Tetrahedron Letters 52 (2011) 1587–1591

Contents lists available at ScienceDirect

Tetrahedron Letters

journal homepage: www.elsevier.com/locate/tetlet

Cross-linked polymer supported palladium catalyzed carbonylative Sonogashira coupling reaction in water

Yan Wang [a,b], Jianhua Liu [a,*], Chungu Xia [a,*]

[a] State Key Laboratory for Oxo Synthesis and Selective Oxidation, Lanzhou Institute of Chemical Physics, Chinese Academy of Sciences, No. 18 Tianshui Middle Road, Lanzhou 730000, China
[b] Graduate School of the Chinese Academy of Sciences, Chinese Academy of Sciences, No. 19 Yuquan Road, Beijing 100049, China

ARTICLE INFO

Article history:
Received 9 December 2010
Revised 12 January 2011
Accepted 21 January 2011
Available online 27 January 2011

Keywords:
Supported catalyst
Palladium
Carbonylative Sonogashira coupling
Recyclable
Water

ABSTRACT

A cross-linked polymer-supported ionic liquid immobilized palladium catalyst, which is prepared by reaction of the $Pd(OAc)_2$ with copolymer of 3-butyl-1-vinylimidazolium iodide and divinylbenzene, was well characterized and employed as an effective heterogeneous catalyst for carbonylative Sonogashira coupling reaction of aryl iodides with terminal alkynes in water, affording the corresponding α,β-alkynyl ketones in good to excellent yields. The catalytic system not only solves the basic problem of homogeneous palladium catalyst recovery and reuse but also avoids the use of toxic phosphine ligands. The stability of supported palladium was also discussed.

From an environmental and economic point of view, the use of volatile organic compounds as solvents for chemical transformations is under critical discussion and alternatives, such as $scCO_2$,[1] ionic liquids,[2] or water[3] are actively studied.[4] Since the RCH/RP hydroformylation process was carried out in an aqueous-organic solvent mixture,[5] water has been receiving special attention as a cheap and non-toxic solvent.

α,β-Alkynyl ketones are important carbonyl compounds, which appear in many biologically active molecules and also play crucial roles as intermediates in the synthesis of natural products.[6] An atom economic route to prepare these compounds is carbonylative Sonogashira coupling reaction: metal-catalyzed direct coupling of aryl halides with terminal alkynes in the presence of carbon monoxide.[7] In the early reports, considerable efforts have been addressed to this reaction.[8] But the most restricting aspect of these studies is that they were focused on homogeneous catalytic systems together with phosphine ligands. Recently, our group had developed the first heterogeneous catalyst based on palladium on charcoal (Pd/C) with good catalytic efficiency for the carbonylative coupling reactions.[9] Although the recycle of expensive transition metal catalyst was achieved, its catalytic performance was still not so efficient. Consequently, it is necessary to investigate another efficient, recyclable, and environmentally benign catalyst system for the reaction. It is well known that heterogeneous catalysts have their advantages such as more easily separated from products and recycled, thus providing an environmentally cleaner process. In recent years, immobilization of catalysts on suitable supports has been a topic of interest, especially; immobilization of catalyst onto ionic liquid containing polymers[10] sharing some properties of ionic liquids has been studied. For example, Han and coworkers[11] synthesized copolymer PDVB-IL from imidazolium IL with an amine group with cross-linker divinylbenzene, which was used for the immobilization of Pd nanoparticles for Heck reaction. However, to the best of our knowledge, there has been no general study of carbonylation reactions catalyzed by ionic liquid containing polymers supported palladium catalysts.

In the framework of our continuous efforts for effective and green processes for the carbonylative Sonogashira coupling reaction,[9,12] herein we report the synthesis of a cross-linked copolymer P(DVB-IL) supported palladium catalyst and illustrate its application in the carbonylative Sonogashira coupling reaction of aryl iodides with terminal alkynes to form α,β-alkynyl ketones in water.

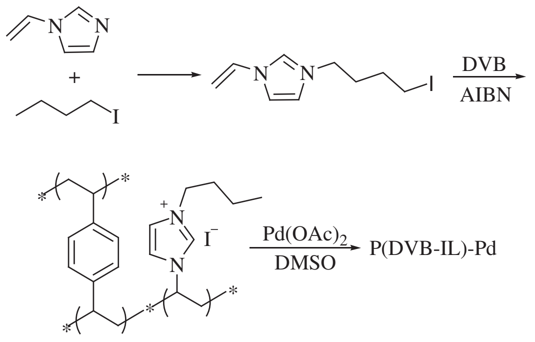
The route to synthesize the ionic liquid composite material supported palladium catalyst[13] is schematically described in Scheme 1.

