Catalysis Science & Technology

Accepted Manuscript

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View Article Online
DOI: 10.1039/C9CY00275H

Journal Name

COMMUNICATION

Aerobic Oxidative Alkynylation of H-Phosphonates and Amides: An Efficient Route for the Synthesis of Alkynylphosphonates and Ynamides by Recyclable Cu-MnO Catalyst

Received 00th January 20xx,
Accepted 00th January 20xx

DOI: 10.1039/x0xx00000x

www.rsc.org/

*Harshvardhan Singh, Tapan Sahoo, Chiranjit Sen, Sunil M. Galani and Subhash Chandra Ghosh**

ABSTRACT: An atom-economical and efficient route for the synthesis alkynylphosphonates and ynamides by aerobic oxidative alkynylation of H-phosphonates and amides with both aliphatic and aromatic alkynes using our synthesized recyclable heterogeneous Cu-MnO catalyst has been developed. The phosphorylation was carried out under base and ligand-free conditions, and in the presence of air as the sole oxidant. The reaction is compatible with a wide variety of functional groups and generates alkynylphosphonates and ynamides products in good to excellent yields. Both the reactions can be scaled up to gram scale without any decrease in the reaction yield and reaction time is less compared to the literature report. The catalyst is recyclable and reused for several times without any significant loss of the reactivity.

Introduction

Direct functionalization of the C(sp)-H bond of the terminal alkyne for the construction of C (sp)-P bond and C (sp)-N bond is highly demanding due to their great interest in chemistry and biology.[1-15] The importance of phosphorous compounds in organic synthesis and their presence in bioactive molecules motivated chemists for the development of new methodologies for C(sp)-P bond forming reactions. [8-15]. Alkynylphosphonates, containing a reactive triple bonds and a phosphoryl groups, are a very important class of functional molecule. Therefore, a considerable effort has been made for the synthesis of alkynylphosphonates. Traditionally, reaction of $(RO)_2P(O)Cl$ as phosphorous electrophile with Li or Mg acetylides is one of the most common and effective method used for the synthesis of alkynylphosphonates. [16-17] However, it has several limitation like a) use of hazardous chemicals and generates toxic waste; and b) poor functional group tolerance. Other alternative strategies for the synthesis of alkynylphosphonates are the reaction of 1,1-dibromo-1-alkenes with H-phosphites, [18-19] oxidative decarboxylative coupling of aryl propiolic acids with dialkyl H-phosphonates, [20-21] cross-coupling with alkynylcopper reagents and 1-alkynyl sulfones [22] and others [23-24]. On the other hand, the atom economical strategy, coupling of terminal alkynes with H-phosphonates to synthesize alkynylphosphonates was not fully explored. In 2009, Zhao and Han *et al.* first reported this strategy using CuI as a catalyst, Et_3N as a base in DMSO solvent. [25-26] Zhao and Chen *et al.* reported a similar reaction using $CuSO_4.5H_2O$ as a catalyst and Et_3N as a base. [27] Base is required for their system to deprotonate the terminal alkyne to prepare intermediate copper acetylide species. Base free approaches were reported by Wang *et al.* using silica-supported carbene-Cu(II) catalyst, [28] but the catalyst preparation is not so straightforward and by Moglie *et al.* using homogeneous Cu_2O as a catalyst.[29] Other than copper, expensive palladium catalyzed, silver mediated dehydrogenative coupling of terminal alkynes with secondary phosphine oxides was reported by Han *et al.*[30] and Lei *et al.* [31] More recently, Han *et al.* reported the same in the absence of silver with only palladium catalyst. [32] Despite the advancement of C(sp)-H bond preparation, the majority of the reactions were carried out under the homogeneous condition, with limitations like the use of an expensive catalyst, recyclability, and chances of metal contamination in the final product which is mostly undesired in the synthesis of pharmaceutical molecules. Hence, the development of an atom-economical, environmentally benign and sustainable heterogeneous catalyst for C(sp)-P bond preparation is still demanding for the advancement in this area. As part of our ongoing research on heterogeneous catalysis, we have reported lotus shaped Cu-MnO catalyzed direct $C(sp^2)$-H halogenation, and amination reaction, [33-35] we have drawn our attention in the field of C(sp)-P bond and C (sp)-N bond construction. Herein, we wish to report an efficient catalytic system for oxidative coupling reaction of terminal alkynes with H-phosphonates to synthesize alkynylphosphonates using our recently developed reusable spherical Cu-MnO catalyst; the same catalyst also works for the synthesis of ynamides from amide and alkyne coupling.

