FULL PAPERS

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C-C Bond Formation *via* C-H Activation and C-N Bond Formation *via* Oxidative Amination Catalyzed by Palladium-Polyoxometalate Nanomaterials Using Dioxygen as the Terminal Oxidant

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Abstract: An efficient heterogeneous palladiumpolyoxometalate catalyst with the formula Pd- $H_6PV_3Mo_9O_{40}/C$ has been successfully developed for carbon-carbon (C–C) bond formation *via* carbon-hydrogen (C–H) activation and carbon-nitrogen (C–N) bond formation *via* oxidative amination using oxygen as the terminal oxidant. The coupling processes are simple, and use relatively mild conditions

Introduction

Transition metal-catalyzed carbon-carbon (C-C) bond formation via carbon-hydrogen (C-H) activation and carbon-nitrogen (C-N) bond formation via C-H activation and oxidative amination have been the subject of intense investigation in recent years.^[1] Various transition metals, for example, Pd, $^{[1a-h,l,m,2]}$ Ru, $^{[1c,d,g,h,3]}$ Rh, $^{[1c,d,f,g,i,j,4]}$ Cu, $^{[1c-h,5]}$ and Fe, $^{[1d,h,k,6]}$ have been studied in different types of C-H activation and oxidative coupling reactions. In particular, Pd-catalyzed C–H activation coupling reactions^[2a-d,i,j]</sup> and oxi-dative amination reactions^{<math>[2e-h,k]}</sup> have emerged as effi-</sup></sup> cient synthetic methods for the construction of C-C and C-N bonds. These coupling reactions offer a greener and more atom-efficient approach towards the synthesis of complex molecules as they do not require the presence of a functional group such as halide, tosylate, mesylate or organometallic moeity in the starting materials. Hence, less waste would be generated, and the overall cost and efficiency of the synthetic process would be improved.

The construction of C–C or C–N bonds by using only C–H bonds would only occur under oxidative conditions (Scheme 1). In homogeneous Pd-catalyzed to form the desired products. In addition, less waste is generated as no additional reagents such as organic/inorganic oxidants are required, and water is the only by-product generated.

Keywords: C–H activation; heterogeneous catalysis; nanomaterials; palladium; polyoxometalates

C–H activation coupling reactions, a variety of organic and inorganic oxidants such as benzoquinone,^[2a,7] PhI(OAc)₂,^[8] AgOAc,^[9] Ag₂CO₃,^[10] Cu(OAc)₂,^[11] and oxone,^[12] has been used. These external oxidants would reduce the overall "greenness" of the process since more waste would be produced. A greener approach would involve the use of O₂ as the stoichiometric oxidant since water would be the only by-product formed.^[2b-k] Some of the reported C–H activation coupling reactions and oxidative amination reactions used O₂ as the sole oxidant,^[2c,f-j] while others required the presence of a catalytic amount of a co-oxidant^[2b,k] or an electron-transfer mediator (e.g., polyoxometalates) to facilitate the re-oxidation process.^[2d,e,13] The use of polyoxometalates is particularly attractive as they are oxidatively stable and have been used (on

$$C-H + H-C \xrightarrow{Catalyst} C-C$$

$$C-H + H-N \xrightarrow{Catalyst} C-N$$

Scheme 1. C–C and C–N bond formation *via* C–H activation or oxidative amination.

2988

their own and in combination with Pd) in oxidation reactions.^[14]

The use of heterogeneous catalysts such as supported Pd nanoparticles (NPs) in these C-H activation coupling reactions and oxidative amination reactions would represent a significant step towards green and sustainable chemistry since these catalysts could be recovered and reused multiple times. Pd NPs have been developed for various catalytic reactions.^[15] However, the use of Pd-based nanomaterials in C-H activation or oxidative amination reactions is not well explored in the literature.^[16] To date, the reactions are limited to homo-coupling of 4-methylpyridine,^[16a] direct acylation of aryl bromides and iodides with aldehydes,^[16b] and direct arylation of heteroaromatics with aryl bromides or iodides.^[16c,d] Herein, we report our results on the efficient intermolecular C-C bond formation via C-H activation and C-N bond formation via oxidative amination catalyzed by Pd-polyoxometalate (Pd-POM) nanomaterials^[17] using \hat{O}_2 as the terminal oxidant.

