

# Palladium Immobilized on a Polyimide Covalent Organic Framework: An Efficient and Recyclable Heterogeneous Catalyst for the Suzuki–Miyaura Coupling Reaction and Nitroarene Reduction in Water

Zhenhua Dong<sup>1</sup> · Hongguo Pan<sup>1</sup> · Pengwei Gao<sup>1</sup> · Yongmei Xiao<sup>1</sup> · Lulu Fan<sup>1</sup> · Jing Chen<sup>1</sup> · Wentao Wang<sup>2</sup>

Received: 28 February 2021 / Accepted: 14 April 2021 © The Author(s), under exclusive licence to Springer Science+Business Media, LLC, part of Springer Nature 2021

## Abstract

An efficient and recyclable Pd nano-catalyst was developed via immobilization of Pd nanoparticles on polyimide linked covalent organic frameworks (PCOFs) that was facilely prepared through condensation of melamine and 3,3',4,4'-biphenyltet-racarboxylic dianhydride. The Pd nanoparticles (Pd NPs) catalyst was thoroughly characterized by FT-IR, XRD, SEM, TEM. Furthermore, the catalytic activity of Pd NPs catalyst was evaluated by Suzuki–Miyaura coupling reaction and nitroarene reduction in water, respectively. The excellent yields of corresponding products revealing revealed that the Pd NPs catalyst could be applied as an efficient and reusable heterogeneous catalyst for above two reactions.

#### **Graphical Abstract**



Keywords Covalent organic framework  $\cdot$  Pd nanoparticles  $\cdot$  Porous materials  $\cdot$  Suzuki–Miyaura cross coupling  $\cdot$  Reduction of nitroarenes

Zhenhua Dong zhdong@haut.edu.cn

Wentao Wang wentaowang@dicp.ac.cn

- <sup>1</sup> College of Chemistry and Chemical Engineering, Henan University of Technology, Lianhua Street 100, Zhengzhou 450001, China
- <sup>2</sup> Dalian Institute of Chemical Physics, Chinese Academy of Sciences, Zhongshan Road 457, Dalian 116023, China

# **1** Introduction

As we know, the efficient catalytic process not only refers to produce the target products in high yields via applying high reactive catalyst, but also require the reaction procedure and work-up to easily handle. The heterogeneous catalysis can meet the requirement of such efficient catalytic process because the heterogeneous catalyst can be reused and easily separated from reaction solution, compared with homogeneous catalysis [1–3]. Nano-catalysis, as an emerging frontier in heterogeneous catalysis, has received considerable attention in recent years [4, 5]. Typically, the nano-catalysis applied the noble metal nanoparticles have played quite important role in organic synthesis, and shown a wide range of applications for synthesis of diverse fine chemicals and bioactive compounds [6–11]. The excellent catalytic reactivity of nanoparticles (NPs extremely depend on the metal size, shape and the number of atoms on the NPs surface, because the catalytic process mainly takes place on the metal surface, and the more surface explored by metal could produce more catalytic centers [12–14]. Therefore, it is highly desirable to decreasing metal particle size for improving metal catalytic reactivity. However, a challenge has to be considered is that ultrafine NPs are easy to aggregate to form greater aggregations owing to their high surface energy, greater aggregations result in the loss of catalytic activity gradually. As a result, various supported materials were explored to immobilize the ultrafine NPs, in order to avoid the aggregation of NPs and obtain the stable nano-catalyst. So far, a variety of supported material have been developed, such as metal oxides [15], polymers [16, 17], silica [18] and so on. However, the preparation of stable ultrafine metal NPs still remains a challenging task.

