable yield to benzylideneaniline (>99%), behaving as good as the fresh catalyst. To avoid any possible saturation of catalytic activity due to the used optimised reaction conditions, conversion of benzyl alcohol during the kinetic-controlled region, i.e., the initial stage after 1 h, is examined. The catalyst indeed shows a considerable stability. Moreover, no further conversion of alcohol can be observed during the leaching test by hot filtration to remove the solid catalyst (Fig. 7), which suggests the good retention of catalytic active components. ICP-MS analysis shows that the amount of Au, Al and Zn species present in the filtrate is below the detection limit (2 ppb), confirming no leaching of Au or support in the used reaction mixture. This may be attributed to the existence of strong interaction between the active Au<sup>0</sup> species and the robust Zn<sub>x</sub>Al<sub>2</sub>O<sub>3</sub> support. XRD and TEM measurements on the used catalyst clearly reveal the integrity of the characteristic structure of Zn<sub>x</sub>Al<sub>2</sub>O<sub>3</sub> support and the similarity in size distribution of Au nanoparticles (Fig. S6). In addition, the used catalyst shows no change on the valence state of active components. Moreover, relatively similar acidic-basic property due to  $Zn_XAl_2O_3$  support could be still observed after recycling use.

In the point view of potential industrial application, an ideal heterogeneous catalyst is expected to work efficiently at mild conditions and ought to be applicable to large-scale production. To our satisfaction, the Au/Zn<sub>0.02</sub>Al<sub>2</sub>O<sub>3</sub> catalyst allows effectively coupling benzyl alcohol and aniline at as low as only 30 °C. An excellent yield (98%) to benzylideneaniline can be obtained by simply extending reaction time to 72 h and involving a higher catalyst mass (Table 8). To the best of our knowledge, this is the best data ever reported at a near room temperature for Au-based catalysts (Table 1). The developed Au/Zn<sub>0.02</sub>Al<sub>2</sub>O<sub>3</sub> catalyst is superior to other supported-Au and Au-Pd catalysts in terms of reaction conditions and catalytic efficiency. Our catalyst can work effectively without any base additives at a very mild temperature (30 °C) by using air as oxidant. Moreover, a highest TOF (39.1  $h^{-1}$ ) is obtained at 60 °C based on a >99% yield to benzylideneaniline. Finally, this catalyst shows satisfying stability and reusability. In addition, the catalytic performance at low temperature is found also one of the best compared with CeO<sub>2</sub>-based catalysts recently reported in the literature [19,21,23]. Furthermore, the developed catalyst is tested in the concentrated reactant mixture (Table 8). It enables to synthesise gram-scale benzylideneaniline (1.08 g), and an excellent yield up to 99% is achieved at 60 °C after 24 h. Those above performances suggest a sustainable and practical catalytic system based on the  $Au/Zn_{0.02}Al_2O_3$  catalyst for imine synthesis.

#### 3.5. Substrate scope

Table 9 reports direct oxidative coupling of aniline with various primary alcohols over the Au/Zn<sub>0.02</sub>Al<sub>2</sub>O<sub>3</sub> catalyst at 60 °C. To be



**Fig. 7.** Recycling test of the  $Au/Zn_{0.02}Al_2O_3$  catalyst within kinetic-controlled region and under optimised conditions, and leaching test of metals in the  $Au/Zn_{0.02}Al_2O_3$  catalyst. Reaction conditions: benzyl alcohol, 0.5 mmol; aniline, 0.75 mmol; catalyst, 80 mg; toluene, 5 mL; air, 1 atm; temperature, 60 °C.

#### Table 8

Low-temperature test and scaling-up test for benzylideneaniline synthesis from oxidative coupling of benzyl alcohol and aniline over the Au/Zn<sub>0.02</sub>Al<sub>2</sub>O<sub>3</sub> catalyst.

Entry	Reactants: 1, 2	Catal. mass (g)	T (°C)	Time (h)	Yield <b>3</b> (%)
1 <sup>a</sup>	0.5 mmol, 0.75 mmol	0.16	30	72	98
2 <sup>b</sup>	6 mmol (0.65 g), 9 mmol (0.84 g)	0.72	60	24	99 (1.08 g)

Reaction conditions:

<sup>&</sup>lt;sup>a</sup> toluene, 5 mL; air, 1 atm. The by-product is benzaldehyde.

<sup>&</sup>lt;sup>b</sup> toluene, 10 mL; air, 1 atm.





Reaction conditions: alcohol, 0.5 mmol; aniline, 0.75 mmol; catalyst, 80 mg; toluene, 5 mL; air, 1 atm; temperature, 60 °C. Reaction time, conversion of alcohol and yield of imine were reported, respectively.

recalled, selectivities to the produced imines in Table 9 are found higher than 99%. The substituted benzyl alcohols are first tested. Benzyl alcohol with both electron-donating (MeO, Me and tBu) and electron-withdrawing (NO<sub>2</sub> and Cl) substituents can be effectively converted, and high yield of imines (**3a–3f**, 93–99%) are

obtained. Still, some differences in the yield and the required reaction time may be related with the effect of property and location of substituents. The electron-donating groups would reduce the electrophilicity of benzylic carbon by enriching its electron density, leading consequently to a less reactivity with the nucleophilic

#### Table 10

Oxidative coupling of benzyl alcohol with different primary amines over the Au/Zn<sub>0.02</sub>Al<sub>2</sub>O<sub>3</sub> catalyst.