Results and Discussion

A series of supported Pd-POM nanomaterials on carbon (Pd-POM/C) was prepared via aqueous methods. The Pd NPs were produced by reduction of $Pd(NO_3)_2$ in water with NaBH₄ in the presence of the appropriate POM and the carbon support. The POM was previously well dispersed onto the carbon support via sonication in the solvent water (see Supporting Information). Using this procedure, four different types of Pd-POM/C nanomaterials, $Pd-H_3PMo_{12}O_{40}/C$ $(Pd-PMo_{12}/C), Pd-H_4PVMo_{11}O_{40}/C (Pd-PV_1Mo_{11}/C),$ $Pd-H_5PV_2Mo_{10}O_{40}/C$ $(Pd-PV_2Mo_{10}/C)$ and $Pd-H_6PV_3Mo_9O_{40}/C$ (Pd-PV₃Mo₉/C), were produced. The transmission electron microscopy (TEM) images of the Pd-PMo₁₂/C, Pd-PV₁Mo₁₁/C, Pd-PV₂Mo₁₀/C and Pd-PV₃Mo₉/C nanomaterials showed that the Pd NPs were well dispersed with diameters of 2-3 nm (Figure 1, **a-d**). The Pd loadings on these different Pd-POM/C nanomaterials were determined by inductively-coupled plasma mass spectrometry (ICP-MS) analysis to range from 7.9 to 12.5 wt%, while the POM loadings (14.8–15.2 wt%) showed much less variation. The presence of both Pd and POM in these Pd-POM/C nanomaterials was further confirmed by TEM energy dispersive X-ray (EDX) analysis (Supporting Information, Figure S1).

The presence of POM during the synthesis of the Pd NPs on the carbon support was crucial as it served as a capping agent and ensured that the Pd NPs achieved were small, uniform and well-dispersed. When the Pd NPs were synthesized in the absence of the POM (i.e., as Pd/C nanomaterial), the Pd NPs ob-

tained were not uniform and had a wider size distribution of 3–6 nm (Figure 1, **e**).

The five supported Pd nanomaterials were investigated for their catalytic activities in the oxidative C-C coupling via C-H activation using the model substrates acetanilide and *n*-butyl acrylate (Table 1, entries 1–5). These initial studies showed that with a catalyst loading of 5 mol% of Pd and 0.4–0.6 mol% of POM, the Pd-PV₃Mo₉/C nanomaterial gave the best result for reaction at 60°C in toluene for 16 h using O_2 gas as the terminal oxidant, with a 54% isolated yield of the desired coupled product (Table 1, entry 4). The coupling reaction was selective and occurred at the ortho position in the acetanilide substrate, and a minor quantity (<3%) of the disubstituted product was obtained. The use of other types of POMs resulted in lower yields of the product (Table 1, entries 1–3). The presence of POM was vital for this oxidative C-C coupling reaction since POM served as a re-oxidation catalyst under O₂. In the absence of POM, the Pd/C nanomaterial displayed no catalytic activity in this C-H activation reaction (Table 1, entry 5). When additional PV_3Mo_9 was added to the reaction mixture, the Pd/C nanomaterial did show some catalytic activity, but the yield of the product was low (Table 1, entry 6). Hence, POM has to be incorporated during the synthesis of the Pdbased nanomaterials so that they were well dispersed and in close contact with the Pd NPs.