In the past decade, covalent organic frameworks (COFs) have been developed as a new generation of emerging organic porous polymers formed between C, B, N, O or S by strong covalent bonds [19–22]. They have been applied in gas storage and purification [23], drug delivery [24], catalysis [25], energy storage [26] and so on. Recently, the COFs have been applied as outstanding hosts to support metal NPs [27]. Comparing with traditional supported materials, the COFs possess the following advantages: (1) The COFs have definite pores in their structures, and the metal NPs can grow in the pore channels. The size and shape of metal NPs can be controlled and confined. (2) The aggregation of metal NPs can be minimized because every pore channel is isolated in COFs. (3) The COFs have diverse functional groups that can be coordinated with different metals. (4) In general, COFs are insoluble in most solvents. Thus, it will be stable under various reaction conditions and can be easily separated and recycled.

Suzuki–Miyaura coupling reaction, as a Nobel reaction, has been considered as one of the most efficient methods for the construction of C–C bonds [28–32]. On the other hand, aryl amine is one of most important intermediates in the pharmaceutical and synthesis [33–35]. Although several methods have been developed to synthesize the aryl amines, the reduction of nitroarenes is still one of the most cost-efficient methodologies [36, 37]. Hence, the development of new and more efficient catalytic system is highly desirable for Suzuki–Miyaura coupling reaction and nitroarenes reduction. The COFs supported metal NPs, such as Pd NPs, have exhibited excellent catalytic activities in C–C coupling reaction and nitroarenes reduction, and achieved much attention in the heterogeneous catalysis. However, the reported

catalytic systems were only fit for the sole Suzuki-Miyaura coupling reaction or nitroarenes reduction, could not be applied in both reactions. The development of COFs supported Pd NPs that could catalyze both Suzuki-Miyaura coupling reaction and nitroarenes reduction would highly significant and desirable. Herein, we report an efficient catalytic system to achieve the possibility of supported Pd NPs can catalyze both Suzuki-Miyaura coupling reaction and nitroarenes reduction. Firstly, an ecofriendly and economical method were explored to synthesize a polyimide linked covalent organic frameworks (PCOFs) [38-40] that served as a template for the preparation of nano Pd heterogeneous catalyst. Then the stability and reactivity of Pd@PCOFs catalyst were inspected by Suzuki-Miyaura coupling reaction and nitroarene reduction, and the corresponding products of two reactions were all gained in excellent yields. Comparing with previous reports, the present protocol have the bellow advantages: (1) Polyimide linked COFs were easy to synthesize and the Pd@PCOFs were highly dispersed with low Pd loading. (2) The Suzuki-Miyaura coupling reaction could proceed efficiently with very low Pd loading (up to 0.004 mol% Pd). The catalyst loading is dramatically lower than previous reports. (3) The two reactions both could proceed in aqueous medium under air. (4) The Pd@PCOFs could be recycled with high reactivity.

# 2 Results and Discussion

The polyimide based covalent organic frameworks (PCOFs) was synthesized by the condensation reaction of melamine and 3,3',4,4'-biphenyltetracarboxylic dianhydride (BPDA) as depicted in Scheme 1. The 1:1 molar ratio of melamine and BPDA were initially mixed and ground uniformly. Then the mixture was calcined in an alumina crucible by muffle furnace at 325 °C for 4 h. After that, the resultant solid was washed with water to give pure PCOFs in high yield. Comparing with the preparation of imine linked PCOFs, this synthetic protocol was rather simple, easier to handle and more environmentally-friendly. Furthermore, the polymerization had no need to use sealed reaction tube and no hazardous waste was produced as well. In addition, the PCOFs was stable in air and insoluble in commercially available solvents, including water, DCM, DMF, Toluene, THF, acetone, DMSO, etc. Finally, the structure of PCOFs was confirmed by FT-IR (Fourier transform infrared spectroscopy), SEM (scanning electron microscopy), XRD (X-ray diffraction analysis), TGA (thermal gravimetric analysis). and BET (Brunauer-Emmett-Teller).

The FT-IR spectroscopy was used to characterize the PCOFs as shown in Fig. 1. The disappearance of band at  $1844 \text{ cm}^{-1}$  and  $1775 \text{ cm}^{-1}$  indicated that the starting anhydride monomer BPDA had consumed completely after the

Scheme 1 Preparation of PCOFs and Pd@ PCOFs





Fig. 1 FT-IR spectra of BPDA and PCOFs

reaction (Blue line). While the absorptions at 1759 cm<sup>-1</sup> and 1711 cm<sup>-1</sup> shown in spectrum of PCOFs (red line) demonstrated the existence of C=O groups, indicating the formation of polyimide[39].

