



Cite this: *RSC Adv.*, 2019, 9, 8894

Received 23rd January 2019
 Accepted 6th March 2019

DOI: 10.1039/c9ra00577c

rsc.li/rsc-advances

Synthesis of C4-alkynylisoxazoles via a Pd-catalyzed Sonogashira cross-coupling reaction†

Wen Yang, Yongqi Yao, Xin Yang, Yingying Deng, Qifu Lin and Dingqiao Yang *

A Pd-catalyzed Sonogashira cross-coupling reaction for the synthesis of C4-alkynylisoxazoles from 3,5-disubstituted-4-iodoisoxazoles and terminal alkynes was described, which could afford the corresponding products with high yield (up to 98%). The results indicated that the steric effect from the group at the C3 position of the isoxazole had greater influence on the cross-coupling reaction than that from the group at the C5 position. In addition, the group at the C3 position of the isoxazole showed negligible electronic effects on the cross-coupling reaction. Furthermore, a gram-scale reaction of the Sonogashira coupling reaction was also investigated. Finally, a plausible mechanism for the Sonogashira coupling reaction was proposed.

Introduction

Isoxazole and its derivatives are important structural units of many molecules of biological interest.¹ As a result, numerous synthetic approaches have been made to access the isoxazole core, including the [3 + 2] cycloaddition between alkynes/alkenes and nitrile oxides,² intramolecular cycloisomerization of α,β -unsaturated oximes,³ condensation between hydroxylamine and 1,3-dicarbonyl compounds or α,β -unsaturated carbonyls.⁴ Many of the reported methods have two main limitations, (i) limitation to the preparation of disubstituted isoxazoles, and (ii) low regioselectivity.⁵ In order to overcome these limitations, direct functionalization of isoxazoles or 4-haloisoxazoles has been developed by many research groups.⁶

Transition-metal-catalyzed cross-coupling reactions have become one of the most prominent and reliable methods for the formation of carbon-carbon bonds.⁷ Among them, the Pd-catalyzed Sonogashira cross-coupling reaction between aromatic halides and terminal alkynes is very useful in the synthesis of carbo- and heterocycles, natural products, polymers, and molecular nanostructures.⁸ Using this powerful reaction, some trisubstituted isoxazoles were synthesized. Yamanaka and co-workers first reported that the Pd(PPh₃)Cl₂ catalyzed Sonogashira cross-coupling reaction of 3-substituted-5-methyl-4-iodoisoxazoles with terminal alkynes, affording three examples of 3-substituted-5-methyl-4-alkynylisoxazole products in good yields (up to 86% yield).^{6a} In 2001, Kromann and co-workers explored that Pd(PPh₃)Cl₂ catalyzed

Sonogashira cross-coupling reaction of 3-ethoxy-5-methyl-4-iodoisoxazole with phenylacetylene, giving product of 3-ethoxy-5-methyl-4-phenylethynylisoxazole for only one example in 58% yield.^{6c} Larock and co-workers chose 3-(3,4,5-trimethoxyphenyl)isoxazole-5-methyl-4-iodoisoxazole as a substrate to react with seven terminal alkynes, giving the targeted products with the yields between 30% and 83%.^{6e} In 2005, a series of 3-carboxamide-5-(2,4-dihydroxy-5-isopropylphenyl)-4-alkynylisoxazoles were synthesized through Pd(PPh₃)Cl₂ catalyzed Sonogashira cross-coupling reaction of an alkynyl moiety and an isoxazole scaffold as novel HSP90 inhibitors by Zhang and co-workers.^{6f} Recently, Guo and co-workers reported that Sonogashira cross-coupling reaction of 3-trifluoromethyl-5-phenyl-4-iodoisoxazoles with phenylacetylene in the presence of Pd(PPh₃)₂Cl₂, affording the targeted product in 80% yield.⁹ However, none of the above researches studied the impact of the groups at C3 position and C5 position of isoxazole core on the Sonogashira cross-coupling reaction. Because of the decreased symmetry in isoxazole, when compared to furan, pyrrole, and benzene, reaction channels which are equivalent in furan, pyrrole, and benzene will lead to the different results in isoxazole. For examples, Fall and co-workers discovered that 3-carboxylate-5-methylisoxazole reacted with 1-(4-bromophenyl)ethan-1-one to afford the targeted product, but 4-carboxylate-5-methylisoxazole did not afford desired product.^{6f} Coffman and co-workers investigated the effects of the groups of 3,5-, 4,5-, and 3,4-bis(2-nitrophenyl) isoxazoles on the reaction.¹⁰ Lately, Morita and co-workers reported intramolecular electrophilic aromatic substitution reaction only occurred at the 5-position of isoxazole rather than at the 3-position.¹¹