The five Pd-based nanomaterials were also subjected to X-ray photoelectron spectroscopy (XPS) analysis to determine the surface oxidation state of Pd. As shown in Figure 2, the Pd 3d XPS spectra for the five supported Pd nanomaterials could be deconvoluted into two pairs of doublets. The doublet with a higher binding energy (BE) was attributed to Pd(II), while that with a lower BE was assigned to Pd(0).^[18] All five Pd-based nanomaterials contained more oxidized Pd(II) surface species (~61-77%). The BEs of the Pd(II) $3d_{3/2}$ and $3d_{5/2}$ peaks for the four Pd-POM/C nanomaterials (Pd-PMo₁₂/C, Pd-PV₁Mo₁₁/C, Pd- PV_2Mo_{10}/C and $Pd-PV_3Mo_9/C$) were shifted to higher values (by 0.6-0.9 eV) as compared to Pd/C (see Supporting Information, Table S1). In the oxidative coupling reaction of anilides with acrylates catalyzed by homogeneous $Pd(OAc)_2$, it was proposed that a Pd(II) species was the active catalyst.^[2b] In our studies, the dramatic difference in the catalytic activities between the Pd-POM/C nanomaterials and Pd/C could be attributed to the different types of Pd(II) surface species. The oxidized Pd(II) species in Pd/C might be the inactive PdO that exhibited a Pd $3d_{5/2}$ peak BE at 336.3 eV.^[18] For the four Pd-POM/C nanomaterials, the oxidizing POMs that were in close contact with the Pd NPs could have selectively modified the latter's surface to produce catalytically active Pd(II) species with higher BEs.



Figure 1. TEM of (**a**) Pd-PMo₁₂/C, (**b**) Pd-PV₁Mo₁₁/C, (**c**) Pd-PV₂Mo₁₀/C, (**d**) Pd-PV₃Mo₉/C, and (**e**) Pd/C.

Using the most active $Pd-PV_3Mo_9/C$ catalyst, the reaction conditions for the oxidative C–C coupling reaction was further optimized with respect to the solvent, temperature and the amount of reactant used (Table 2). The nature of the reaction media was first investigated with polar and non-polar solvents. The non-polar solvent toluene was found to be the most effective for this coupling reaction (Table 2, entry 1). Polar solvents such as 1,4-dioxane, methanol and 1,2-

dichloroethane resulted in lower isolated yields of the product (Table 2, entries 3–5), while no product was formed when N,N-dimethylformamide (DMF) was used as the solvent (Table 2, entry 2). Since O₂ was used as the terminal oxidant, its presence was essential in this C–H activation reaction as evident from the lack of catalytic activity when the reaction was performed under argon (Table 2, entry 6), whereas in the presence of air, a lower yield of the product was

Table 1. C-C bond formation via C-H activation catalyzed by palladium-based nanomaterials.^[a]



Entry	Catalyst	Pd loading [wt%] ^[b]	POM loading [wt%] ^[b]	POM used [mol%]	Yield [%] ^[c]
1	Pd-PMo ₁₂ /C	8.1	15.2	0.5	44
2	$Pd-PV_1Mo_{11}/C$	12.5	15.1	0.4	39
3	$Pd-PV_2Mo_{10}/C$	10.4	14.8	0.4	41
4	Pd-PV ₃ Mo ₉ /C	7.9	15.2	0.6	54
5	Pd/C	17.0	0.0	0.0	0
6 ^[d]	$Pd/C + PV_3Mo_9$	17.0	$0.0^{[e]}$	0.6	9

[a] Reaction conditions: Pd catalyst (5 mol%), 1a (0.2 mmol) and 2a (0.4 mmol), toluene (0.45 mL, purged with O₂ for 5 min), 60 °C, under O₂.

^[b] Pd or POM content in nanomaterials was determined from ICP-MS analysis.

^[c] Isolated and unoptimized yield based on **1a**.

^[d] 0.6 mol% of PV_3Mo_9 (H₆PMo₉V₃O₄₀) was added to the reaction mixture.

^[e] POM loading in Pd/C.