The microstructure of PCOFs was characterized by SEM and the images displayed that PCOFs template was porous and resembling spongy (Fig. 2). The cross-linked polymers with crystalline structures could be shown direct visualization. As shown in Fig. S1 (Supporting Information), the N<sub>2</sub> adsorption/ desorption isotherm was measured at 77 K, giving the result of surface area and pore diameter as  $36.36 \text{ m}^2 \text{ g}^{-1}$ .

The immobilization of Pd NPs on PCOFs was subsequently performed. The Pd precursor was firstly deposited into the PCOFs material by adding  $Pd(OAc)_2$  to a suspension of PCOFs with stirring. Then the mixture was reduced by NaBH<sub>4</sub>. After that, the resulted mixture was filtered and the solid was washed and dried under vacuum to provide target



Fig. 2 The SEM images of PCOFs

Pd@ PCOFs nano-catalyst for further use. The Pd content in the Pd@ PCOFs was determined to be 0.42 wt % by inductively coupled plasma (ICP) analysis. The low Pd loading indicated that the Pd NPs might deposit on the surface of PCOFs rather than encapsulate inside the pore channels.

The powder XRD analysis provided the structural regularity and crystalline nature of PCOFs and Pd@ PCOFs as shown in Fig. 3. The relatively strong diffraction peaks at  $2\theta = 14.14$  and  $26.86^{\circ}$  of PCOFs (blue line) exhibited that the crystallinities of PCOFs were acceptable. However, no significant changes were observed from the XRD of Pd@ PCOFs, indicating that the loading amount of Pd NPs was relatively low. This result was consistent with the data of ICP-AES. In addition, the stability of the catalyst was explored by thermogravimetric analysis (TGA). As shown in Fig. S2 (Supporting Information), The result displayed excellent thermal stability of Pd@PCOFs with thermal decomposition temperatures exceeding 457.2 °C.

The shape and morphology of Pd NPs supported on PCOFs was determined by TEM analysis. The TEM images suggested that Pd nanoparticles were uniformly distributed



Fig. 3 XRD images of PCOFs and Pd@ PCOFs

in the PCOFs. The particle size of Pd@ PCOFs was in the 3–5 nm range and the shapes were spherical (Fig. 4).

Subsequently, the catalytic activity of Pd@PCOFs was evaluated against the Suzuki-Miyaura coupling reaction by using iodine benzene (1a) and phenyl boronic acid (2a) as model substrates. The reaction parameters such as catalyst loading, base, solvent and temperature were examined to optimized the reaction conditions and the results were summarized in Table 1. When the reaction was carried out using 10 mg Pd@PCOFs as heterogeneous catalyst and K<sub>2</sub>CO<sub>3</sub> as base in DMSO at 110 °C for 6 h, the coupling product biphenyl (3a) was obtained in excellent yield (Table 1, entry 1). While, the reaction could not produce neither in the absence of Pd@PCOFs catalyst nor in the presence of PCOFs alone (Table 1, entries 2 and 3). These results revealed that the key role of Pd nanoparticles as catalysts in the Suzuki-Miyaura coupling reaction. The optimizations of base were then checked by using Cs<sub>2</sub>CO<sub>3</sub> and tBuOK respectively. Unfortunately, no improvement of yield was achieved (Table 1, entries 4 and 5). Meanwhile, the reaction did not occur when the base was absent (Table 1, entry 6). A variety of solvents, such as DMF, toluene and H<sub>2</sub>O were next investigated (Table 1, entries 7–9). To our delight, the quantitative yield of 3a was obtained when H<sub>2</sub>O was used as solvent at 80 °C (Table 1, entry 9). However, the reduction of temperature resulted in the decreasing yield dramatically (Table 1, entries 10 and 11). Notably, the catalyst loading could be diminished to 0.004 mol% palladium loading (using 5 mg Pd@PCOFs) without any loss of the yield of **3a** (Table 1, entry 12). The comparison between previous reported works and the present work for Suzuki-Miyaura coupling reaction has been summarized in Table S1 in supporting information accompanying this paper.