P(DVB-IL) and P(DVB-IL)-Pd catalyst were characterized by thermogravimetric analysis (TGA). The thermograms are shown in Figure 1. The small weight loss of P(DVB-IL) before 210 °C under an argon atmosphere was attributed to the loss of the adsorbed water. It can be seen from the two thermograms that the weight loss between 210 °C and 410 °C was due to the elimination of the

---

* Corresponding authors. Fax: +86 931 8277088 (J.L.).
E-mail addresses: jhliu@licp.cas.cn (J. Liu), cgxia@licp.cas.cn (C. Xia).

0040-4039/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.tetlet.2011.01.095



Scheme 1. Synthesis of the cross-linked polymer supported palladium.

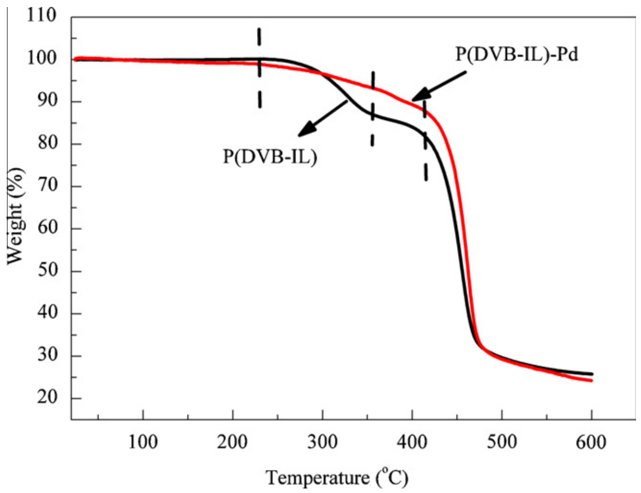


Figure 1. The thermogram of P(DVB-IL)-Pd under nitrogen at a heating rate of 10 °C/min.

ILs immobilized on the polymers. Further weight loss at a higher temperature (above 410 °C) was attributed to the decomposition of PDVB.[11]

Figure 2 shows the typical transmission electron microscopy (TEM) images of the catalyst (P(DVB-IL)-Pd). The dark spots in the TEM image indicate the presence of palladium nanoparticles that were bound to the copolymers. The diameter of palladium nanoparticles was about 20 nm and the size distribution was very narrow (Fig. 2a). Palladium can disperse very well after carbonylation reaction.

The catalyst P(DVB-IL)-Pd was also characterized by X-ray photoelectron spectroscopy (XPS) before reaction and the results are shown in Figure 3. Obviously, C, O, N, I, and Pd appeared on the activated surfaces (Fig. 3a). It can be seen that the Pd 3d spectrum was resolved into two spin–orbit pairs with binding energies of 338.0 eV and 343.3 eV, respectively, which are assigned to electron transitions of $3d_{5/2}$ and $3d_{3/2}$ of Pd^{2+} (Fig. 3b). On the basis of previous measurements, the Pd $3d_{5/2}$ signal for PdI_2 was reported at 336.2 eV and the Pd $3d_{5/2}$ signal for $Pd(OAc)_2$ was reported at 338.6 eV. And electron transition of the O $3d_{5/2}$ in the catalyst is shown at 533.0 eV, which is consistent with standard spectrum O of acetate. So we can speculate there may be an electrostatic interaction between the Pd atoms with the iodine atoms and the oxygen atoms of acetate. In other words, the Pd atom may form a bond with iodine atom, oxygen atom, and the support, Pd particle was immobilized on the cross-linked polymer through a covalent bonding as the supported palladium N-heterocyclic carbene (NHC). The content of Pd in the catalyst was 3.13 wt % (0.295 mmol g^{-}1), as determined by the AAS analysis.