Figure 2. Pd 3*d* XPS spectra of (**a**) Pd-PMo₁₂/C, (**b**) Pd-PV₁Mo₁₁/C, (**c**) Pd-PV₂Mo₁₀/C, (**d**) Pd-PV₃Mo₉/C and (**e**) Pd/C. Approximately 77%, 71%, 72%, 61% and 68% of the Pd in the samples (**a**), (**b**), (**c**), (**d**) and (**e**) are in the Pd(II) oxidation state, respectively.

attained (Table 2, entry 7). Increasing the Pd catalyst loading to 10 mol% led to a small increase in the product yield (Table 2, entry 12) at 60 °C. In contrast, the catalytic activity of the Pd-PV₃Mo₉/C nanomaterial could be improved substantially by increasing the reaction temperature (Table 2, entries 8 and 9). Upon heating the reaction mixture at 80 °C for 16 h, the yield of the product was increased by 22% to 76%. At 80 °C, the yield of the product was reduced to 65% and 60% upon decreasing the Pd catalyst loading to 3 mol% (Table 2, entry 10) and reducing the amount of butyl acrylate to 1.2 molar equivalents (Table 2, entry 11), respectively.

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Table 2. C-C bond formation via C-H activation catalyzed by Pd-PV₃Mo₉/C nanomaterial.^[a]



Entry	Pd [mol%]	Butyl acrylate [mmol]	Solvent	Temperature [°C]	Atmosphere	Yield [%] ^[b]
1	5	0.4	toluene	60	O ₂	54
2	5	0.4	DMF	60	$\tilde{O_2}$	0
3	5	0.4	1,4-dioxane	60	$\tilde{O_2}$	40
4	5	0.4	CH ₃ OH	60	$\tilde{O_2}$	13
5	5	0.4	1,2-dichloroethane	60	$\tilde{O_2}$	48
6 ^[c]	5	0.4	toluene	60	argon	0
7 ^[d]	5	0.4	toluene	60	air	37
8	5	0.4	toluene	70	O_2	62
9	5	0.4	toluene	80	$\tilde{O_2}$	76
10 ^[e]	3	0.4	toluene	80	$\overline{O_2}$	65
11	5	0.24	toluene	80	$\tilde{O_2}$	60
12 ^[f]	10	0.4	toluene	60	$\overline{O_2}$	58

^[a] Reaction conditions: Pd catalyst, PV_3Mo_9 (0.6 mol%), **1a** (0.2 mmol), **2a** (0.24 or 0.4 mmol), solvent (0.45 mL, purged with O_2 for 5 min), 60–80 °C, under O_2 .

^[b] Isolated yield based on **1a**.

^[c] Toluene used was stored in the argon glovebox.

^[d] Toluene was purged with air for 5 min.

^[e] 0.36 mol% of PV_3Mo_9 was used.

^[f] 1.2 mol% of PV_3Mo_9 was used.

The recyclability of the Pd-PV₃Mo₉/C catalyst was investigated by recovering the nanomaterial *via* centrifugation, and reloading the recovered solids with PV₃Mo₉ prior to the next run (Supporting Information, Table S2). ICP-MS analysis of the PV₃Mo₉ loading of the recovered catalyst showed that there was a significant loss of the PV₃Mo₉ content (54% reduction) after the coupling reaction. Reloading the recovered catalyst with PV₃Mo₉ (to restore the PV₃Mo₉) loading back to its original value) was necessary as the yield of the product would decrease substantially (by 23%) if such a step was not undertaken. There was no change in the size of the Pd NPs after the coupling reaction, as confirmed by their TEM images (Figure 3). The Pd-PV₃Mo₉/C catalyst retained 97% of its reactivity (74% yield) after the first recycle, and 79% of its activity (60% yield) was still preserved in the fourth run. To determine if the Pd-PV₃Mo₉/C cat-



Figure 3. TEM images of Pd-PV₃Mo₉/C (a) before and (b) after the C–C bond formation reaction.