With the optimized reaction conditions in hand, the catalytic applicability of Pd@PCOFs was explored subsequently for various aryl iodides and arylboronic acids in water. As Fig. 4 The TEM images of Pd@PCOFs



shown in Table 2, a series of aryl iodides with electron-withdrawing and electron-donating groups proceeded smoothly to provide the corresponding products in excellent yields (Table 2, entries 2–6). Meanwhile, various substituted boronic acid partners were also tolerated well for the reaction to generate the products 3d to 3e with 95–99% yields (Table 2, entries 7–9).

Aromatic primary amines were widely used as important organic intermediates in the chemical industry for the production of pharmaceuticals, agrochemicals, polymers, and dyes. The reduction of nitroarenes has been utilized as a quite effective method for the synthesis of aromatic primary amines. For further exploring the utility of Pd@ PCOFs as heterogeneous nano-catalyst, we assessed the possibility of synthesizing aromatic primary amines by Pd@ PCOFs catalyzed reduction of nitroarenes. When the reaction was performed with 3 equivalent of NaBH<sub>4</sub> as reductive reagent and water as solvent at room temperature, aniline product (**5a**) was obtained in 99% yield by using 10 mg Pd@ PCOFs (0.04 mol% catalyst loading) in 24 h. With this optimized reaction conditions, various nitroarenes were further evaluated to explore the substrate scope. The results were collected in Table 3. A series of substituted nitroarenes were reacted very well to give the corresponding primary amines in high to excellent yields. For instance, the nitroarenes with substituted CH<sub>3</sub>, Cl, Br, I, MeO groups, were all tolerated well in this catalytic system (Table 3, entries 2–10). There had no obvious difference on the reactivity for electrondonating and withdrawing groups. The 4-Cl-substituted aniline (5e) and 2-Cl-substituted aniline (5 g) were produced in 99% and 82% yield respectively, which suggested that the steric hindrance might has slight effect in this transformation (Table 3, entries 5 and 7). In addition, this methodology could be applied to the reduction of aromatic heterocyclic compounds as well. When 2-chloro-3-nitropyridine (4 k) were introduced in this reaction, the corresponding product was obtained in 99% isolated yields, respectively. In all cases of Tables 1, 2 and 3, the isolated yields were calculated after flash column chromatography. The purity of all products was determined by thin layer chromatography (TLC).

The recyclability of Pd@PCOFs was further investigated using Suzuki–Miyaura coupling reaction and reduction of nitroarenes. The catalyst was separated by centrifugation from the reaction mixture. The recovered catalyst was Table 1 Optimization of reaction conditions of Suzuki reaction<sup>a</sup>



Entry	Catalyst	Base	Solvent	Temperature	Yield <sup>b</sup> (%)
1	Pd@PCOFs	K <sub>2</sub> CO <sub>3</sub>	DMSO	110	98
2	-	K <sub>2</sub> CO <sub>3</sub>	DMSO	110	0
3	PCOFs	K <sub>2</sub> CO <sub>3</sub>	DMSO	110	0
4	Pd@PCOFs	Cs <sub>2</sub> CO <sub>3</sub>	DMSO	110	96
5	Pd@PCOFs	tBuOK	DMSO	110	93
6	Pd@PCOFs	-	Water	80	0
7	Pd@PCOFs	K <sub>2</sub> CO <sub>3</sub>	DMF	110	96
8	Pd@PCOFs	K <sub>2</sub> CO <sub>3</sub>	Toluene	110	90
9	Pd@PCOFs	K <sub>2</sub> CO <sub>3</sub>	Water	80	99
10	Pd@PCOFs	K <sub>2</sub> CO <sub>3</sub>	Water	60	81
11	Pd@PCOFs	K <sub>2</sub> CO <sub>3</sub>	Water	40	63
12 <sup>c</sup>	Pd@PCOFs	K <sub>2</sub> CO <sub>3</sub>	Water	80	99