Natural Products and Green Chemistry Division
Academy of Scientific and Innovative Research,
CSIR-Central Salt and Marine Chemicals Research Institute, G.B. Marg, Bhavnagar-364002, Gujarat, India.
E-mail: scghosh@csmcri.res.in; schandra1976@gmail.com

Electronic Supplementary Information (ESI) available: experimental details, copy of ^1H and ^{13}C and ^{31}P NMR spectra See DOI: 10.1039/x0xx00000x

Result and discussions

Catalyst preparation

The spherical γ-MnO_2 was prepared by our reported procedure,[36] first the $MnCO_3$ was synthesized by hydrothermal conditions, using $Mn(OAc)_2$,$4H_2O$, ammonium carbonate, and oxalic acid as a chelating agent. After that, the material was calcined at 350°C in aerobic conditions to get spherical shape γ-MnO_2. Later, copper [$Cu(OAc)_2$.H_2O] impregnation was carried out by evaporating to dryness methodology [33] followed by calcination at 350 °C under 10% H_2 in N_2 flow, for 6h. The synthesized Cu-MnO catalyst was fully characterized by SEM, TEM, XRD, and XPS, during calcination, under a hydrogen atmosphere, the manganese (IV) oxide reduces to manganese (II) oxide. From SEM and TEM images (Figure 1, a-d) revealed that the Cu-MnO catalyst is spherical in nature with a diameter of 3-4 µm. In the XRD pattern of 5 %, Cu-MnO, a tiny peak of metallic Cu was observed (figure 1 e), which indicates that upon calcination under reducing environment Cu(II) reduces to Cu(0) species and homogeneously distributed over the MnO moiety as confirmed by elemental mapping in EDS-SEM analysis (see ESI for details) . XPS spectra confirmed the presence of both Cu (0) and Cu (II) species in the surface of the catalyst. [33]

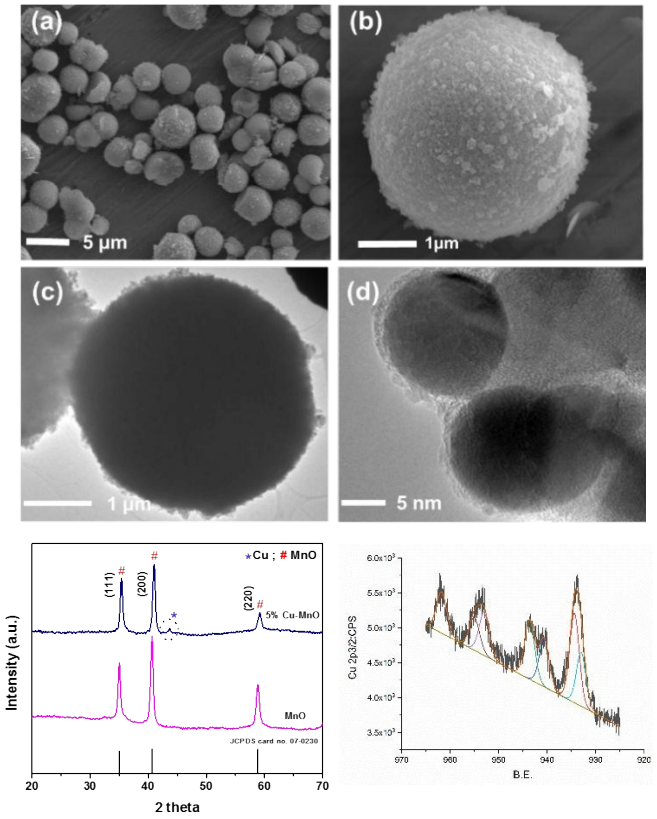
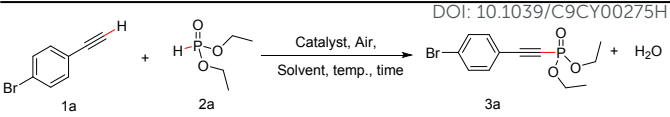


Figure 1: (a) and (b) SEM images, (c) and (d) TEM images of the synthesized Cu-MnO catalyst, (e) XRD pattern of synthesized Cu-MnO and MnO catalyst; (f) Cu 2p XPS spectra of the 5% Cu-MnO catalyst

Reaction Optimization

After synthesis and complete characterization of the Cu-MnO catalyst, we have started our investigation, for C-P bond formation

Table 1: Optimization of alkynylation of dialkyl phosphites [a]