Herein, we investigated the effect of the groups at C3 and C5 positions of the isoxazole on the Sonogashira cross-coupling reaction. Using 3,5-disubstituted-4-iodoisoxazoles and

Key Laboratory of Theoretical Chemistry of Environment, Ministry of Education, School of Chemistry and Environment, South China Normal University, Guangzhou 510006, People's Republic of China. E-mail: yangdq@scnu.edu.cn

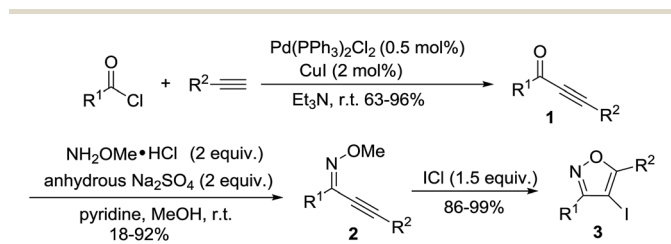
† Electronic supplementary information (ESI) available. See DOI: 10.1039/c9ra00577c



terminal alkynes as the substrates, we synthesized a series of 3,5-disubstituted-4-alkynylisoxazole products.

Results and discussion

During our investigation, intermediate ynones **1** were prepared by the Sonogashira cross-coupling of an acid chloride and a terminal alkyne in the presence of Pd(PPh₃)₂Cl₂. The *O*-methyl oximes **2** were prepared by the reaction of ynones **1** with methoxylamine hydrochloride in the presence of pyridine and anhydrous Na₂SO₄. The substrates of 3,5-disubstituted-4-iodoisoxazoles **3** were prepared through the electrophilic cyclization of *O*-methyl oxime **2** in the presence of ICl (Scheme 1).



Scheme 1 Preparation of 3,5-disubstituted-4-iodoisoxazoles **3**.

Table 1 Effects of catalyst precursors, ligands and catalyst loadings^a

Entry	Catalyst (mol%)	Ligand (mol%)	3a conv. ^b (%)	4a yield ^b (%)
1	Pd(PPh ₃) ₂ Cl ₂ (5)	—	47	26
2	Pd(PPh ₃) ₂ Cl ₂ (5)	PPh ₃ (10)	49	30
3	Pd(PPh ₃) ₂ Cl ₂ (5)	PCy ₃ (10)	48	28
4	Pd(PPh ₃) ₂ Cl ₂ (5)	DPPP (5)	35	20
5	Pd(PPh ₃) ₄ (5)	—	43	26
6	Pd(OAc) ₂ (5)	PPh ₃ (10)	52	31
7	Pd(TFA) ₂ (5)	PPh ₃ (10)	24	18
8	Pd(MeCN) ₂ Cl ₂ (5)	PPh ₃ (10)	50	29
9	Pd(acac)₂ (5)	PPh₃ (10)	66	60
10	Pd(acac) ₂ (5)	PCy ₃ (10)	42	26
11	Pd(acac) ₂ (5)	TFP (10)	56	46
12	Pd(acac) ₂ (5)	DPPP (5)	36	22
13	Pd(acac) ₂ (3.5)	PPh ₃ (7)	48	35
14	Pd(acac) ₂ (7.5)	PPh ₃ (15)	64	58

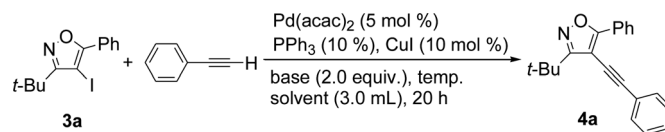
^a Reaction condition: **3a** (0.3 mmol, 1 equiv.), phenylacetylene (0.6 mmol, 2 equiv.), [Pd], ligand, CuI (10 mol%), Et₂NH (2 equiv.), DMF (3 mL), 60 °C under N₂ protection. ^b Isolated yield.