<sup>a</sup>Iodobenzene (5 mmol, 1020.1 mg), phenyl boronic acid (7.5 mmol, 914.5 mg), base (10 mmol), Pd@PCOFs (Pd 0.42 wt%) 10 mg, solvent (5.0 mL) for 6 h. <sup>b</sup>Isolated yield. <sup>c</sup>Using 5 mg Pd@PCOFs

Table 2 Substrate scope of the Pd@PCOFs catalyzed Suzuki-Miyaura coupling reaction<sup>a</sup>

	Ar₁—I + Ar	B(OH) 0.004 mol% Pd@PCOFs	$\Delta r = \Delta r$	
	1	<b>2</b> K <sub>2</sub> CO <sub>3</sub> , water, 80 °C, 6h	<b>3</b>	
Entry	Ar <sub>1</sub>	Ar <sub>2</sub>	Product ( <b>3</b> )	Yield(%) <sup>b</sup>
1	Ph	Ph	<b>3</b> a	99
2	$4-Cl-C_6H_4$	Ph	3b	94
3	$3-Cl-C_6H_4$	Ph	3c	97
4	4-MeO-C <sub>6</sub> H <sub>4</sub>	Ph	3d	99
5	$3-\text{MeO-C}_6\text{H}_4$	Ph	3e	93
6	$4-CH_3CO-C_6H_4$	Ph	3f	99
7	Ph	4-MeO-C <sub>6</sub> H <sub>4</sub>	3d	99
8	Ph	3,4-(MeO) <sub>2</sub> -C <sub>6</sub> H <sub>4</sub>	3 g	98
9	Ph	$3-MeO-C_6H_4$	3e	95

<sup>a</sup>Reaction conditions: aryl iodines 1 (5 mmol), arylboronic acids 2 (7.5 mmol),  $K_2CO_3$  (10 mmol), Pd@PCOFs (5 mg), water (5 mL) at 80 °C for 6 h. <sup>a</sup>Isolated yields

carefully washed by ethanol, then dried and reused for next reactions without further purification. The reaction of iodobenzene with phenylboronic acid was initially conducted using 5 mg Pd@PCOFs catalyst under the optimized reaction conditions. The results were summarized in Fig. 5. The reaction outcomes indicated that the Pd@PCOFs catalyst could be used two times without obvious loss of catalytic activity. However, a slight loss in catalytic activity was observed in the third run. In addition, the recyclability of Pd@PCOFs was also tested for the reduction of nitroarene. The results demonstrated that Pd@PCOFs catalyst could also be used twice with the product retaining in 99% yield

Table 3 The Pd@PCOFs catalyzed reduction of nitroarenes<sup>a</sup>

ArNO<sub>2</sub> + NaBH<sub>4</sub> 
$$\xrightarrow{0.04 \text{ mol}\% \text{ Pd}@\text{PCOFs}}$$
 ArNH<sub>2</sub>  
water, r. t. ,24 h

Entry	ArNO <sub>2</sub> ( <b>4</b> )	Product ( <b>5</b> )	Yield (%) <sup>b</sup>
1	PhNO <sub>2</sub>	5a	99
2	$4-CH_3-C_6H_4NO_2$	5b	99
3	3-CH <sub>3</sub> -C <sub>6</sub> H <sub>4</sub> NO <sub>2</sub>	5c	99
4	$2-CH_3-C_6H_4NO_2$	5d	99
5	$4-\text{Cl-C}_6\text{H}_4\text{NO}_2$	5e	99
6	3-Cl-C <sub>6</sub> H <sub>4</sub> NO <sub>2</sub>	5f	85
7	$2-Cl-C_6H_4NO_2$	5 g	82
8	$4-I-C_6H_4NO_2$	5 h	98
9	$4-Br-C_6H_4NO_2$	5i	99
10	$2-\text{MeO-C}_6\text{H}_4\text{NO}_2$	5j	88
11		5 k	99