The catalytic activity of P(DVB-IL)-Pd was examined for its ability to catalyze the carbonylative Sonogashira coupling. In order to optimize the reaction conditions, the carbonylative coupling of iodobenzene and phenylacetylene was carried out with P(DVB-IL)-Pd as a model reaction. Different solvent, base, reaction temperature, and time were investigated (Table 1). The solvent plays an important role in the reaction: when the reaction was performed in acetonitrile, THF and acetone, the isolated yields reached 62%, 85%, 46% (Table 1, entries 2, 3 and 5). Toluene and H_2O both lead to the yield of α,β-alkynyl ketones in excellent yield (Table 1, entries 1 and 4). Therefore, water was chosen as a non-toxic solvent and the best mediate. Noteworthy, Et_3N was the most suitable base for the water system. Increasing the reaction temperature and time also had a positive effect on the catalytic activity (Table 1, entries 8–11).

With water as the solvent, 0.5 mmol % Pd catalyst loading, starting with terminal alkynes and aryl iodides, we carried out the carbonylative Sonogashira coupling reaction under 3.0 MPa CO with Et_3N as the base. To explore the generality and scope of the carbonylative coupling reaction, we evaluated various aryl iodides and terminal alkynes as substrates.[14,15] The results are given in Table 2. A wide range of aryl iodides bearing an electron-withdrawing group or an electron-donating group all gave corresponding carbonyl products in excellent yields when they react with phenylacetylene (entries 1–13). Iodobenzenes containing substituents at the 2-position gave poorer results because of the steric influence (entry 3). 2-Iodoanisole, 3-iodoanisole, and 4-iodoanisole were converted smoothly into the corresponding products in 81%, 88%,

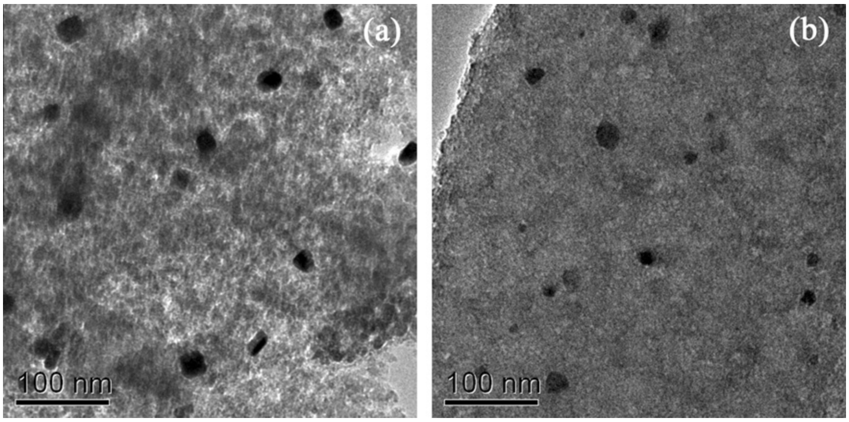


Figure 2. (a) The TEM images of the fresh P(DVB-IL)-Pd; (b) The TEM image of the recovered P(DVB-IL)-Pd after being reused five times in carbonylative Sonogashira coupling reaction.

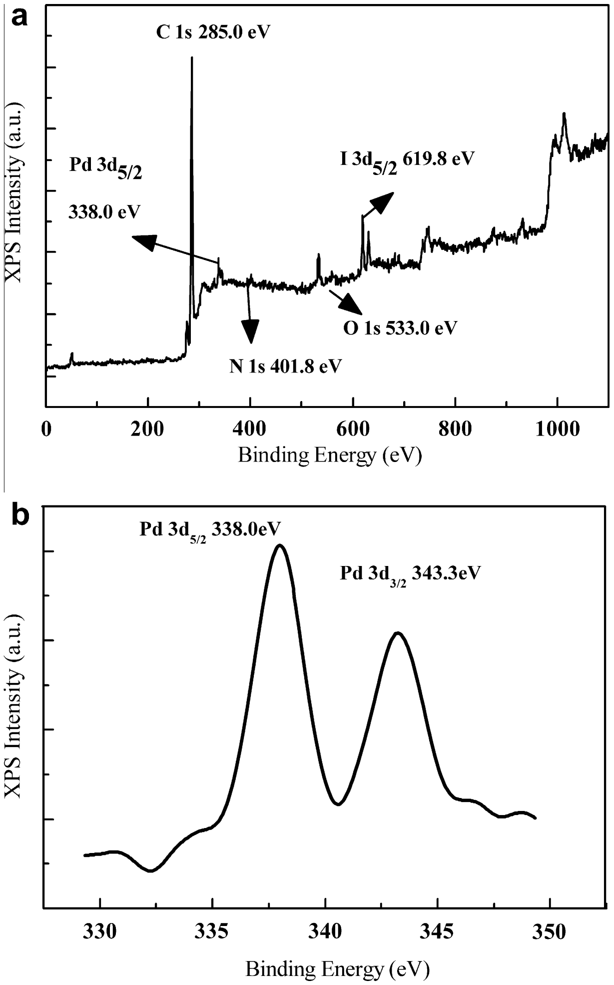


Figure 3. XPS spectra of the catalyst (a) and the Pd atom (b).