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alyst was leaching to form a homogeneous active species, a reaction was prematurely stopped after heating at 80 °C under O₂ for 4 h (i.e., 40% product yield by GC-MS analysis), and filtered hot to remove the solids. Heating of the filtrate at 80 °C under O₂ for 12 h showed no further product formation. ICP-MS analysis of the filtrate confirmed that only traces of Pd were detected in the solution (7 ppm).

The surface chemistry of the Pd-PV₃Mo₉/C catalyst before and after the C–C coupling reaction (first and fourth runs) was subjected to XPS analysis (Supporting Information, Figure S2). There was no significant change in the quantity of the oxidized active Pd(II) species in the Pd-PV₃Mo₉/C catalyst before and after the C–C coupling reactions. Hence, the small decrease in the isolated yield of the C–C coupled product in the recycling experiments was probably not due to deactivation of the active catalytic species, but could be attributed to some loss of the nanomaterial in the recovery process.

Using the optimized set of reaction conditions, we investigated the scope of the oxidative C-C coupling reactions with a variety of substituted anilides and acrylates (Table 3). Functional groups on the acetanilide substrates have a significant impact on the efficacy of the coupling reaction. With an electron-donating CH₃ substituent at the *para* position to the acetamide moiety, the coupling reaction proceeded smoothly with a good yield of 79% (Table 3, 3b). On the other hand, the presence of a stronger electron-donating group such as OCH₃, or an electron-withdrawing group such as F or CF_3 at the para position to the acetamide moiety resulted in lower yields of the desired products (46–63%, Table 3, 3c–e). Electron-donating and electron-withdrawing functional groups such as CH₃, OCH₃, F, Cl and CF₃ at the meta position to the acetamide moiety were also examined. Good yields of 78-80% were attained with the electron-donating CH₃ or the electron-withdrawing F group at the *meta* position to the acetamide moiety (Table 3, 3f and 3h). However, low to moderate yields of 21-53% were achieved in the presence of a stronger electron-donating group such as OCH₃ or electron-withdrawing groups such as Cl and CF₃ at the meta position (Table 3, 3g, 3i, 3j).

From the above results, it appeared that the oxidative C–C coupling reaction catalyzed by Pd-PV₃Mo₉/ C catalyst was suitable for anilide substrates with weakly activating functional groups (CH₃). Anilide substrates with electron-withdrawing groups (F, Cl and CF₃) or stronger electron-donating groups (OCH₃) would lead to lower product yields. However, the substrate **1h** (product **3h**, Table 3) did not follow the above trend. In this case, the F substituent was at the *para* position to the Csp²–H bond undergoing the oxidative coupling reaction. Although the F group has an inductive electron-withdrawing effect, its lone**Table 3.** Scope of C–C bond formation *via* C–H activation catalyzed by Pd-PV₃Mo₉/C nanomaterial.^[a]





^[a] Reaction conditions: Pd catalyst (5 mol%), PV₃Mo₉ (0.6 mol%), **1** (0.2 mmol) and **2** (0.4 mmol), toluene $(0.45 \text{ mL}, \text{ purged with } O_2 \text{ for 5 min})$, 80°C, 16 h, under O_2 .

pairs of electrons could result in an electron-releasing influence through conjugation. Hence, the combination of these two factors could result in an overall weakly activating effect, leading to a good yield of the desired product.

		Ph N H H CO ₂ -	<i>n</i> -Bu DMF, O ₂ 60 °C, 6 h	СО ₂ - <i>п</i> -Ви	
		4a 2a	5a		
Entry	Catalyst	Pd loading [wt%] ^[b]	POM loading [wt%] ^[b]	POM used [mol%]	Yield [%] ^[c]
1	Pd-PMo ₁₂ /C	8.1	15.2	0.5	86
2	$Pd-PV_1Mo_{11}/C$	12.5	15.1	0.4	78
3	$Pd-PV_2Mo_{10}/C$	10.4	14.8	0.4	74
4	Pd-PV ₃ Mo ₉ /C	7.9	15.2	0.6	87
5	Pd/C	17.0	0.0	0.0	0
6 ^[d]	$Pd/C + PV_3Mo_9$	17.0	0.0 ^[e]	0.6	<1

5 mol%

Table 4. C-N bond formation via oxidative amination catalyzed by palladium-based nanomaterials.^[a]

^[a] *Reaction conditions:* Pd catalyst (5 mol%), **4a** (0.2 mmol) and **2a** (0.6 mmol), DMF (0.4 mL, purged with O₂ for 5 min), 60 °C, under O₂.

