Check for updates

# RESEARCH ARTICLE



# Nickel/ $\beta$ -CD-catalyzed Suzuki–Miyaura cross-coupling of aryl boronic acids with aryl halides in water

- 1

Sara Payamifar 💿

| Foad Kazemi D

Babak Kaboudin 回

Department of Chemsitry, Institute for Advanced Studies in Basic Sciences, Zanjan, Iran

#### Correspondence

Babak Kaboudin, Department of Chemsitry, Institute for Advanced Studies in Basic Sciences, Gava Zang, Zanjan 45137-66731, Iran. Email: kaboudin@iasbs.ac.ir

Funding information Institute for Advanced Studies in Basic Sciences

#### Abstract

In this study, a convenient nickel-catalyzed protocol has been introduced for the Suzuki–Miyaura coupling reaction. A simple mixture of Ni(II) and unfunctionalized  $\beta$ -cyclodextrin ( $\beta$ -CD) was used to cross-coupling of aryl halides with aryl boronic acids for the synthesis of biaryls in water.  $\beta$ -CD is a water-soluble seminatural cyclic oligosaccharide, environmentally friendly biomaterial, inexpensive, and commercially available ligand. This ligand with low solubility in usual organic solvents has been used for the synthesis of biaryls in good to excellent yields. The cross-coupling results in the presence of Ni(II)/ $\beta$ -CD catalytic system showed that the coupling reaction carried out with appropriate yields for both electron-rich and electron-deficient aryl halides. The coupling reaction completed in water as a green solvent. The catalyst was also recycled for four runs with a small decrease in its catalytic activity. The presented new method allows an easier and more cost-efficient synthesis of biaryls from the reaction of arylboronic acids with various aryl halides in water.

#### K E Y W O R D S

aryl boronic acids, biaryls, nickel, Suzuki-Miyaura coupling, β-Cyclodextrin

# **1** | INTRODUCTION

The new bond formation is an important and applicable process for the synthesis of valuable materials. The crosscoupling reactions are efficient method for the carbon– carbon bond generation that has developed by chemistry scientists. The Suzuki–Miyaura coupling reaction is one of the most utilized and general synthetic organic transformation tools for the  $C(sp^2)-C(sp^2)$  bond formation.<sup>[1–13]</sup> The Suzuki–Miyaura coupling reaction is the coupling between the organoboron reagents with organic halides. The method is an extremely important and clean protocol for the creation of different types of compounds, especially biphenyls. Biaryl are versatile structural units that have found many applications in natural products, synthetic bioactive compounds, pharmaceuticals, liquid crystals, and conjugate polymers (Scheme 1).<sup>[14-19]</sup> The costly palladium is the most routine catalyst for the various cross-coupling reactions.<sup>[5,6,20]</sup> Due to high cost and toxicity of palladium metal, the usage of the low-cost transition metal complexes for the coupling reactions has grown attention. In particular, nickel has been recognized as a popular choice to replace with Pd for crosscoupling reactions due to lower cost, high reactivity, and earth-abundant.<sup>[21-23]</sup> Nickel catalysts in Suzuki-Miyaura cross-coupling reactions commonly involve a combination of simple nickel salt with standard ligands such as phosphines, N-heterocyclic carbenes, and pyridine derivatives.<sup>[24-32]</sup> To date, many efforts have been made for the development of Ni-based Suzuki reaction. For instance, Lipshutz et al. reported nickel on charcoal as an effective heterogeneous catalyst for the Suzuki



SCHEME 1 Examples of biaryl structure applications

reaction of functionalized aryl chlorides with boronic acids.<sup>[33]</sup>

Recently, chemists have been more interested in the use of water as an environmentally friendly, easily available, and nonflammable solvent in organic synthesis.<sup>[34–37]</sup> Reactions in aqueous media usually lead to high selectivity, which cannot be obtained with organic solvents.<sup>[38–42]</sup>