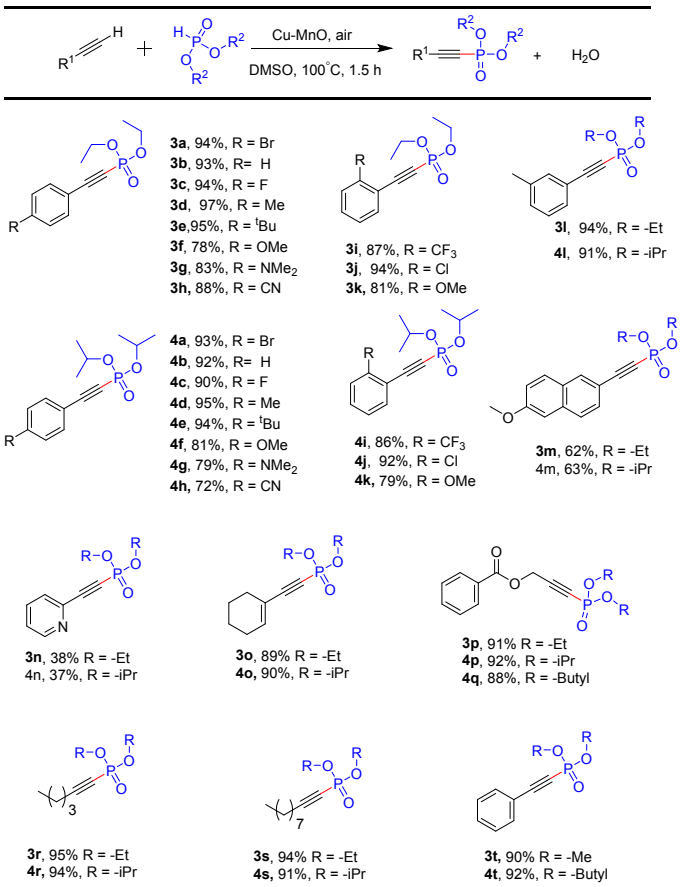
Entry	Catalyst	Solvent	T (°C)	Yield (%)
1	5 wt% Cu-MnO	Toluene	100	32
2	5 wt% Cu-MnO	THF	100	Trace
3	5 wt% Cu-MnO	CH_3CN	100	Trace
4	5 wt% Cu-MnO	DMF	100	38
5	5 wt% Cu-MnO	DMSO	100	94
6	5 wt% Cu-MnO	DMSO	50	56
7	5 wt% Cu-MnO	DMSO	rt	trace
8	5 wt% Cu-MnO	DMSO	100	58[b]
9	MnO	DMSO	100	NR
10	γ-MnO_2	DMSO	100	NR
11	-	DMSO	100	NR
12	5 wt% Cu-MnO	DMSO	100	NR[c]
13	5 wt% Cu-MnO	DMSO	100	94[d]

a) Standard reaction conditions: 0.25 mmol, H-phosphonates 2 equiv, solvent 1 ml, catalyst 12 mg (3.75 mol% Cu), temp: as mentioned in the table, in Air, for 1.5h; b) diethyl phosphite 1 equiv.; c) reaction in N_2 atmosphere; d) oxygen atmosphere

with 4-bromophenylacetylene (1a), and diethyl phosphite (2a) was selected as a model substrate to optimize the reaction condition (Table 1). Our initial investigation started using our developed catalyst 5 wt% Cu on MnO, 1a reacted with 2a (2 equiv.), in toluene solvent at 100°C in a closed carousel reaction tube with Air, for 1.5 h 40% consumption of 1a was observed and produced desired coupled product diethyl ((4- Bromophenyl)ethynyl)phosphonate, 3a in 32% isolated yield (Table 1, entry 1). Encouraged by the result, we first screen the solvents for this coupling reaction, as reported[29] solvents also play a crucial role in this reaction. However, THF, acetonitrile does not work well (entry 2 and 3), whereas DMF showed similar reactivity, 38% of the desired product was obtained (entry 4). To our delight, when DMSO was used solvent reaction goes smoothly, and excellent yield of 3a (94%, entry 5) was observed. We have tried to reduce the reaction temperature at 50°C only 56% and at room temperature trace amount of product was obtained. When we reduce the loading of phosphite to 1 equiv, (1: 1 ratio), we observed 58% of the 3a. Then, we check the reaction without Cu, in both MnO and MnO_2 under similar reaction condition no reaction takes place, so copper is essential for the reaction. As expected, in the absence of catalyst no reaction was observed (entry 11). After that we have carried out the reaction under the inert condition to check the role of oxygen, no reaction took place, so oxygen is also essential for the reaction. Instead of air when we carried out the reaction under oxygen, similar reactivity was observed (entry 13).

With the optimization condition in hand (Table 1, entry 5), we next examined the scope and limitation of the substituted phenylacetylene. As shown in Table 2, various functional group including electron donating group and electron withdrawing group at the *para* position of the phenyl ring works well and provided alkynylphosphonates products in good to excellent yields.

Table 2: Substrate scope of alkynylation of H-phosphonates[a]



[a] Standard reaction conditions: 0.25 mmol, H-Phosphonates 2 equiv, DMSO 1 ml, 5% Cu-MnO catalyst 12 mg (3.75 mol% Cu), 100 °C, in Air, for 1.5h

Simple phenyl acetylene went very well, and excellent yield was observed (93%, entry 3b), other moderate to weak electron withdrawing group and electron donating group like bromo, fluoro, methyl, tert-butyl showed high reactivity and furnished the desired product in excellent yields (entries 3a-3e).The derivatives with strong electron donating group such as methoxy (78%, 3f), and dimethylamine (83%, 3g) produced the desired products in good yields. Whereas strong electron withdrawing group nitrile works well, excellent yield (88%, 3h) of the desired product was observed. Keeping the functional group, e.g., trifluoromethyl, chloro, methoxy, and methyl at ortho and meta position of the phenyl ring, similar reactivity was observed (81-94%, entries 3i-3l). Other aromatic and heteroaromatic alkynes were also tested and found to be a good substrate, phosphorylation takes place with moderate to good yields. Low yield of pyridine derivative (3n, 38%) was achieved, may be due to the coordination of copper with pyridine. Aliphatic terminal alkynes were also successfully phosphorylated under our advanced catalytic system and gave excellent yields of desired alkynylphosphonates products (3o-3s, 89-95%). Next, we examined diisopropyl phosphite as phosphorylating agent for all the substrates, to our delight phosphorylation proceeds smoothly and furnished the corresponding alkynylphosphonates in good to excellent yield (up to 95%, entries 4a-4s) for both aromatic and aliphatic alkynes. Besides diethyl phosphite and diisopropyl phosphite other alkyl H-phosphonate like dimethyl phosphite and dibutyl phosphites were also tested with a coupling reaction with phenylacetylene, and we got excellent yield (3t, 90% and 4t, 92%) of the corresponding alkynylphosphonates products. One interesting thing we have observed that when free lone pair is available in the aryl substituents, like presence of OMe, NMe_2 or CN functional group (3f,g,h, k, m and 4f,g,h, k, m) on aromatic ring, little lower yield was observed, might be they act as a ligands (Lewis base donors) and coordinates with the copper.