We chose 3-(*tert*-butyl)-4-iodo-5-phenylisoxazole (**3a**) with phenylacetylene as a model substrate to identify the feasibility of our process. When **3a** reacted with phenylacetylene in anhydrous DMF at 60 °C in the presence of Pd(PPh₃)₂Cl₂ (5 mol%), CuI (10 mol%), and Et₂NH (2 equiv.) under nitrogen atmosphere, the desired product **4a** was obtained in 26% yield after 20 h and the conversion of starting material **3a** was 47% (Table 1, entry 1). To improve the reaction efficiency, three kinds of phosphine ligands, such as PPh₃, PCy₃ and DPPP, were examined for this reaction under similar condition (Table 1 entries 2–4). Unfortunately, the yield of targeted product **4a** could only be up to 30% (Table 1, entry 2). Then, different palladium catalysts were screened for the reaction (Table 1, entries 5–9). Among them, **3a** reacted with phenylacetylene to afford the corresponding product **4a** in 60% yield and the conversion of **3a** could be increased to 66% in the presence of Pd(acac)₂ (Table 1, entry 9). Encouraged by this result, a series of phosphine ligands, such as PPh₃, TFP, PCy₃ and DPPP, were tested for this reaction under similar condition (Table 1, entries 9–12). The general trends in yields of product **4a** related to different phosphine ligands were as followed: PPh₃ > TFP > PCy₃ > DPPP. The impact of the catalyst loading on the reaction was also investigated, and the yield of **4a** was strongly influenced by the amount of catalyst loading (Table 1, entries 13 and 14). The yield of **4a** was decreased with the amount of catalyst loading decreased to 3.5 mol% (Table 1, entry 13). However, a further increase the amount of catalyst loading did not improve the yield of **4a** (Table 1, entry 14).

The effects of bases, solvents and temperatures were then examined (Table 2). No reaction took place without bases (not shown in Table 2). Moderate yields were obtained when Et₂NH and Et₃N were used as bases (Table 2, entries 1 and 2). As we added the base *n*-butylamine or DIPEA (*N,N*-diisopropylethylamine) to this reaction system, the reaction proceeded to give the targeted product **4a** with low yields (25% and 18%, respectively) (Table 2, entries 3 and 4). The selection of solvents proved to have a dramatic influence on the reaction (Table 2, entries 1, 5–8). When the reaction was carried out in anhydrous DMF, a dipolar aprotic solvent, targeted product **4a** could be obtained in 60% yield (Table 2, entry 1). Other solvents, such as anhydrous THF, MeCN, toluene and DCE, resulted in low yields (30%, 25%, 22% and 20%, respectively) (Table 2, entries 5–8). At last, the effects of temperatures on the reaction were investigated (Table 2, entries 1 and 9 and 10). The results showed that the optimum reaction temperature was 60 °C in terms of yield (Table 2, entry 1).

With the above optimized reaction condition in hand (5 mol% Pd(acac)₂, 10 mol% PPh₃, 10 mol% CuI, and 2 equiv. Et₂NH in anhydrous DMF at 60 °C under N₂ atmosphere), the effects of the substituent at 3 and 5 position of the isoxazole were examined (Table 3). We used the substrate **3a** to react with three different kinds of terminal alkynes, affording the corresponding targeted products (**4a**, **4b**, and **4c**) with the yields of 60%, 61%, and 63%, respectively (Table 3). For these reactions, the substrate **3a** couldn't be completely transferred, and its conversion was 66%, 68%, and 69%, respectively.



Table 2 Effects of bases, solvents and temperatures^a

Entry	Base	Solvent	Temp. (°C)	3a conv. ^b (%)	4a yield ^b (%)
1	Et ₂ NH	DMF	60	66	60
2	Et ₃ N	DMF	60	63	58
3	<i>n</i> -Butylamine	DMF	60	38	25
4	DIPEA	DMF	60	25	18
5	Et ₂ NH	THF	60	41	30
6	Et ₂ NH	MeCN	60	46	35
7	Et ₂ NH	Toluene	60	33	22
8	Et ₂ NH	DCE	60	26	20
9	Et ₂ NH	DMF	30	38	22
10	Et ₂ NH	DMF	90	82	40

^a The reaction was carried out with **3a** (0.3 mmol, 1 equiv.), phenylacetylene (0.6 mmol, 2 equiv.), CuI (10 mol%), base (2.0 equiv.) in the solvent at the stated temperature in the presence of Pd(acac)₂ (5 mol%) and PPh₃ (10 mol%) under N₂ atmosphere. ^b Isolated yield.