^[b] The Pd and POM contents in nanomaterials were determined from ICP-MS analysis.

^[c] Isolated and unoptimized yield based on **4a**.

^[d] 0.6 mol% PV_3Mo_9 (H₆PMo₉V₃O₄₀) was added to the reaction mixture.

^[e] POM loading in Pd/C.

The effect of different substituents on the amide moiety was compared using the acetyl, pivaloyl and benzoyl substitution. Replacing the acetyl group with the pivaloyl group afforded comparable yields of the desired coupled product (Table 3, **3a** and **3k**). However, replacement with the benzoyl group resulted in a lower product yield of 45% (Table 3, **3l**). Thus, aliphatic acyl groups were more tolerated in this C–C coupling reaction as compared to the aromatic acyl group.

Different types of acrylates were also investigated with the Pd-PV₃Mo₉/C nanomaterial. In addition to *n*butyl acrylate, other acrylates such as methyl acrylate, ethyl acrylate and isobutyl acrylates also coupled effectively in this reaction (Table 3, 3m-o). However, if the acrylate substrate became too bulky (e.g., with a *t*-Bu group), no coupling reaction occurred.

Besides the oxidative C-C coupling reactions, the Pd-POM/C nanomaterials were also examined for the C-N bond formation *via* oxidative amination using the model substrates diphenylamine and *n*-butyl acrylate (Table 4, entries 1–5). The initial screening results showed that with 5 mol% Pd and a reaction time of 6 h at 60 °C in DMF under O_2 , the Pd-PMo₁₂/C and Pd-PV₃Mo₉/C nanomaterials displayed the highest activities, giving the coupled amine product in 86–87% isolated yields (Table 4, entries 1 and 4). The other two Pd-POM/C nanomaterials gave slightly lower yields of the desired product (Table 4, entries 2 and 3). As with the oxidative C-C coupling reaction, the Pd/C nanomaterial displayed no catalytic activity in this oxidative amination reaction (Table 4, entry 5), even when additional PV₃Mo₉ was added to the reaction mixture (Table 4, entry 6).

To further optimize the oxidative amination reaction conditions over the Pd-PV₃Mo₉/C catalyst, the reaction media, temperature and time were examined systematically (Table 5). The solvent used has a significant impact on this oxidative amination reaction. DMF was the best solvent for this reaction (Table 5, entry 1). No product was obtained when other polar solvents (i.e., 1,4-dioxane, methanol and 1,2-dichloroethane) and non-polar solvent (i.e., toluene) were used (Table 5, entries 2–5). O_2 gas was again critical in this oxidative amination reaction. No product was formed when the reaction was performed under argon (Table 5, entry 6), and a lower yield of 63% was achieved when air was used instead of O_2 (Table 5, entry 7). The catalytic activity of the Pd-PV₃Mo₀/C nanomaterial was not improved through the use of a higher reaction temperature (Table 5, entry 8) or a longer reaction time (Table 5, entry 10). In fact, with a higher reaction temperature of 80°C, the yield of the product was reduced to 66%. Decreasing the amount of *n*-butyl acrylate to 1.5 molar equivalent (Table 5, entry 9) resulted in a lower product yield at 60°C.