On the other hand, Ynamides are also essential synthetic intermediate in organic synthesis, and they are also a useful substrate in several organic transformations. [37-48] Cu-catalyzed oxidative direct amidation of a terminal alkyne with amide for the synthesis of ynamides are first reported by Stahl and co-workers using 5 equivalent amides, 20 mol% catalyst loading and ligand. [49] $Cu(OH)_2$ catalyzed cross-coupling of a terminal alkyne with amides (3 equivalent) reported by Mizuno and co-workers. [50-51] Where they have mentioned that highly dispersed $Cu(OH)_2$ supported on Al_2O_3 and TiO_2 as a catalyst were not effective for cross coupling. Several groups also reported the Cu catalyzed oxidative amidation of a terminal alkyne with N-nucleophile. [52-53] We believe that our developed heterogeneous Cu-MnO catalyst could be a suitable catalyst for cross-coupling reaction of a terminal alkyne with amide. We have begun to investigate the reaction with phenylacetylene and oxazolidin-2-one (2 equiv) in the presence of our developed 5 wt% Cu-MnO catalyst under an oxygen atmosphere in toluene at 100 °C, but unfortunately the desired ynamide was not obtained. We realized that a Brønsted base might be required for this reaction, which could help to abstract the proton from the alkyne to generate reactive copper acetylides and also abstract proton from amide derivatives to make it more reactive, so we have planned to use Na_2CO_3 and $NaHCO_3$ as a base. To our delight, in the presence of a suitable base, the reaction proceeds excellently, and almost quantitative yield of ynamide was obtained (97-98%, entries 2-3, table 3). Further screening of solvents revealed that toluene was the best solvent (ESI, table S1). We have run the reaction in the presence of air instead of pure oxygen, and slightly lower yield (75%, entry 4) was observed. On the contrary, in the inert atmosphere, no

Table 3: Optimization for ynamide synthesis[a]

Entry	Catalyst	Solvent	Base	T (°C)	Yield (%)
1	5 wt% Cu-MnO	toluene	-	100	0
2	5 wt% Cu-MnO	toluene	Na_2CO_3	100	98
3	5 wt% Cu-MnO	toluene	$NaHCO_3$	100	97
4	5 wt% Cu-MnO	toluene	Na_2CO_3	100	75[b]
5	5 wt% Cu-MnO	toluene	Na_2CO_3	100	Trace[c]
6	5 wt% Cu-MnO	toluene	Na_2CO_3	100	58[d]

a) Standard reaction conditions: 0.25 mmol phenylacetylene, 2-Oxazolidone (2 equiv., 0.5 mmol), solvent 1 ml, catalyst 12 mg (3.75 mol% Cu), base (2 equiv.), 100°C, under O_2 atm., for 2h; b) reaction in air atm.; c) reaction in N_2 atmosphere; d) 2-oxazolidone 1.2 equiv.

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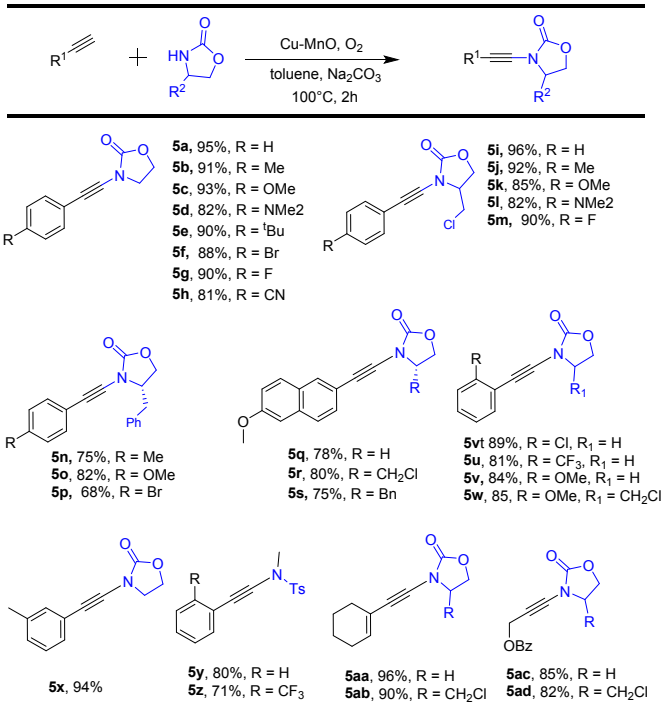
ynamides product was obtained, which indicates that molecular oxygen as an oxidant is essential for this reaction. Further decreasing the amount of nucleophile, leads to lower in ynamides yield and increase the yield of Glaser coupling product. The coupling of several oxazolidinones and other nitrogen nucleophiles with various aryl and alkyl acetylene derivatives were next investigated with our optimized