Cyclodextrins (CDs) are nontoxic materials that prepared on large scale via the enzymatic degradation of starch.<sup>[43,44]</sup> CDs have a hydrophobic inner cavity and a hydrophilic outside with their ability to form inclusion complexes with various kinds of molecules.<sup>[45-47]</sup> CDs can be used as promoters or catalysts for various organic reaction processes such as carbon-carbon bond formations, asymmetric synthesis oxidation, reduction, hydrolysis, and condensation.<sup>[48-54]</sup> Recently, functionalized CDs have attracted attention for Suzuki-Miyaura coupling reactions.<sup>[55-62]</sup> We have reported synthesis and application of Cu(II) $-\beta$ -CD complex in the homocoupling reaction of aryl boronic acids.<sup>[63,64]</sup> Recently, we have also reported Pd(II)-\beta-CD complex for the selective Suzuki–Miyaura coupling reaction in water.<sup>[65]</sup> In continuation of our interest for application of CDs in coupling reactions, herein, we report a greener methodology for the synthesis of biaryl compounds using a simple mixture of Ni(II)/ $\beta$ -CD in water. In this report, we describe a cross-coupling reaction of aryl halide compounds (X = I, I)Br) with arylboronic acids in water in the presence of catalytic amount of mixture of Ni(OAc)<sub>2</sub> and  $\beta$ -CD.

# 2 | RESULTS AND DISCUSSION

Initially, the reaction of 4-iodotoluene (1a) with phenylboronic acid (2a) was chosen as the model

reaction (Table 1). In order to optimize the reaction conditions, the screening of various parameters such as solvent, base, kind and amount of catalyst, and reaction temperature were investigated, and the results are summarized in Table 1. As indicated in Table 1, we examined a set of experiments for optimizing the reaction conditions. We have already reported the experimental data for the screening of different copper salts on the coupling reaction. In continuation, to find out the convenient catalyst, three commercial Ni(II), Co(II), and Fe(III) salts (5 mol%) were examined in the cross-coupling of 1a with 2a (1.2 equiv) in water as a solvent in the presence  $K_2CO_3$  (1.5 equiv) as a base at 65°C under Ar. Results showed that the reaction failed to give any desired product 3a for 24 h. It was found that the reaction proceeded with a mixture of transition metal salts (Ni, Co, and Fe) with  $\beta$ -CD (5 mol%) (Entries 1–7). Screening of various salts showed that the best result was obtained in the presence of Ni(II) sources, specially Ni(OAc)<sub>2</sub>. To get more information on the optimal catalyst conditions, the reaction was examined in different ratios of Ni(OAc)<sub>2</sub> and  $\beta$ -CD (Table 1). The reaction yield decreased to 49% when the reaction was performed in 10 mol%  $\beta$ -CD (Entry 8). Surprisingly, the compound 3a was obtained in 95% yield in the presence of 2.5 mol% of  $\beta$ -CD (Entry 9). The reaction proceeded smoothly to give compound 3a in only 13% yield with decreasing amount of Ni(OAc)<sub>2</sub> to 2.5 mol % (Entry 10). A decrease in yield was observed when the reaction was carried out under air (Entry 11). The compound 3a was obtained in 55% yield when the reaction was performed at room temperature for 48 h (Entry 12). Screening of various bases DABCO, Na<sub>2</sub>CO<sub>3</sub>, Et<sub>3</sub>N, and NaHCO<sub>3</sub> showed that the K<sub>2</sub>CO<sub>3</sub> is the best (Entries 13-16). The results in Table 1 showed that H<sub>2</sub>O was found as a suitable solvent for the reaction while the reaction yields decreased in other organic solvents (Entries 17-20). Therefore, the best reaction conditions for the employ of a mixture of Ni(OAc)<sub>2</sub> and  $\beta$ -CD for the synthesis of biaryl 3a contained the use of 5 and 2.5 mol% of Ni(OAc)<sub>2</sub> and  $\beta$ -CD, respectively, per mmol of **1a** at 65°C in water for 24 h under Ar.

Under the above optimized condition, the scope and limitations of the mixed Ni(OAc)<sub>2</sub>/β-CD-catalyzed crosscoupling reaction of various aryl halides with aryl boronic acids were studied. The obtained results are summarized in Table 2. The cross-coupling of phenyl boronic acid with various aryl iodides having electron-rich and electron-poor groups gave corresponding biaryls 3 in good to excellent yields (Entries 1-6). The reaction of 4-iodotoluene with 1-naphthalene boronic acid, 2-benzofuranyl, and 3-thienyl boronic acid led to the corresponding cross-coupling compound product with good yields (Table 2, Entries 7-9).