When we used **3b** as the substrate, with a phenyl group at the 3 position and a *tert*-butyl group at the 5 position to react with three kinds of terminal alkynes, the targeted products (**4d–4f**) were obtained in high yields (up to 97%) and almost full conversion of **3b** was gained within 8 h. Such phenomena were very interesting, which encouraged us to investigate the impact of the groups at the 3 and 5 positions of 4-iodoisoxazoles on the reaction. First, we studied the impact of the group at the 5 position of 4-iodoisoxazoles on the reaction. When we used the substrate **3c** (5 position was cyclopropyl group) or **3d** (5 position was *n*-pentyl group) to react with the three kinds of terminal alkynes, all of the products (**4g–4l**) could be obtained in high yields, accompanied by almost full conversion of **3c** or **3d** within 8 h. Second, we examined the effect of the group at the 3 position of 4-iodoisoxazole on the reaction. We chose the substrate **3e**, with an isopropyl group at the 3 position, to react with the three kinds of terminal alkynes, affording the targeted products (**4m**, **4n**, and **4o**) in high yields (90%, 91%, and 93%, respectively), and **3e** was almost transferred in the three reactions. As the steric hindrance from the *tert*-butyl group is greater than that from the isopropyl group, this implied that 4-iodoisoxazoles containing large steric hindrance functional groups at the 3 position was poor for this type Sonogashira cross-coupling reaction. Then, we further investigated the electronic effects of the group at the 3 position of 4-iodoisoxazoles. We chose **3f** containing strong electron donor group (OCH₃) and **3g** containing strong electron-withdrawing group (CF₃) to test the electronic effects on the reaction. To our delight, all of the targeted products (**4p–4u**) could be obtained with high yields and the starting materials (**3f** and **3g**) could be completely transferred with 8 h. The results implied that the steric effect rather than the electronic effect of the group at the 3 position affected the efficiency of the cross-coupling reactions.

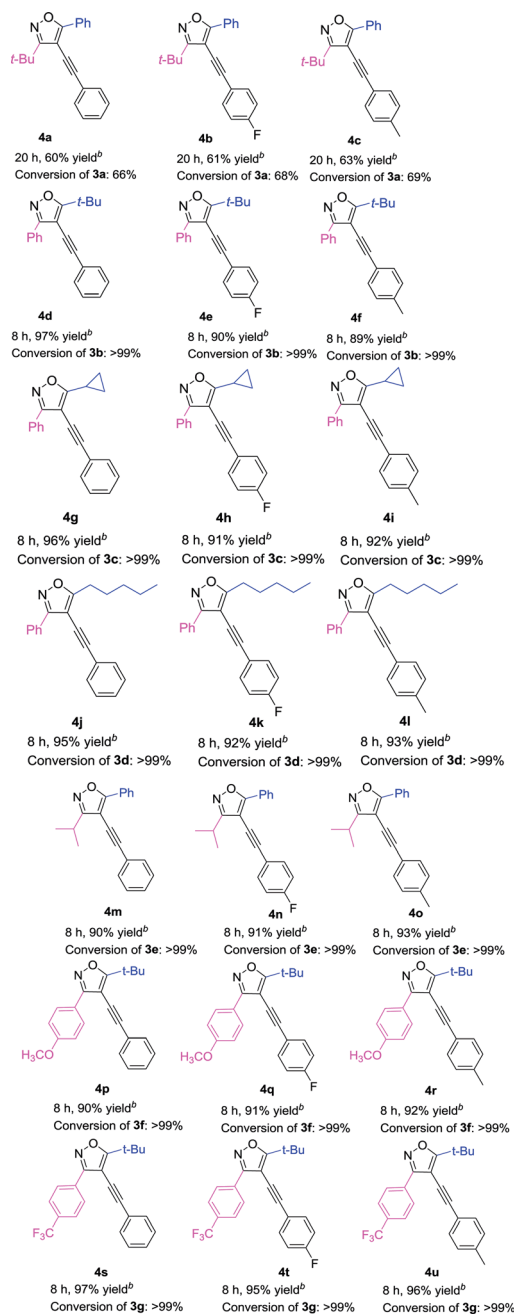
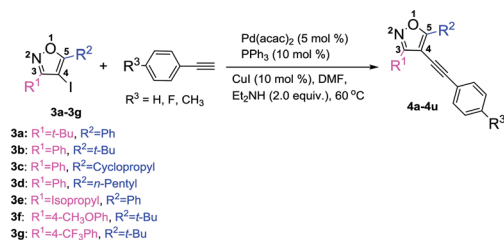
Based on the above results (Table 3), 3,5-diphenyl-4-iodoisoxazole **3h** was chosen as a substrate to react with a variety of terminal alkynes in the presence of Pd(acac)₂/PPh₃ complex (Table 4). The results showed that both electron-donating and electron-withdrawing substituents on the phenyl groups of the terminal alkynes were well accommodated, achieving the desired products (**5a–5g**) in high yields. The 4-ethynyl-1,1'-biphenyl could also be converted into **5h** in 53% yield. Furthermore, R³ = thiophenyl was also afforded the targeted product **5i** in 91% yield. Both 1-ethynylcyclohexene and 1-ethynylcyclohexane could be component coupling partner for this transformation (**5j–5k**). And 3-methoxyprop-1-yne could achieve the desired product **5l** in 80% yield as well.