Table 4: Substrate scope of amidation [a]



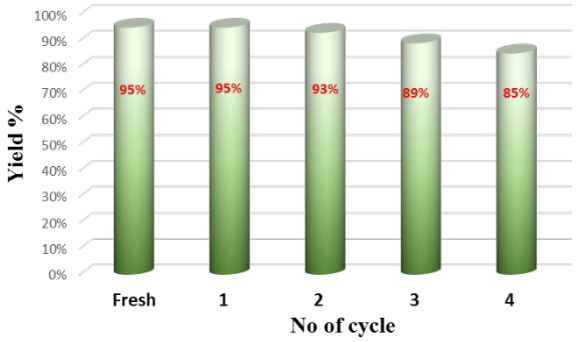
[a] Standard reaction conditions: 0.25 mmol, amide 2 equiv, Na_2CO_3 2 equiv.; toluene 1 ml, 5% Cu-MnO catalyst 12 mg (3.75 mol% Cu), 100 °C, in Air, for 2h

condition. The results are summarized in Table 4. Aromatic alkynes consisting with both electron donating and electron withdrawing functional groups, such as Me, OMe, NMe_2, ^{t}Bu, Br, F, and CN on the para-position of the phenyl ring reacted with oxazolidin-2-one very well and produced the corresponding ynamide in good to excellent yields (Table 4, entries 5a-5h). We have next investigated with other cyclic carbamates like 4-(chloromethyl)oxazolidin-2-one and (S)-4-benzyloxazolidin-2-one, showed similar reactivity and gave the desired ynamides in good to excellent yields (entries 5i-5p). Other aromatic alkynes, such as 2-Ethynyl-6-methoxynaphthalene reacts well oxazolidin-2-one and derivatives and lead to good yields of corresponding ynamides (entries 5q-5s). The substitution of the functional group at ortho and *meta* position in the phenyl ring does not have much effect in the coupling reactions, high yields of desired ynamides were obtained (entries 5v-5x). Another nitrogen nucleophile, *N*-Methyl-*p*-toluenesulfonamide also a viable substrateand afforded ynamides in good yields (entries 5y-5z). Next, we have investigated reaction scope with alkyl substituted terminal alkynes with different oxazolidinone coupling partners, afforded ynamides in good to excellent yields (entries 5aa-5ad).

The reaction with phenylacetylene and oxazolidinone are scaled up to a gram scale, ynamides (5a) was successfully synthesized in comparable yields (92%). Similarly, phosphorylation was also scaled up to 1 gram scale, alkynylphosphonates (3b) was successfully prepared with similar yields (93%).

The hot filtration test confirmed the heterogeneity of the reaction. We monitored the reaction progress after taking out the reaction mixture via cannula to remove the catalyst. No, the further reaction was observed, which suggests that the active catalyst was not leached out to the solution and the reaction is heterogeneous in nature. ICP-AES analysis of the filtrate of the standard reaction (synthesis of 3a and 5a), also tested catalyst leaching after completion of the reaction, a negligible amount of Cu (<2 ppm) leached in the filtrate for both the cases. After completion of the reaction catalyst was filtered, washed and calcined for recycling, and it exhibited good reusability (table 5).

Table 5: Reusability of the catalyst



Catalyst was filtered and thoroughly washed with water and acetone, dried in vacuum, followed by calcination at 350 °C under 10% H_2 in N_2 flow, for 6h, then reused.

Kinetic study

In order to better understand the reaction profile, kinetic studies were performed using phenylacetylene and diethyl H-phosphonate as a reactant. The production of alkynylphosphonates and the Glaser coupling product[54] diyne was monitored by HPLC analysis. When 2 equiv. of H-phosphonates (**Fig 2a**) was used reaction, the reaction is very fast at the beginning, almost 75% product was obtained within 20 min, and the reaction was completed in 90 min, 94% of desired alkynylphosphonates was obtained with ca. 2% diyne. Upon reducing the amount of H-phosphonates to 1.2 equivalent (**Fig 2b**), within 10 min, 12% diyne and 55% of desired alkynylphosphonates were identified. Finally, we have observed, with less amount of coupling partner, increased the production of unwanted homocoupled dimer product(~15%) and subsequently, the yield of desired product diminished. In the case of ynamide synthesis (**Fig. 2c** and **2d**), using phenyl acetylene and oxazolidin-2-one as a substrate, a similar result was observed, reducing the amount of N-nucleophile to 1.2 equivalent, increased the production of Glaser coupling diyne product.[54] Also, the amidation reaction rate is little slower than the phosphorylation reaction as observed from the reaction kinetics. From the kinetic studies, it was confirmed that excess nucleophile is required for both the reaction to prevent the homocoupled diyne product formation.