## Applied Organometallic\_WILEY Chemistry 3 of 8

SCHEME 2 The coupling reaction of arylboronic acids with aryl halides for the synthesis of biaryl 3

 $H_2O($ 

Catalyst/B-CD

TABLE 1 Reaction of 4-iodotoluene 1a with phenylboronic acid 2a in various reaction conditions

		<u> </u>	<sup>2</sup> Base, Solvent	t (1 mL)	/
	1a	2a		3а	
Entw	Catalust	Solvent	Paga	Proaction time (h)	Viold 0 <sup>(a</sup> 2a
Entry	Catalyst	Solvent	Dase	Reaction time (II)	rielu % Sa
1	NiCl <sub>2</sub> .6H <sub>2</sub> O	H <sub>2</sub> O	K <sub>2</sub> CO <sub>3</sub>	24	41
2	$Ni(NO_3)_2.6H_2O$	$H_2O$	K <sub>2</sub> CO <sub>3</sub>	24	37
3	$Ni(SO_4)_2.6H_2O$	$H_2O$	K <sub>2</sub> CO <sub>3</sub>	24	34
4	CoCl <sub>2</sub> .6H <sub>2</sub> O	$H_2O$	$K_2CO_3$	24	20
5	$Co(OAc)_2.6H_2O$	$H_2O$	$K_2CO_3$	24	22
6	FeCl <sub>2</sub> .6H <sub>2</sub> O	$H_2O$	K <sub>2</sub> CO <sub>3</sub>	24	29
7	Ni(OAc) <sub>2</sub> .4H <sub>2</sub> O	$H_2O$	$K_2CO_3$	24	61
8	Ni(OAc) <sub>2</sub> .4H <sub>2</sub> O	$H_2O$	K <sub>2</sub> CO <sub>3</sub>	24	49 <sup>b</sup>
9	Ni(OAc) <sub>2</sub> .4H <sub>2</sub> O	$H_2O$	$K_2CO_3$	24	95 <sup>c</sup>
10	Ni(OAc) <sub>2</sub> .4H <sub>2</sub> O	$H_2O$	$K_2CO_3$	24	13 <sup>d</sup>
11	Ni(OAc) <sub>2</sub> .4H <sub>2</sub> O	$H_2O$	$K_2CO_3$	24	63 <sup>e</sup>
12	Ni(OAc) <sub>2</sub> .4H <sub>2</sub> O	$H_2O$	$K_2CO_3$	48	55 <sup>f</sup>
13	Ni(OAc) <sub>2</sub> .4H <sub>2</sub> O	$H_2O$	DABCO	48	53
14	Ni(OAc) <sub>2</sub> .4H <sub>2</sub> O	$H_2O$	Et <sub>3</sub> N	48	trace
15	Ni(OAc) <sub>2</sub> .4H <sub>2</sub> O	$H_2O$	NaHCO <sub>3</sub>	48	trace
16	Ni(OAc) <sub>2</sub> .4H <sub>2</sub> O	$H_2O$	Na <sub>2</sub> CO <sub>3</sub>	48	85
17	Ni(OAc) <sub>2</sub> .4H <sub>2</sub> O	DMSO	$K_2CO_3$	48	4
18	Ni(OAc) <sub>2</sub> .4H <sub>2</sub> O	MeCN	$K_2CO_3$	48	5
19	Ni(OAc) <sub>2</sub> .4H <sub>2</sub> O	EtOH	$K_2CO_3$	48	78
20	-	$H_2O$	$K_2CO_3$	48	_g

 $^{a}$ GC yield (1-mmol **1a**, 1.2-mmol **2a**, 2-mmol base, metal salt [5 mol%],  $\beta$ -CD [5 mol%] in solvent [1 mL] under Ar at 65°C).

 $^{b}\text{The}$  reaction with 10 mol% of  $\beta\text{-CD}.$ 

<sup>c</sup>The reaction with 2.5 mol% of  $\beta$ -CD.

<sup>d</sup>The reaction with 2.5 mol% of Ni (OAc)<sub>2</sub>.

<sup>e</sup>The reaction carried out under air.

<sup>f</sup>The reaction carried out at room temperature.

<sup>g</sup>The reaction failed without any metal catalyst.