Table 1
Evaluation of the reaction parameters[a]

$$\text{Ph-I} + \text{CO} + \equiv\!\!-\text{R} \xrightarrow{\text{P(DVB-IL)-Pd}} \text{Ph}-\overset{\text{O}}{\overset{\|}{\text{C}}}-\!\equiv\!-\text{R}$$

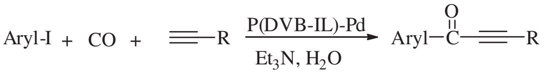
Entry	Solvent	Base	T (°C)	t (h)	Yield[b] (%)
1	Toluene	NEt_3	130	6	89
2	CH_3CN	NEt_3	130	6	62
3	THF	NEt_3	130	6	85
4	H_2O	NEt_3	130	6	90
5	Acetone	NEt_3	130	6	46
6	–	NEt_3	130	6	21
6	H_2O	Cs_2CO_3	130	6	15
7	H_2O	Pyridine	130	6	47
8	H_2O	NEt_3	120	6	88
9	H_2O	NEt_3	100	6	46
10	H_2O	NEt_3	130	2	80
11	H_2O	NEt_3	130	3	87

[a] Reaction condition: iodobenzene 1.0 mmol, phenylacetylene 1.2 mmol, solvent 5.0 mL, base 2.0 mmol.
[b] Isolated yield.

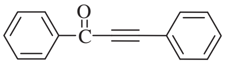
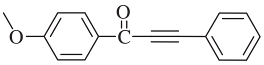
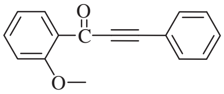
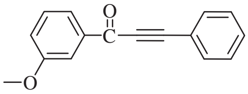
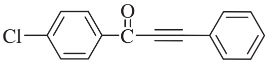
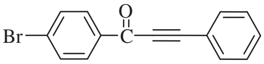
and 95% yields, respectively (Table 2, entries 2–4). The reaction of 4-chloro-iodobenzene, 4-bromo-iodobenzene, and phenylacetylene also afforded the corresponding products in satisfactory yields (Table 2, entries 5–7). When 4-methyl-iodobenzene, 2-methyl-iodobenzene and 4-ethyl-iodobenzene were employed in the reaction with phenylacetylene, the desired products were isolated in excellent yields (Table 2, entries 8–10). We also investigated several acetylenes containing different groups for the reaction. All substituted phenylacetylenes were coupling with iodobenzene to afford α,β-alkynyl ketones in good to excellent yield (Table 2, entries 13–15). While the reaction of 1-hexyne with iodobenzene only 27% yield of the carbonylative coupling product was obtained (Table 2, entry 16). The results demonstrated that the catalytic system was not suitable for the carbonylative coupling of aliphatic acetylene with iodobenzene.

To evaluate the recyclability of P(DVB-IL)-Pd in the carbonylative Sonogashira coupling reaction, the continuous carbonylative coupling reaction of iodobenzene with phenylacetylene in water

Table 2
Carbonylative Sonogashira coupling terminal alkynes with aryl iodides to form α,β-alkynyl ketones in water[a]

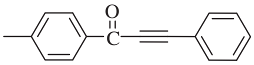
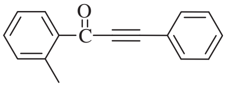
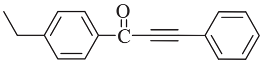
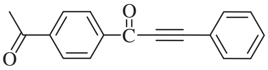
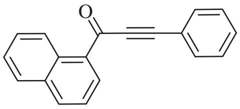
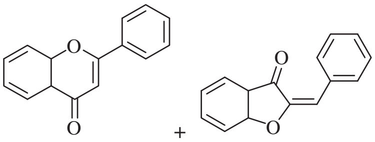
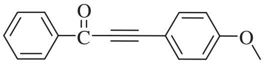
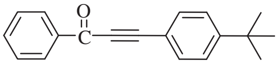
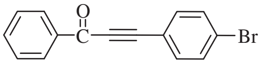
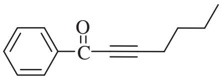


$$\text{Aryl-I} + \text{CO} + \equiv\!\!-\text{R} \xrightarrow[\text{Et}_3\text{N, H}_2\text{O}]{\text{P(DVB-IL)-Pd}} \text{Aryl}-\overset{\text{O}}{\overset{\|}{\text{C}}}-\!\equiv\!-\text{R}$$