The recyclability of the Pd-PV₃Mo₉/C catalyst was examined after recovery of the nanomaterial *via* centrifugation, followed by reloading of the catalyst with PV₃Mo₉ (Supporting Information, Table S3). Reloading of the catalyst with PV₃Mo₉ was essential as the activity of the catalyst would decrease dramatically (by 87% to 10% yield) without reloading PV₃Mo₉. ICP-MS analysis of the PV₃Mo₉ loading in the recovered catalyst (prior to reloading PV₃Mo₉) showed that there was a 70% loss of the PV₃Mo₉ content after the coupling reaction. TEM analysis of the recovered catalyst confirmed that there were no significant changes

	$ \begin{array}{c} Ph \\ N \\ Ph \\ Ph$					
		4a 2a	5a			
Entry	Butyl acrylate [mmol]	Solvent	Temperature [°C]	Atmosphere	Time [h]	Yield [%] ^[b]
1	0.6	DMF	60	O ₂	6	87
2	0.6	toluene	60	$\overline{O_2}$	6	<1
3	0.6	1,4-dioxane	60	$\overline{O_2}$	6	<1
4	0.6	CH ₃ OH	60	$\overline{O_2}$	6	<1
5	0.6	1,2-dichloroethane	60	$\overline{O_2}$	6	<1
6 ^[c]	0.6	DMF	60	argon	6	0
7 ^[d]	0.6	DMF	60	air	6	63
8	0.6	DMF	80	O_2	6	66
9	0.3	DMF	60	$\tilde{O_2}$	6	66
10	0.6	DMF	60	O_2	14	82

Table 5. C-N bond formation via oxidative amination catalyzed by Pd-PV₃Mo₉/C nanomaterial.^[a]

[a] Reaction conditions: Pd catalyst (5 mol%), PV₃Mo₉ (0.6 mol%), 4a (0.2 mmol), 2a (0.3 or 0.6 mmol), solvent (0.4 mL, purged with O₂ for 5 min), 60–80 °C, under O₂.

^[b] Isolated yield based on **4a**.

^[c] DMF used was stored in the argon glovebox.

^[d] DMF was purged with air for 5 min.

to the size and morphology of the Pd NPs after the coupling reaction (Figure 4). XPS analysis of the Pd-PV₃Mo₉/C catalyst after the C–N coupling reaction (fourth run) revealed that a comparable amount of the oxidized active Pd(II) species was still present in the nanomaterial (Supporting Information, Figure S3). After one successive cycle, the catalyst retained 91% of its activity (79% yield), and after three successive cycles, 77% of the reactivity (67% yield) was obtained. To verify if a homogeneous active species was leached from the Pd-PV₃Mo₉/C catalyst, a reaction mixture was heated at 60°C under O₂ for 30 min (30% product yield by GCMS analysis), and then filtered hot to remove the catalyst.

filtrate was heated further at 60 °C under O_2 for 5.5 h. There was an increase in the product yield (from 30% to 45%), indicating that some homogeneous Pd species were leached into the reaction mixture, giving rise to the catalytic activity in the heated filtrate.

To investigate the scope of the oxidative amination reaction catalyzed by the Pd-PV₃Mo₉/C catalyst, different types of secondary amines and olefins were examined (Table 6). Substituents on the aromatic amines have a considerable effect on the amination reaction. With a CH₃ substituent at the *para* position on one of the aromatic rings, the electron-donating CH₃ group resulted in a lower yield of the coupled amine product (77%, Table 6, **5b**). This yield was fur-



Figure 4. TEM images of Pd-PV₃Mo₉/C (a) before and (b) after the C–N bond formation reaction.

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Table 6. Scope of C–N bond formation *via* oxidative amination catalyzed by Pd-PV₃Mo₉/C nanomaterial.^[a]



[a] *Reaction conditions:* Pd catalyst (5 mol%), PV₃Mo₉ (0.6 mol%), 4 (0.2 mmol) and 2 (0.6 mmol), DMF (0.4 mL, purged with O₂ for 5 min), 60 °C, 6 h, under O₂.
 [b] 20 h at 80 °C.