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DOI: 10.1039/C9CY00275H

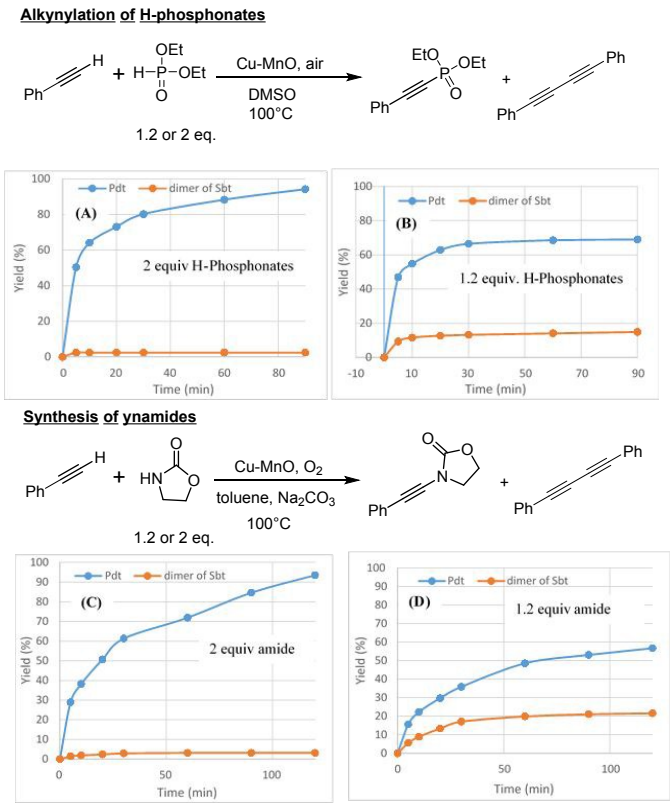
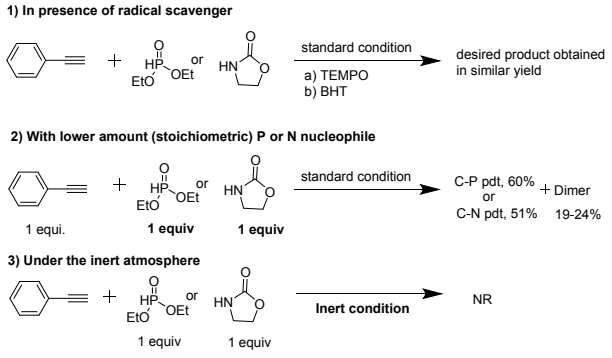


Figure 2: Kinetics for alkynylation of H-phosphonates (a) with 2 equiv. H-phosphonates (b) with 1.2 equiv. H-phosphonates and synthesis of ynamides (c) with 2 equiv. amides (d) with 1.2 equiv. amides. Reaction progress was monitored by HPLC

To get some insight into the reaction mechanism, we have carried out some controlled experiment. Both the reaction goes smoothly in the presence of radical scavenger like BHT and TEMPO (Scheme 1, eq 1), the similar yield of the desired coupling product was observed, which clearly indicates that reaction does not proceed through the radical pathway. With decreasing the amount of phosphorylation or amidation reagent, the yield of the C-P (60%) and C-N (51%) coupled product decreases, whereas C-C homo-coupled Glaser coupling product formation increases (19-24%) under this condition as reported by others.[49] However, under complete inert conditions both the reaction does not proceed, these results suggest that oxygen is essential for these reactions.



Scheme 1: Control experiments to understand the mechanism

Conclusions

In conclusion, we have developed a very efficient and reusable heterogeneous Cu-MnO catalyst for the aerobic oxidative coupling of a terminal alkyne with H-phosphonates and amides to synthesis alkynylphosphonates and ynamides respectively in excellent yields. A variety of terminal alkynes included electron rich, and electron poor aromatic, as well as aliphatic alkynes with several H-phosphonates, delivered corresponding alkynylphosphonates in very good to excellent yields. Our catalyst is highly reactive, as revealed by kinetics study, for both the cases reaction time is shorter compared to the literature report,[23-32, 49] where it takes mostly more than 12h, but in our case reaction completed within 2h. The added advantage is phosphorylation reaction is base and additive free. For ynamides synthesis, a variety of terminal alkyne and different oxazolidinones was successfully utilized and generated the desired product in good to excellent yields. Other nitrogen nucleophile such as N-Methyl-p-toluenesulfonamide also a viable substrate and afforded C-N coupled product in good yields. This methodology could be scaled up to gram scales and tolerate several functional groups. In addition, the catalyst showed very good reusability, up to fifth recycle it showed similar productivity.

Conflicts of interest: There are no conflicts to declare

Experimental Section

General procedure I for phosphorylation:

In a carousel reaction tube Cu-MnO catalyst (12 mg) was taken, terminal alkyne (0.25 mmol), dialkyl phosphate (0.5 mmol) and 1 mL DMSO was added over it. The reaction mixture was stirred at 100 °C for 1.5h under air atmosphere. After completion of the reaction, the crude reaction mixture was filtered and washed with ethyl acetate (25 mL). The organic layer was washed with water, and then the water layer was re-extracted with ethyl acetate (2x 25 mL). The combined organic layer was washed with brine solution, dried over Na_2SO_4, and then concentrated under reduced pressure. The resulting residue was purified by flash chromatography (ethyl acetate: hexane) to afford the desired alkynylphosphonates.