We have also examined the Suzuki reaction of aryl bromides. For this goal, the reaction of 4-bromoanisole with phenylboronic acid was studied and the reaction gave the compound 3i in 50% yield. However, when the reaction temperature was increased to 85°C, the reaction yield was increased to 88%. Therefore, we studied the coupling reaction of different aryl bromides with aryl boronic acid at 85°C in water. Generally, the results showed that aryl bromides having electron-donating or electron-withdrawing groups afforded biaryl compound 3 in good yields (Table 2, Entries 10–16).

The reusability of the mixture catalyst of Ni(OAc)<sub>2</sub>/  $\beta$ -CD was also studied. The aqueous solution of the catalyst was collected after washing the reaction mixture with *n*-hexane. The catalytic activity did not decrease considerably after four catalytic cycles (Table 3).

Entry	R	X	Ar	Product	Yield (%) <sup>a</sup>
1	<i>p</i> -Me	Ι	Ph	Me-	91
2	Н	Ι	Ph	⟨	98 <sup>b</sup>
3	p-MeO	Ι	Ph	MeO-	90
4	p-Cl	Ι	Ph		85
5	p-NO <sub>2</sub>	Ι	Ph	0 <sub>2</sub> N-\	90
6	<i>p</i> -F	Ι	Ph	F-	89 <sup>b</sup>
7	<i>p</i> -Me	Ι	1-naphthyl	Me J J Jg	82 <sup>b</sup>
8	<i>p</i> -Me	Ι	2-benzofuranyl	Me 3h	75 <sup>b</sup>
9	<i>p</i> -Me	Ι	3-thienyl	S Me 3i	87 <sup>b</sup>
10	<i>p</i> -Me	Br	Ph	Me - 3a	87 <sup>c</sup>

TABLE 2	The reaction of aryl halide $1 (1 \text{ mmol})$ with arylboronic acid (1.2 mmol) in the presence of Ni(OAc) <sub>2</sub> / $\beta$ -CD catal	yst
---------	---	-----

PAYAMIFAR ET AL.

4 of 8 WILEY Organometallic

TABLE 2	(Continued)				
Entry	R	X	Ar	Product	Yield (%) <sup>a</sup>
11	Н	Br	Ph	3b	90 <sup>c</sup>
12	p-MeO	Br	Ph	MeO-	88 <sup>c</sup>
13	p-NO <sub>2</sub>	Br	Ph	O <sub>2</sub> N-	90°
14	p-CHO	Br	Ph	O H J Jj	90°
15	p-CN	Br	Ph		91°
16	p-Acyl	Br	Ph	Me 31	90°
<sup>a</sup> Yields refer to <sup>b</sup> GC yield.	isolated yields.				

<sup>c</sup>Reaction carried out at 85°C.

 $\begin{array}{ll} TABLE \ 3 & \mbox{Reusability test of the} \\ Ni(OAc)_2/\beta\mbox{-}CD \ catalyst \ in \ the \ reaction \ of \ 4\ iodotoluene \ 1a \ with \ phenylboronic \ acid \ 2a \ in \ water \end{array}$ 



Ni(II)/ $\beta$ -CD complex formation was examined by ultraviolet–visible (UV–vis) spectroscopy. The absorbance was recorded from 200 to 600 nm. The UV–vis absorption spectra of Ni(OAc)<sub>2</sub>,  $\beta$ -CD, and complex of Ni(II)/ $\beta$ -CD was shown in Figure S17. The results showed that the peak at 273 nm in Ni(OAc)<sub>2</sub> was disappeared in the Ni(II)/ $\beta$ -CD complex spectrum. This is an evidence that Ni(II) has good

interaction with CD in Ni(II)/ $\beta$ -CD complex (Figure S18). All efforts failed to prepare of appropriate crystal samples of Ni(II)/ $\beta$ -CD complex for X-ray analysis.

On the basis of previous literature reports,  $^{[23,66,67]}$  we propose a plausible mechanism for the synthesis of biaryl via the Ni(II)/ $\beta$ -CD-catalyzed coupling of aryl halides with arylboronic acids (Scheme 3).



At the first, Ni(0) species is generated in the presence of  $\beta$ -CD. We assume that the role of  $\beta$ -CD is to stabilize the active catalyst. The reaction may proceed via oxidative addition of arylhalides to yield Ni(II) intermediate **A**. In continuation, transmetalation of the aryl boronic acid to intermediate **A** gives intermediate **B**. Finally, the cross-coupled product is produced by a reductive elimination of intermediate **B** with regenerating the active Ni(0) species.