Entry	Aryl	R	Product	Yield[b] (%)
1	Ph	Ph		90 81[c]
2	4-CH_3O-Ph	Ph		95
3	2-CH_3O-Ph	Ph		81
4	3-CH_3O-Ph	Ph		88
5	4-Cl-Ph	Ph		92
6	4-Br-Ph	Ph		92

(continued on next page)

Table 2 (*continued*)

Entry	Aryl	R	Product	Yield[b] (%)
7	4-CH_3-Ph	Ph		93
8	2-CH_3-Ph	Ph		89
9	4-C_2H_5-Ph	Ph		91
10	4-CH_3CO-Ph	Ph		82
11	Naphthalene	Ph		85
12[d]	2-OH-Ph	Ph		88
13	Ph	4-CH_3O-Ph		94
14	Ph	4-*t*Bu-Ph		94
15	Ph	4-Br-Ph		87
16	Ph	*n*Bu		27

Reaction time was 4h.

[a] Reaction condition: aryl iodide (1 mmol), terminal alkyne (1.2 mmol), P(DVB-IL)-Pd (20 mg, 0.005 mmol Pd), Et_3N (0.4 mL), distilled water (5.0 mL), temperature: 130 °C, time: 6 h, CO pressure: 3.0 MPa.

[b] Isolated yield.

[c] Reaction time was 4 h.

[d] The total yield of the two products.

was investigated and the results are presented in Figure 4. The catalyst could be reused five times only with a slight loss of activity (the fifth recycle yield still can obtain 83.8%). The aggregation of the Pd particles in the used catalyst was not obvious, which obtains from TEM in Figure 2b, and the content of Pd in the catalyst was 2.43 wt % (0.229 mmol $g^{-}1$), as determined by the AAS analysis.

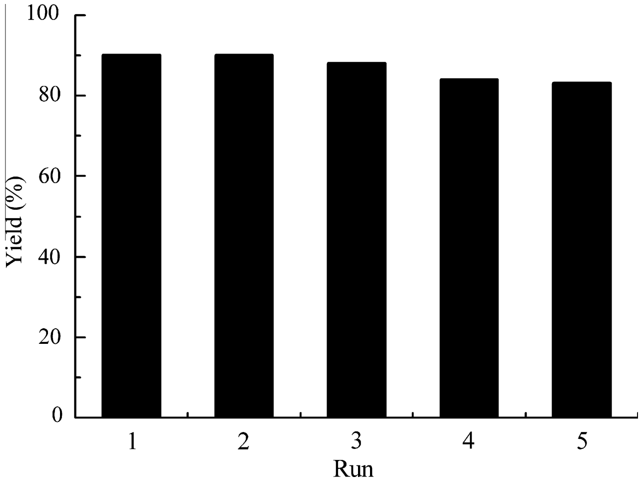


Figure 4. The reuse of carbonylative Sonogashira coupling with iodobenzene and phenylacetylene in water.

In summary, a highly cross-linked polymer matrix was successfully prepared and proved to be an effective support for immobilizing palladium complex. The polymer supported palladium catalyst exhibited high efficiency for the carbonylative Sonogashira coupling of aryl iodides with terminal alkynes in water. In addition, the catalyst offered practical advantages such as easy separation from the products and reuse without activity loss. The heterogeneous carbonylation reaction provides a practical and environmentally friendly procedure for the synthesis of α,β-alkynyl ketones.

Acknowledgment

This work was financially supported by the National Natural Science Foundation of China (Nos. 20625308, 21073209).

Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.tetlet.2011.01.095.

References and notes

1. (a) Jessop, P. G.; Leitner, W. *Chemical Synthesis using Supercritical Fluids*; Wiley-VCH: Weinheim, 1999; (b) Leitner, W. *Acc. Chem. Res.* **2002**, *35*, 746–756.
2. Wasserscheid, P.; Welton, T. *Ionic Liquids in Synthesis*; Wiley-VCH: Weinheim, 2003.
3. Cornils, B.; Herrmann, W. A. *Aqueous-Phase Organometallic Catalysis*; Wiley-VCH: Weinheim, 2004.