General procedure II for Ynamide synthesis:

In a carousel reaction tube, Cu-MnO catalyst (12 mg) and Na_2CO_3 (53 mg, 0.5 mmol) were taken, the tube was then evacuated and refilled with oxygen three times. Next, the terminal alkyne (0.25 mmol), oxazolidin-2-one (0.5 mmol) and 1 mL Toluene were added over it via syringe. The reaction mixture was stirred at 100 °C for 2h under an oxygen atmosphere. After completion of the reaction, the crude reaction mixture was filtered and washed with ethyl acetate (25 mL). The organic layer was washed with water and brine solution, dried over Na_2SO_4, and then concentrated under reduced pressure. The resulting residue was purified by flash chromatography (ethyl acetate: hexane) to afford the desired ynamides.

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DOI: 10.1039/C9CY00275H

Acknowledgments

CSIR-CSMCRI Communication No. 183/2018. We are thankful to the SERB, DST, India (EMR/2016/002427), for financial support for this work. Special thanks to Dr. Asit B. Panda for helpful discussion in material synthesis and characetrization. We are also grateful to Dr. S. Karan for his help in XPS analysis. The authors also acknowledge the Analytical and Environmental Science Division and Centralized Instrument Facility of CSIR-CSMCRI for all characterization. HS, TS, and CS thanks to UGC, DST, and CSIR for their fellowship respectively.