In summary, herein, we reported a highly efficient strategy Ni(II) catalyst for the Suzuki–Miyaura coupling reaction of aryl halides with aryl boronic acids. The catalyst was successfully applied for the coupling reaction of a wide variety aryl halides (including electron-donating and electron-withdrawing groups) with aryl boronic acids in the presence of a mixture of Ni(OAc)<sub>2</sub> (5 mol%)/ $\beta$ -CD (2.5 mol%). The  $\beta$ -CD is a green, nontoxic, abundant, inexpensive, and degradable natural product that can be used as a ligand with Ni(OAc)<sub>2</sub>. This catalytic system is environmentally green and cost-effective that could be recycled and reused at least four times with a small loss of catalytic activity. The presented process is a useful method to present methodologies due to reusability of the catalyst, use of water as a solvent, and clean reactions.

## **3** | EXPERIMENTAL SECTION

#### 3.1 | General

All chemicals were commercial products. Nuclear magnetic resonance (NMR) spectra were obtained with a 400-MHz Bruker Avance instrument with the chemical shifts being reported as  $\delta$  ppm and couplings expressed in

Hertz (CDCl<sub>3</sub> as solvent with reference chemical shifts of  $\delta = 7.26$  for <sup>1</sup>H NMR and  $\delta = 77.0$  for <sup>13</sup>C NMR). Silica gel column chromatography was carried out with Silica gel 100 (Merck No. 10184). Merck Silica-gel 60 F254 plates (No. 5744) were used for the preparative thin layer chromatography (TLC). Melting points are uncorrected. Gas chromatography was performed on a Varian CP-3800 chromatograph. UV–vis spectra were recorded on a JASCO, UV-550 UV–vis spectra of the complex formation of a mixture of Ni(OAc)<sub>2</sub>.4H<sub>2</sub>O and  $\beta$ -CD).

## 3.2 | General procedure for the crosscoupling aryl halides with aryl boronic acids

In a 5-mL flask, Ni(OAc)<sub>2</sub>.4H<sub>2</sub>O (5 mol %) and  $\beta$ -CD (2.5 mol %) were added to distilled water (1 mL), and the mixture was stirred for 10 min. Aryl halide (0.2 mmol), phenylboronic acid (0.24 mmol), and  $K_2CO_3$  (0.3 mmol) were added to the reaction mixture. The mixture was stirred at 65°C (aryl iodides) or 85°C (aryl bromides) for 24 h. The reaction mixture was cooled to room temperature; the crude product was extracted three times with *n*-hexane  $(3 \times 5 \text{ mL})$  and dried over Na<sub>2</sub>SO<sub>4</sub>. The product was purified by column chromatography with n-hexane-EtOAc (9:1) to afford pure biaryl product 3 in good to high yields (Table 2). All products were known and confirmed by <sup>1</sup>H NMR and <sup>13</sup>C NMR (see Supporting Information). All products gave satisfactory spectral data in accord with the assigned structures and literature reports (Figures S1-S16).

#### ACKNOWLEDGMENT

The authors gratefully acknowledge support by the Institute for Advanced Studies in Basic Sciences (IASBS) Research Council.

#### **AUTHOR CONTRIBUTIONS**

Sara Payamifar: Investigation; methodology. Foad Kazemi: Methodology. Babak Kaboudin: Investigation; methodology; supervision.

## **CONFLICT OF INTEREST**

The authors declare no conflict of interest.

## DATA AVAILABILITY STATEMENT

Data availability statement: The data that supports the findings of this study are available in the supplementary material of this article.

#### ORCID

Sara Payamifar D https://orcid.org/0000-0002-8651-0102 Foad Kazemi D https://orcid.org/0000-0001-8877-1173 Babak Kaboudin D https://orcid.org/0000-0003-0495-0006