4. Cole-Hamilton, D. J. *Science* **2003**, *299*, 1702–1706.
5. Kohlpaintner, C. W.; Fischer, R. W.; Cornils, B. *Appl. Catal., A: Gen.* **2001**, *221*, 219–225.
6. (a) Chowdhury, C.; Kundu, N. G. *Tetrahedron* **1999**, *55*, 7011–7016; (b) Kadnikov, D. V.; Larock, R. C. *J. Organomet. Chem.* **2003**, *687*, 425–435.
7. Beletskaya, I. P.; Cheprakov, A. V. In *Comprehensive Organometallic Chemistry III*; Hiyama, T., Ed.; Elsevier: Oxford, 2007; Vol. 11, p 411.
8. (a) Tambade, P. J.; Patil, Y. P.; Nandurkar, N. S.; Bhanage, B. M. *Synlett.* **2008**, 886–888; (b) Sans, V.; Trzeciak, A. M.; Luis, S.; Ziółkowski, J. *Catal. Lett.* **2006**, *109*, 37–41; (c) Taifur Rahman, M.; Fukuyama, T. X.; Kamata, N.; Sato, M.; Ryu, I. *Chem. Commun.* **2006**, 2236–2238; (d) Ma, W.; Li, X.; Yang, J.; Liu, Z.; Chen, B.; Pan, X. *Synthesis* **2006**, 2489–2492; (e) Ahmed, M. S. M.; Mori, A. *Org. Lett.* **2003**, *5*, 3057–3060; (f) Arcadi, A.; Cacchi, S.; Marinelli, F.; Pace, P.; Sanzi, G. *Synlett.* **1995**, 823–824; (g) Liang, B.; Huang, M.; You, Z.; Xiong, Z.; Lu, K.; Fathi, R.; Chen, J.; Yang, Z. *J. Org. Chem.* **2005**, *70*, 6097–6100.
9. Liu, J.; Chen, J.; Xia, C. *J. Catal.* **2008**, *253*, 50–56.
10. (a) Green, O.; Grubjesic, S.; Lee, S.; Firestone, M. A. *J. Macro. Sci., Part C: Polym. Rev.* **2009**, *49*, 339–360; (b) Lu, J.; Yan, F.; Texter, J. *Prog. Polym. Sci.* **2009**, *34*, 431–448.
11. Liu, G.; Hou, M.; Song, J.; Jiang, T.; Fan, H.; Zhang, Z.; Han, B. *Green Chem.* **2010**, *12*, 65–69.
12. Liu, J.; Peng, X.; Sun, W.; Zhao, Y.; Xia, C. *Org. Lett.* **2008**, *10*, 3933–3936.
13. Xie, Y.; Zhang, Z.; Jiang, T.; He, J.; Han, B.; Wu, T.; Ding, K. *Angew. Chem., Int. Ed.* **2007**, *46*, 7255–7258.
14. *General procedure for catalytic carbonylative Sonogashira coupling of iodobenzene and phenylacetylene in water:* In a typical experiment, known quantities of iodobenzene (1.0 mmol), phenylacetylene (1.2 mmol), P(DVB-IL)-Pd (20 mg, Pd 0.5 mol %), Et_3N (0.4 mL, 2.4 mmol), and distilled water (5.0 mL) were charged into the reactor. The autoclave was closed, purged three times with CO, pressurized to 3.0 MPa with CO, and then stirred at 130 °C for 6 h. After cooling down to room temperature, the reaction mixture was analyzed by GC–MS and then worked up by removing water under vacuum and the residue was purified by chromatography on silica gel (eluting solvent hexane:ethyl acetate).
15. *NMR data for selected products:* 1,3-diphenylprop-2-yn-1-one (Table 2, entry 1): ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.29–7.33 (m, 3H), 7.35–7.43 (m, 2H), 7.50–7.54 (m, 1H), 7.54–7.60 (m, 2H), 8.11 (d, J = 8.4 Hz, 2H); ^{13}C NMR (400 MHz, $CDCl_3$) δ: 86.9, 93.2, 120.1, 128.8, 128.7, 129.6, 130.9, 133.1, 134.2, 136.9, 178.0.