<sup>a</sup>Reaction conditions: nitroarenes **4** (1 mmol), NaBH<sub>4</sub> (3 mmol), Pd@PCOFs (0.04 mol% loading, 10 mg), room temperature, 2 mL water as solvent, 24 h. <sup>b</sup>Isolated yield





Fig. 6 The recyclability of Pd@PCOFs in the reduction of nitroarene

Fig. 5 The recyclability of Pd@PCOFs in the reaction of iodobenzene with phenylboronic acid

(Fig. 6). However, the yield of target product decreased to 85% after two recycle use of Pd@PCOFs, showing the

catalyst reactivity has diminished slightly. The leaching of the catalyst was investigated. The ICP-AES analysis of the first recycled filtrate showed that trace amounts of Pd (about 0.01% Pd) were leached into the solution. The results revealed that the Pd maybe incorporated on the surfaces of PCOFs and the coordination was relatively weak. All the products were characterized by <sup>1</sup>H NMR.

# 3 Conclusion

In conclusion, heterogeneous polyimide based covalent organic framework was synthesized by the solid-state thermal condensation reaction of melamine with BPDA. Subsequently, highly dispersed Pd nanoparticles were successfully immobilized on PCOFs and its catalytic performance was evaluated for the Suzuki-Miyaura coupling reaction and efficient reduction of aromatic nitro compounds. The reaction conditions were environmentally favorable with excellent yields. For electronically and structurally varied aryl halides, arylboronic acids and nitroarenes, the Pd@PCOFs catalyst works effectively to give good to excellent yield of the corresponding biphenyl and aniline products. The catalytic system works in environmentally benign water solvent with NaBH<sub>4</sub> as a hydrogen donor to generate the corresponding amines under mild reaction conditions. The advantages of the Pd@PCOFs catalyst are that it is robust and is accessible from inexpensive raw materials. Furthermore, the catalyst was easy to separate by simple filtration and reused for three times. Further studies to elucidate the mechanism of the current transformation and to extend the scope of the synthetic utility are in progress in our laboratory.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10562-021-03637-1.

Acknowledgements The authors are grateful to the Doctor Fund of Henan University of Technology (No. 2015BS013) and The Colleges and Universities Key Research Program Foundation of Henan Province (No. 20A150014). The Project was also Supported by State Key Laboratory of Materials Processing and Die & Mould Technology, Huazhong University of Science and Technology (P2019-004)

## References

- 1. Hulsey MJ, Lim CW, Yan N (2020) Chem Sci 11:1456–1468
- 2. Li Z, Ji SF, Liu YW, Cao X, Tian SB, Chen YJ, Niu ZG, Li YD (2020) Chem Rev 120:623–682
- 3. Molnár Á, Papp A (2017) Coord Chem Rev 349:1-65
- 4. Karimi B, Mansouri F, Mirzaei HM (2015) ChemCatChem 7:1736–1789
- 5. Gao YX, Ding Y (2020) Chemistry-a European Journal 26:8845-8856
- Gholinejad M, Naghshbandi Z, Najera C (2019) ChemCatChem 11:1792–1823
- Hong K, Sajjadi M, Suh JM, Zhang K, Nasrollahzadeh M, Jang HW, Varma RS, Shokouhimehr M (2020) ACS Applied Nano Materials 3:2070–2103
- 8. Shokouhimehr, Yek, Nasrollahzadeh (2019) Appl. Sci. 9:4183.
- Kim A, Rafiaei SM, Abolhosseini S, Shokouhimehr M (2015) Energy Environ Focus 4:18–23