To further demonstrate the synthetic application of the developed protocol, a gram-scale reaction was tested using substrates **3h** to react with phenylacetylene, and it could proceed smoothly, affording the targeted product **5a** in high yields (Scheme 2).

In addition, to gain insight into the mechanism of the Sonogashira coupling reaction, a control experiment had been conducted (Scheme 3). The yield of targeted product **4a** was slightly decreased when run in the presence of radical inhibitor (2.0 equiv. TEMPO). The result excluded the possible involvement of radical species.

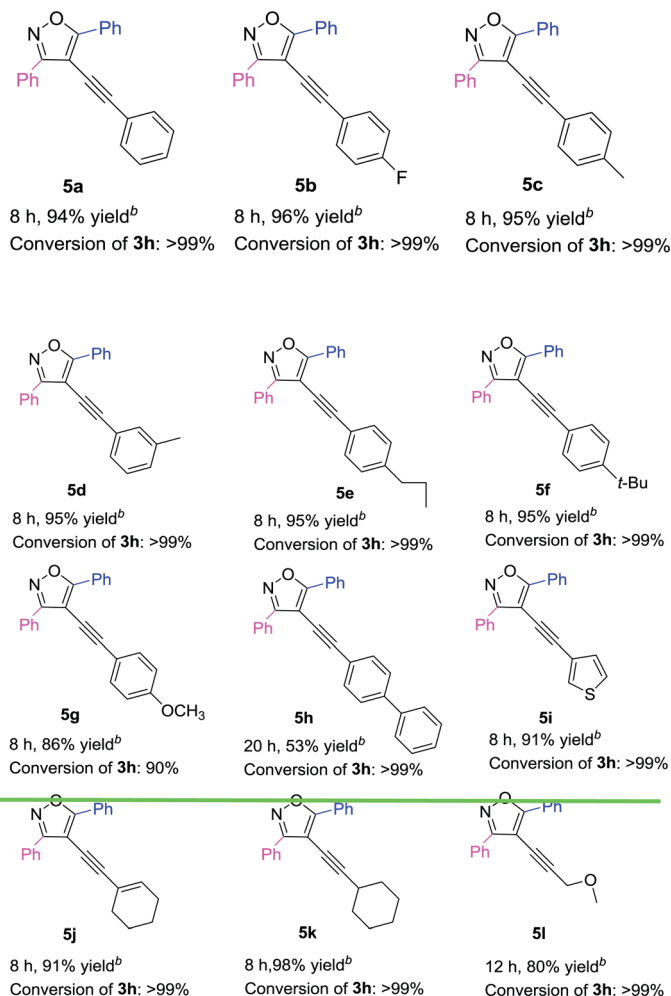
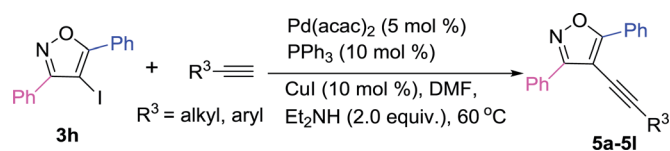
Based on the above experiments and classical description of the Sonogashira coupling reaction, a plausible mechanism for the reaction was depicted in Scheme 4, involving two connected catalytic cycles (cycle A and cycle B).^{8,12} In the cycle A, the catalytically active species Pd[0](PPh₃)₂ **D** was formed by reduction of Pd[II](PPh₃)₂(acac)₂ **C** (activation) which was produced *in situ* by combination two equivalents of triphenylphosphine with a Pd(II)(acac)₂. Oxidative addition of palladium[0] catalyst **D** to 4-iodoisoxazoles **3** produced intermediate **E**, followed by