## REFERENCES

- N. Miyaura, T. Yanagi, A. Suzuki, Synt. Commun. 1981, 11, 513.
- [2] N. Miyaura, A. Suzuki, Chem. Rev. 1995, 95, 2457.
- [3] F. Alonso, M. Yus, I. Beletskaya, Tetrahedron 2008, 64, 3047.
- [4] A. Suzuki, Angew. Chem. Int. Ed. 2011, 50, 6722.
- [5] C. C. Johansson Seechurn, M. O. Kitching, T. J. Colacot, V. Snieckus, Angew. Chem. Int. Ed. 2012(51), 5062.
- [6] H. Li, C. C. Johansson Seechurn, T. J. Colacot, ACS Catal. 2012(2), 1147.
- [7] M. M. Heravi, E. Hashemi, Tetrahedron 2012, 68, 9145.
- [8] F.-S. Han, Chem. Soc. Rev. 2013, 42, 5270.
- [9] I. Maluenda, O. Navarro, *Molecules* **2015**, *20*, 7528.
- [10] A. Chatterjee, T. R. Ward, *Catal. Lett.* **2016**, *146*, 820.
- [11] A. Biffis, P. Centomo, A. del Zotto, M. Zecca, Chem. Rev. 2018, 118, 2249.
- [12] P. Devendar, R.-Y. Qu, W.-M. Kang, B. He, G.-F. Yang, J. Agric. Food Chem. 2018, 66, 8914.
- [13] S. E. Hooshmand, B. Heidari, R. Sedghi, R. S. Varma, Green Chem. 2019, 21, 381.
- [14] G. Bringmann, R. Walter, R. Weirich, Angew. Chem. Int. Ed. 1990, 29, 977.
- [15] R. Capdeville, E. Buchdunger, J. Zimmermann, A. Matter, *Nature Rev. Drug Disc.* 2002, 1, 493.
- [16] M. Kertesz, C. H. Choi, S. Yang, Chem. Rev. 2005, 105, 3448.
- [17] J.-P. Corbet, G. Mignani, Chem. Rev. 2006, 106, 2651.
- [18] F. S. Han, M. Higuchi, D. G. Kurth, Org. Lett. 2007, 9, 559.
- [19] N. K. Adlington, L. R. Agnew, A. D. Campbell, R. J. Cox, A. Dobson, C. F. Barrat, M. A. Gall, W. Hicks, G. P. Howell, A. Jawor-Baczynska, J. Org. Chem. 2018, 84, 4735.
- [20] I. P. Beletskaya, F. Alonso, V. Tyurin, Coord. Chem. Rev. 2019, 385, 137.
- [21] S. Z. Tasker, E. A. Standley, T. F. Jamison, *Nature* 2014, 509, 299.
- [22] V. P. Ananikov, ACS Catal. 2015, 5, 1964.
- [23] J. B. Diccianni, T. Diao, Trends Chem. 2019, 1(9), 830.
- [24] V. Percec, G. M. Golding, J. Smidrkal, O. Weichold, J. Org. Chem. 2004, 69, 3447.
- [25] B. M. Rosen, C. Huang, V. Percec, Org. Lett. 2008, 10, 2597.
- [26] D. A. Wilson, C. J. Wilson, B. M. Rosen, V. Percec, Org. Lett. 2008, 10, 4879.
- [27] Z.-Y. Tang, Q.-S. Hu, J. Org. Chem. 2006, 71, 2167.
- [28] B.-T. Guan, Y. Wang, B.-J. Li, D.-G. Yu, Z.-J. Shi, J. Am. Chem. Soc. 2008, 130, 14468.
- [29] C. Chen, L.-M. Yang, Tetrahedron Lett. 2007, 48(13), 2427.
- [30] X.-H. Fan, G. Li, L.-M. Yang, J. Organomet. Chem. 2011, 696, 2482.
- [31] Y. L. Zhao, Y. Li, S. M. Li, Y. G. Zhou, F. Y. Sun, L. X. Gao, F. S. Han, Adv. Synth. Catal. 2011, 353, 2881.
- [32] Y.-L. Zhao, G.-J. Wu, F.-S. Han, Chem. Commun. 2012, 48, 5868.
- [33] B. H. Lipshutz, J. A. Sclafani, P. A. Blomgren, *Tetrahedron* 2000, 56, 2139.