Notes and References

1 For some reviews, see: M. R. Tracey, R. P. Hsung, J. Antoline, K. C. M. Kurtz, L. Shen, B. W. Slafer, Y. Zhang, and S. M. Weinreb, Ed.; Thieme: Stuttgart, Germany, 2005; Vol. **21**, p 387.
2 B. Witulski, C. Alayrac and A. de Meijere, Ed.; Thieme: Stuttgart, Germany, 2005; Vol. **24**, p 1031.
3 G. Evano, A. Coste and K. Jouvin, *Angew. Chem., Int. Ed*., 2010, **49**, 2840.
4 Y. Gao, G. Wu, Q. Zhou and J. Wang, *Angew. Chem.,* 2018, **130**, 2746.
5 R. H. Dodd and K. Cariou, *Chem. Eur. J.,* 2018**, 24**, 2297.
6 K. A. DeKorver, H. Li, A. G. Lohse, R. Hayashi, Z. Lu, Y. Zhang and R. P. Hsung, *Chem. Rev.,* 2010, **110,** 5064.
7 H. Krishna and M. H. Caruthers, *J. Am. Chem. Soc*., 2012, **134**, 11618.
8 C. S. Demmer, N. Krogsgaard-Larsen and L. Bunch, *Chem. Rev.,* 2011, **111**, 7981.
9 L. Peng, F. Xu, Y. Suzuma, A. Orita and J. Otera, *J. Org. Chem.,* 2013, **78**, 12802.
10 P. L. Xu, F. Shinohara, K. Orita and A. Otera, *J. Chem. Lett*., 2014, **43,** 1610.
11 K. Van derpoorten and M. E. Migaud, *Org. Lett.,* 2004, ***6,*** 3461.
12 H. Krishna and M. H. Caruthers, *J. Am. Chem. Soc.,* 2012, 134, 11618.
13 T. Huang, Y. Saga, H. Guo, A. Yoshimura, A. Ogawa and L.-B. Han, *J. Org. Chem*., 2018, **83**, 8743.
14 T. Chen, C.-Q. Zhao and L.-B. Han, *J. Am. Chem. Soc.,* 2018*,* **140,** 3139.
15 D. G. Salomon, S. M. Grioli, M. Buschiazzo, E. Mascaró, C. Vitale, G. Radivoy, M. Perez, Y. Fall, E. A. Mesri, A. C. Curino and M. M. Facchinetti, *ACS Med. Chem. Lett.,* 2011, **2**, 503.
16 B. Iorga, F. Eymery, D. Carmichael and P. Savignac, *Eur. J. Org. Chem*., 2000, 3103.
17 M. Lera and C. J. Hayes, *Org. Lett*., 2000, **2**, 3873.
18 Y. Wang, J. Gan, L. Liu, H. Yuan, Y. Gao, Y. Liu and Y. Zhao, *J. Org. Chem*., 2014, **79**, 3678.
19 M. Lera and C. J. Hayes, *Org. Lett.,* 2000, **2**, 3873.
20 X. Li, F. Yang, Y. Wu and Y. Wu, *Org. Lett.,* 2014, **16**, 992.
21 J. Hu, N. Zhao, B. Yang, G. Wang, L.-N. Guo Y.-M. Liang and S.-D. Yang, *Chem. Eur. J.,* 2011, **17,** 5516.
22 Y. Yatsumonji, A. Ogata, A. Tsubouchi and T. Takeda, *Tetrahedron letters,* 2008, **49**, 2265.
23 K. Jouvin, J. Heimburgera and G. Evano, *Chem. Sci*., 2012, **3**, 756.
24 T. Yuan, F. Chen and G.-P. Lu, *New J. Chem.,* 2018**, 42,** 13957.
25 Y. Gao, G. Wang, L. Chen, P. Xu, Y. Zhao, Y. Zhou and L.-B. Han, *J. Am. Chem. Soc.,* 2009, **131**, 7956.
26 M. Niu, H. Fu, Y. Jiangab and Y. Zhao, *Chem. Commun*., 2007, 272.
27 Z. Qu, X. Chen, J. Yuan, L. Qu, X. Li, F. Wang, X. Ding and Y. Zhao, *Can. J. Chem.,* 2012, **90**, 747.
28 P. Liua, J. Yanga, P. Lia and L. Wanga, *Appl. Organometal. Chem.,* 2011, **25**, 830.
29 Y. Moglie, E. Mascaró, V. Gutierrez, F. Alonso and G. Radivoy, *Org. Chem.,* 2016, **81**, 1813.
30 J. Yang, T. Chen, Y. Zhou, S. Yina and L.-B. Han, *Chem. Commun.,* 2015, **51**, 3549.
31 T. Wang, S. Chen, A. Shao, M. Gao, Y. Huang, and A. Lei, *Org. Lett.,* 2015, **17**, 118.
32 J.-Q. Zhang, T. Chen, J.-S. Zhang and L.-B. Han, *Org. Lett.,* 2017, **19**, 4692.
33 P. Pal, H. Singh, A. B. Panda and S. C. Ghosh, *Asian J. Org. Chem*., 2015, **4**, 879.
34 H. Singh, P. Pal, C. Sen, A. B. Panda and S. C. Ghosh, *Asian J. Org. Chem*., 2017**, 6,** 702.
35 H. Singh, C. Sen, T. Sahoo and S. C. Ghosh, *Eur. J. Org. Chem.,* 2018, 4748.
36 P. Pal, S. K. Pahari, A. K. Giri, S. Pal, H. C. Bajaj and A. B. Panda, *J. Mater. Chem. A,* 2013, **1**, 10251.
37 B. Gourdet and H. W. Lam, *J. Am. Chem. Soc.,* 2009, 131, 3802.
38 K. Dooleweerdt, T. Ruhland and T. Skrydstrup, *Org. Lett.,* 2009, **11,** 221.
39 R. Plamont, L. V. Graux and H. Clavier, *Eur. J. Org. Chem*., 2018, 1372.
40 M. Lin, L. Zhu, J. Xia, Y. Yu, J. Chen, Z. Mao and X. Huang, *Adv. Synth. Catal.,* 2018, **360,** 2280.
41 Y. Zhang, K. A. DeKorver, A. G. Lohse, Y.-S. Zhang, J. Huang and R. P. Hsung, *Org. Lett.,* 2009, **11**, 899.
42 C. Alayrac, D. Schollmeyer and B. Witulski, *Chem. Commun.,* 2009, 1464.
43 P. Garcia, S. Moulin, Y. Miclo, D.Leboeuf, V. Gandon, C. Aubert and M. Malacria, *Chem. Eur. J.,* 2009, **15**, 2129.
44 X. Zhang, R. P. Hsung, H. Li, Y. Zhang, W. L. Johnson and R. Figueroa, *Org. Lett.,* 2008, **10,** 3477.
45 J. Oppenheimer, W. L. Johnson, M. R. Tracey, R. P. Hsung, P.-Y. Yao, R. Liu and K. Zhao, *Org. Lett.,* 2007, **9,** 2361.
46 K. Tanaka, K. Takeishi and K. Noguchi, *J. Am. Chem. Soc.,* 2006, **128**, 4586.
47 S. Couty, C. Meyer and J. Cossy, *Angew. Chem., Int. Ed.,* 2006, **45**, 6726.
48 J. P. Das, H. Chechik and I. Marek, *Nat. Chem.,* 2009, **1,** 128.
49 T. Hamada, X. Ye and S. S. Stahl, *J. Am. Chem. Soc.,* 2008**, 130,** 833.
50 X. Jin, K. Yamaguchia and N. Mizuno, *Chem. Commun.,* 2012, ***48***, 4974.
51 X. Jin, K. Yamaguchia and N. Mizuno, *Chem. lett.,* 2012, **41,** 866.
52 W. Jia and N. Jiao, *Org. Lett.* 2010, **12**, 2000.
53 H. T. N. Le, T. V. Tran, N. T. S. Phan and T. Truong, *Cat. Sci. Tech*., 2015, **5,** 851
54 (a) C. Glaser, *Ber. Dtsch. Chem. Ges*. 1869, **2,** 422-424. (b) A. S. Hay, *J. Org. Chem*. 1962, **27,** 3320-3321. (c) P. Siemsen, R. C. Livingston, F. Diederich, *Angew. Chem., Int. Ed*. 2000, **39,** 2632-2657.

View Article Online
DOI: 10.1039/C9CY00275H

Graphical abstract

Aerobic Oxidative Alkynylation of H-Phosphonates and Amides: An Efficient Route for the Synthesis of Alkynylphosphonates and Ynamides by Recyclable Cu-MnO Catalyst

Harshvardhan Singh, Tapan Sahoo, Chiranjit Sen, Sunil M. Galani and Subhash Chandra Ghosh*

Developed a straightforward, atom-economical and scalable route for the synthesis of alkynylphosphonates and ynamides using reusable Cu-MnO catalyst.