Table 3 Pd-catalyzed Sonogashira cross-coupling between 3,5-disubstituted-4-iodoisoxazoles **3a–3g** and terminal alkynes^a

^a Reaction condition: **3** (0.3 mmol, 1 equiv.), terminal alkynes (0.6 mmol, 2 equiv.), Pd(acac)₂ (5 mol%), PPh₃ (10 mol%), CuI (10 mol%), Et₂NH (2 equiv.), and DMF (3 mL) under N₂ protection. ^b Isolated yield.

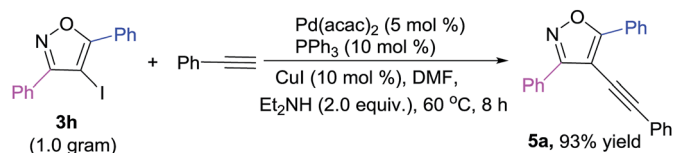


Table 4 Pd-catalyzed Sonogashira cross-coupling between 3,5-diphenyl-4-iodoisoxazole **3h** and various terminal alkynes^a

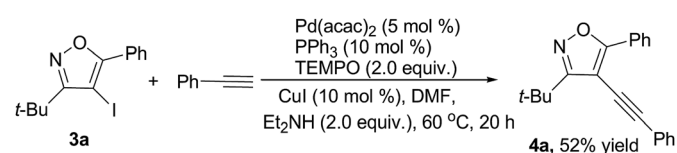
^a Reaction condition: **3h** (0.3 mmol, 1 equiv.), terminal alkynes (0.6 mmol, 2 equiv.), Pd(acac)₂ (5 mol%), PPh₃ (10 mol%), CuI (10 mol%), Et₂NH (2 equiv.), and anhydrous DMF (3 mL) under N₂ protection. ^b Isolated yield.

a transmetalation reaction of intermediate **E** with alkynyl copper **F** to give intermediate **G**. Reductive elimination of intermediate **G** to give the targeted product **4** and **5**. Meanwhile, the generating Pd[0](PPh₃)₂ **D** promoted the next catalytic cycle.

In the cycle **B**, terminal alkyne reacted with Et₂NH and CuI to form alkynyl copper **F**, followed *via* transmetalation with intermediate **E** to afford intermediate **G** and regenerate CuI for the next catalytic cycle.

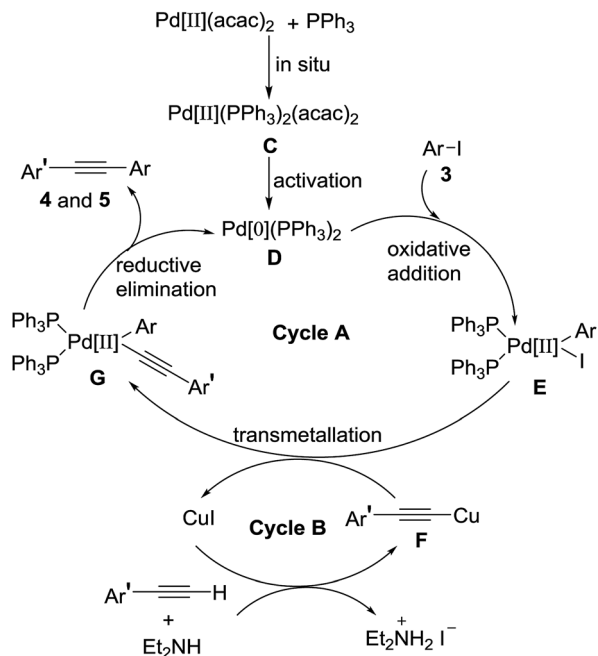


Scheme 2 A gram-scale reaction.