- [34] P. A. Grieco, Organic Synthesis in Water, Springer Science & Business Media 1997.
- [35] C.-J. Li, T.-H. Chan, Organic Reactions in Aqueous Media, Wiley 1997.
- [36] P. T. Anastas, J. C. Warner, Green Chem.: Theory Pract. 1998, 29.
- [37] P. Tundo, P. Anastas, D. S. Black, J. Breen, T. Collins, S. Memoli, J. Miyamoto, M. Polyakoff, W. Tumas, *Pure Appl. Chem.* 2000, 72(7), 1207.
- [38] M.-O. Simon, C.-J. Li, Chem. Soc. Rev. 2012, 41(4), 1415.
- [39] R. A. Sheldon, Chem. Soc. Rev. 2012, 41(4), 1437.
- [40] T. Kitanosono, K. Masuda, P. Xu, S. Kobayashi, *Chem. Rev.* 2018, 118(2), 679.
- [41] G. Cravotto, E. Borretto, M. Oliverio, A. Procopio, A. Penoni, *Cat. Com.* 2015, 63, 2.
- [42] R. N. Butler, A. G. Coyne, Org. Biomol. Chem. 2016, 14(42), 9945.
- [43] J. Szejtli, Chem. Rev. 1998, 98(5), 1743.
- [44] G. Crini, Chem. Rev. 2014, 114(21), 10940.
- [45] A. R. Khan, P. Forgo, K. J. Stine, V. T. D'Souza, Chem. Rev. 1998, 98(5), 1977.
- [46] G. Gattuso, S. A. Nepogodiev, J. F. Stoddart, Chem. Rev. 1998, 98(5), 1919.
- [47] E. Engeldinger, D. Armspach, D. Matt, Chem. Rev. 2003, 103(11), 4147.
- [48] S. V. Bhosale, S. V. Bhosale, Mini-Rev. Org. Chem. 2007, 4(3), 231.
- [49] C. C. Bai, B. R. Tian, T. Zhao, Q. Huang, Z. Z. Wang, *Molecules* 2017, 22(9), 1475.
- [50] L. Marinescu, M. Bols, Curr. Org. Chem. 2010, 14(13), 1380.
- [51] K. R. Rao, Y. V. D. Nageswar, R. Sridhar, V. Reddy, Curr. Org. Chem. 2010, 14(13), 1308.
- [52] C. J. Easton, Pure Appl. Chem. 2005, 77(11), 1865.
- [53] R. Breslow, S. D. Dong, Chem. Rev. 1998, 98(5), 1997.
- [54] I. Tabushi, Acc. Chem. Res. 1982, 15(3), 66.
- [55] M. Qi, P. Z. Tan, F. Xue, H. S. Malhi, Z.-X. Zhang, D. J. Young, T. A. Hor, *RSC Adv.* 2015, 5(5), 3590.
- [56] A. Cassez, A. Ponchel, F. Hapiot, E. Monflier, Org. Lett. 2006, 8(21), 4823.
- [57] Y. Guo, J. Li, X. Shi, Y. Liu, K. Xie, Y. Liu, Y. Jiang, B. Yang, R. Yang, *Appl. Organomet. Chem.* **2017**, *31*(4), e3592.
- [58] F.-X. Legrand, M. Ménand, M. Sollogoub, S. Tilloy, E. Monflier, *New J. Chem.* **2011**, *35*(10), 2061.
- [59] V. V. Shinde, D. Jeong, S. Jung, Catalysts 2019, 9(2), 111.
- [60] A. Z. Asadabadi, S. J. Hoseini, M. Bahrami, S. M. Nabavizadeh, *New J. Chem.* **2019**, *43*(17), 6513.
- [61] X. Zhao, X. Liu, M. Lu, Appl. Organomet. Chem. 2014, 28(8), 635.
- [62] R. I. Khan, K. Pitchumani, Green Chem. 2016, 18(20), 5518.
- [63] B. Kaboudin, Y. Abedi, T. Yokomatsu, Eur. J. Org. Chem. 2011, 2011(33), 6656.
- [64] B. Kaboudin, R. Mostafalu, T. Yokomatsu, Green Chem. 2013, 15, 2266.
- [65] B. Kaboudin, H. Salemi, R. Mostafalu, F. Kazemi, T. Yokomatsu, J. Organomet. Chem. 2016, 818, 195.
- [66] J. M. Bhojane, S. A. Sarode, J. M. Nagarkar, New J. Chem. 2016, 40, 1564.
- [67] X. Lei, K. A. Obregon, J. Alla, Appl. Organomet. Chem. 2013, 27, 419.

Applied Organometallic\_WILEY<sup>7 of 8</sup> Chemistry



# SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

**How to cite this article:** S. Payamifar, F. Kazemi, B. Kaboudin, *Appl Organomet Chem* **2021**, e6378. <u>https://doi.org/10.1002/aoc.6378</u>