^[c] 24 h at 60 °C.

ther decreased to 57% when both aromatic rings contained a CH₃ group at their *para* positions (Table 6, **5d**). When the CH₃ substituent was at the *meta* position on either one or both aromatic rings, the coupling reaction went efficiently and good yields of 86– 90% were achieved (Table 6, **5c** and **5e**). A good yield of 82% was also achieved when the electron-withdrawing F group was present at the *para* position on one of the aromatic rings (Table 6, **5f**). However, the presence of a stronger electron-donating group (OCH₃) or an electron-withdrawing group (Cl or Br) at the *meta* position resulted in lower yields of the desired products (12–57%, Table 6, **5g–5i**). Replacement of an aromatic ring with an alkyl chain in the secondary amine substrate would also result in a low yield of the coupled amine product (Table 6, **5j**).

The above results showed that, in general, the oxidative amination reaction catalyzed by Pd-PV₃Mo₉/C catalyst was more suited for secondary amine substrates with weakly activating functional groups (CH₃ or F) in the aromatic ring. Secondary amine substrates with electron-withdrawing groups (Cl and Br) or stronger electron-donating groups (OCH₃) would result in lower product yields. For the substrate **4d** (product **5d**, Table 6), the lower yield could be due to the presence of the *para* CH₃ group in both of the aromatic rings.

Various acrylates were tested with the $Pd-PV_3Mo_9/C$ catalyst. In general, the acrylates (methyl, ethyl, isobutyl and *tert*-butyl acrylates) coupled smoothly in this reaction to give the desired product in good yields (Table 6, **5**k–**5**n). The electron-deficient olefin, methyl vinyl ketone, also reacted with diphenylamine, although the yield of the product was low (Table 6, **5**o).

Conclusions

In conclusion, we have successfully developed an efficient heterogeneous Pd-PV₃Mo₉/C catalyst for the C– C bond formation *via* C–H activation and the C–N bond formation *via* oxidative amination using O_2 as the terminal oxidant under relatively mild conditions. The coupling reactions are simple, green processes as no additional reagents (such as acid, base or organic/ inorganic oxidant) besides the reactants are required, and water is the only by-product that is generated.

Experimental Section

General Procedure for the C–C Coupling Reaction of Anilides with Acrylates (Table 3, 3a–o)

A mixture of the Pd-PV₃Mo₉/C nanomaterial (5 mol% Pd, 0.6 mol% PV₃Mo₉), anilide (0.2 mmol), acrylate (0.4 mmol) and dry toluene (0.45 mL, purged with O₂ for 5 min) were added to an 8-mL glass vial equipped with a screw cap. The headspace in the glass vial was purged with O₂. The reaction mixture was heated at 80 °C under O₂ for 16 h. The mixture was centrifuged at 7500 rpm for 10 min. The organic layer containing the product was separated, and the solids were washed with hexane/dichloromethane (2×3 mL). The solvent was removed by rotary evaporation, followed by purification using column chromatography (silica gel, 10% EtOAc in dichloromethane).

General Procedure for the C–N Coupling Reaction of Secondary Amines with Olefins (Table 6, 5a–o)

A mixture of the Pd-PV₃Mo₉/C nanomaterial (5 mol% Pd, 0.6 mol% PV₃Mo₉), secondary amine (0.2 mmol), olefin (0.6 mmol) and dry DMF (0.4 mL, purged with O_2 for 5 min) were added to an 8-mL glass vial equipped with a screw cap. The headspace in the glass vial was purged with O_2 . The reaction mixture was heated at 60 °C under O_2 for 6 h. The mixture was centrifuged at 7500 rpm for 10 min. The organic layer containing the product was separated, and the solids were washed with hexane/dichloromethane $(2 \times$ 3 mL). The solvent was removed by rotary evaporation, dichloromethane (20 mL) was added, and the organic layer was washed with water $(3 \times 10 \text{ mL})$. The organic layer was separated, dried over Na₂SO₄, and the solvent was removed by rotary evaporation, followed by purification using column chromatography (silica gel, dichloromethane/hexanes = 1:1).

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