- Shokouhimehr M, Asl MS, Mazinani B (2017) Res Chem Intermed 44:1617–1626
- Zhang K, Hong K, Suh JM, Lee TH, Kwon O, Shokouhimehr M, Jang HW (2018) Res Chem Intermed 45:599–611
- 12. Yang X-F, Wang A, Qiao B, Li J, Liu J, Zhang T (2013) Acc Chem Res 46:1740–1748
- 13. Zhang H, Liu G, Shi L, Ye J (2018) Adv Energy Mater 8:1701343
- 14. Liu L, Corma A (2018) Chem Rev 118:4981–5079
- 15. Dong ZH, Yuan JW, Xiao YM, Mao P, Wang WT (2018) J Org Chem 83:11067–11073
- Liu Y-X, Ma Z-W, Jia J, Wang C-C, Huang M-L, Tao J-C (2010) Appl Organomet Chem 24:646–649
- Motevalizadeh SF, Alipour M, Ashori F, Samzadeh-Kermani A, Hamadi H, Ganjali MR, Aghahosseini H, Ramazani A, Khoobi M, Gholibegloo E (2018) Appl Organomet Chem 32:e4123
- Khajehzadeh M, Moghadam M (2018) J Organomet Chem 863:60–69
- Waller PJ, Gandara F, Yaghi OM (2015) Acc Chem Res 48:3053–3063
- 20. Ding SY, Wang W (2013) Chem Soc Rev 42:548–568
- Feng X, Ding X, Jiang D (2012) Chem Soc Rev 41:6010–6022
  Kandambeth S, Dey K, Banerjee R (2019) J Am Chem Soc
- 141:1807–1822
- 23. Gao X, Zou X, Ma H, Meng S, Zhu G (2014) Adv Mater 26:3644–3648
- Fang Q, Wang J, Gu S, Kaspar RB, Zhuang Z, Zheng J, Guo H, Qiu S, Yan Y (2015) J Am Chem Soc 137:8352–8355
- 25. Guo J, Jiang D (2020) ACS Cent Sci 6:869–879
- 26. Wu C, Liu Y, Liu H, Duan C, Pan Q, Zhu J, Hu F, Ma X, Jiu T, Li Z, Zhao Y (2018) J Am Chem Soc 140:10016–10024
- 27. Liu R, Tan KT, Gong Y, Chen Y, Li Z, Xie S, He T, Lu Z, Yang H, Jiang D (2021) Chem Soc Rev 50:120–242
- Niakan M, Masteri-Farahani M, Karimi S, Shekaari H (2021) J Mol Liq 324:115078
- Niakan M, Asadi Z, Masteri-Farahani M (2019) ChemistrySelect 4:1766–1775
- Huang P, Zeng X, Du F, Zhang L, Peng X (2019) Catal Lett 150:1011–1019
- Hooshmand SE, Heidari B, Sedghi R, Varma RS (2019) Green Chem 21:381–405
- Han Y, Di JQ, Zhao AD, Zhang ZH (2019) Appl Organomet Chem 33:e5172
- Antony R, Marimuthu R, Murugavel R (2019) ACS Omega 4:9241–9250
- Chakraborty S, Mruthunjayappa MH, Aruchamy K, Singh N, Prasad K, Kalpana D, Ghosh D, Sanna Kotrappanavar N, Mondal D (2019) ACS Sustain Chem Eng 7:14225–14235
- Uberman PM, García CS, Rodríguez JR, Martín SE (2017) Green Chem 19:739–748
- Du J, Chen J, Xia H, Zhao Y, Wang F, Liu H, Zhou W, Wang B (2020) ChemCatChem 12:2426–2430
- Wang G, Yuan S, Wu ZQ, Liu WY, Zhan HJ, Liang YP, Chen XY, Ma BJ, Bi SX (2019) Appl Organomet Chem 33:e5159
- Jiang L, Tian Y, Sun T, Zhu Y, Ren H, Zou X, Ma Y, Meihaus KR, Long JR, Zhu G (2018) J Am Chem Soc 140:15724–15730
- Han Y, Zhang M, Zhang Y-Q, Zhang Z-H (2018) Green Chem 20:4891–4900
- Rangel Rangel E, Maya EM, Sánchez F, de la Campa JG, Iglesias M (2015) Green Chem 17:466–473

**Publisher's Note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.