Reaction conditions: benzyl alcohol, 0.5 mmol; amine, 0.75 mmol; catalyst, 80 mg; toluene, 5 mL; air, 1 atm; temperature, 60 °C. Reaction time, conversion of benzyl alcohol and yield of imine were reported, respectively.

amine. The electron-withdrawing groups could facilitate removing hydrogen from hydroxyl group. The deprotonated alcohol or alkoxide would abstract hydride from benzylic carbon via oxidative dehydrogenation to generate carbonyl compound that reacts immediately with aniline to form imine. Besides, the effect of location (**3b** and **3c**) and steric hindrance (**3d**) of substituents cannot be disregarded. Cyclohexylmethanol and pyridin-4-methanol are examined in this reaction, to respectively afford 95% (3g) and 93% (3h) yield to the desired imines, respectively. The aliphatic 1-octanol shows as expected a much lower yield to the imine 3i (30%), which is well recognised by the difficulty in activating the non-branched fatty alcohols. Furthermore, several complex alcohols including 3,4-(methylenedioxy)benzyl alcohol, 2-naphthalenemethanol and 2-thiophenemethanol can be also activated and converted to the corresponding imines (**3j-3l**) with a moderate to low vield.

Table 10 reports direct oxidative coupling of benzyl alcohol with various primary amines over the Au/Zn<sub>0.02</sub>Al<sub>2</sub>O<sub>3</sub> catalyst at 60 °C. To be noted, selectivities to the produced imines in Table 10 are found higher than 99%. As is previously disclosed the selective oxidation of benzyl alcohol is the key step in the tandem coupling process. Thereby, the nature of amines may probably have an impact on the conversion and product yield. The Au/Zn<sub>0.02</sub>Al<sub>2</sub>O<sub>3</sub> catalyst shows a high imine yield of **3m** to **3q** (94–99%) from the substituted anilines. As expected, electron-withdrawing group (Cl) and electron-donating groups (MeO and Me) could enhance the nucleophilicity of aniline and thus promote the nucleophilic attack, despite some minor variations could be observed due to the property and the location of substituents. Compared with aniline, coupling benzyl alcohol with benzyl amine also yields a high imine **3r** (96%), which may be due to the high basicity of benzyl amine and/or the possibility of its self-coupling reaction to form imine. The linear aliphatic 1-octanamine would afford a high desired imine production (3s, 92%). Thereby, it is evident again of that, when comparing to the yield of 3i, the conversion of an alcohol to an aldehyde is the rate- and yield-determining step in the cross-coupling of alcohols with amines to imines. *t*-Butylamine and cyclohexylamine could also react with benzyl alcohol to yield the desired imines (**3t**, **3u**) in a moderate to low yield. In addition, pyridin-4-amine offers a low imine yield to **3v** (28%), which is probably influenced by the basicity of pyridine group. In summary, the Au/Zn<sub>0.02</sub>Al<sub>2</sub>O<sub>3</sub> catalyst shows a wide scope in activating various primary alcohols and amines for imine synthesis via direct oxidative coupling. The electron effect of substituents, the nucleophilicity and/or electrophilicity of substrates, and even the acidic-basic properties of substrates and catalysts, are worth studying comprehensively in a future work.

# 4. Conclusions

In summary, we developed a novel, efficient and sustainable Au-based catalytic system for imine synthesis from the direct oxidative coupling of alcohol and amine under air atmosphere. Au nanoparticles loaded on Zn-doped  $\gamma$ -Al<sub>2</sub>O<sub>3</sub> was reported for the first time as active, selective and stable heterogeneous catalyst for a wide scope of imine productions from the primary alcohols and amines at very mild conditions. It was demonstrated that the uniform and small (2.9 nm) Au nanoparticles in metallic state were active sites and responsible for activating and converting an alcohol to an aldehyde, i.e., the rate-determining step. The subsequent condensation of aldehyde with amine was found fast and uncatalysed. The variation of Zn<sup>2+</sup> doping and calcination temperature would modify the textural property, acidity-basicity and surface oxygen species for support materials, which were decisive for the excellent performance of Au/Zn<sub>x</sub>Al<sub>2</sub>O<sub>3</sub> catalyst for imine

synthesis from direct oxidative coupling of alcohol and amine. The basic sites ( $M^{n+}-O^{2-}$  pairs and  $O^{2-}$  ions) on the Zn<sub>x</sub>Al<sub>2</sub>O<sub>3</sub> support could be benefit to activating the O-H bond to form the alkoxide intermediate. And then the reactive surface  $O_{\beta}$  species may abstract the  $\beta$ -H proton from the alkoxide intermediate to thus form an aldehyde. Finally the acidic sites ( $M^{n+}$  ions) on the  $Zn_xAl_2$ -O<sub>3</sub> support may participate in the transformation of Au–H hydride which was believed to be oxidized by  $O_2$  to yield water.

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#### **Appendix A. Supplementary material**

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jcat.2019.07.027.

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