Scheme 3 The control experiment.





Scheme 4 Plausible reaction mechanism.

Conclusions

In summary, we report herein the Pd(acac)₂/PPh₃ complex catalyzed Sonogashira cross-coupling reaction of 3,5-disubstituted-4-iodoisoxazoles with terminal alkynes, which affords 3,5-disubstituted-4-alkynylisoxazole products in excellent yields. The effects of the groups at C3 and C5 positions of the isoxazole on the Sonogashira cross-coupling reaction were investigated. The group at C3 position of the isoxazole has great influence on the reaction due to steric effect, whereas the electric effect of the group at C3 position was negligible. Furthermore, a gram-scale reaction demonstrated potential synthetic application of this protocol.

Experimental section

General procedure (I) for the preparation of intermediate ynones (1)

Intermediates **1** were prepared according to a literature.^{3d} To a 50 mL round-bottomed flask were added CuI (19 mg, 0.1 mmol), Pd(PPh₃)₂Cl₂ (14 mg, 0.02 mmol), and triethylamine (10 mL). The flask was flushed with nitrogen atmosphere, and the terminal acetylene (5.0 mmol) was added to the stirred suspension, followed by immediately dropwise addition of acyl chloride (6.5 mmol). The resulting mixture was allowed to stir at room temperature overnight. Water (10 mL) was added to the reaction mixture to work up. The resulting mixture was extracted with ethyl acetate (3 × 20 mL). The organic layers were combined and dried over anhydrous MgSO₄. The solvent was removed under a vacuum, and the residue was purified by column chromatography on silica gel (200–300 mesh) using ethyl acetate/petroleum ether as the eluent to afford the desired products **1**.

4,4-Dimethyl-1-phenylpent-1-yn-3-one (1a). Prepared according to general procedure (I). Intermediate **1a** was obtained as yellow oil (753.7 mg, 81% yield). The ¹H NMR spectral data are in good agreement with the literature data.¹³

4,4-Dimethyl-1-phenylpent-2-yn-1-one (1b). Prepared according to general procedure (I). Intermediate **1b** was obtained as yellow oil (770.8 mg, 77% yield). The ¹H NMR spectral data are in good agreement with the literature data.¹⁴

3-Cyclopropyl-1-phenylprop-2-yn-1-one (1c). Prepared according to general procedure (I). Intermediate **1c** was obtained as yellow oil (646.4 mg, 76% yield). The ¹H NMR spectral data are in good agreement with the literature data.¹⁵

1-Phenyloct-2-yn-1-one (1d). Prepared according to general procedure (I). Intermediate **1d** was obtained as yellow oil (900.5 mg, 90% yield). The ¹H NMR spectral data are in good agreement with the literature data.¹⁶

4-Methyl-1-phenylpent-1-yn-3-one (1e). Prepared according to general procedure (I). Intermediate **1e** was obtained as yellow oil (602.3 mg, 70% yield). The ¹H NMR spectral data are in good agreement with the literature data.¹⁷

1-(4-Methoxyphenyl)-4,4-dimethylpent-2-yn-1-one (1f). Prepared according to general procedure (I). Intermediate **1f** was obtained as a yellow oil (780.9 mg, 73% yield). The ¹H NMR spectral data are in good agreement with the literature data.¹⁸

4,4-Dimethyl-1-(4-(trifluoromethyl)phenyl)pent-2-yn-1-one (1g). Prepared according to general procedure (I). Intermediate **1g** was obtained as yellow oil (889.4 mg, 70% yield). ¹H NMR (600 MHz, CDCl₃) δ 8.21 (d, *J* = 8.3 Hz, 2H), 7.73 (d, *J* = 8.3 Hz, 2H), 1.39 (s, 9H). ¹³C NMR (150 MHz, CDCl₃) δ 177.2, 139.7, 135.5, 133.7 (q, *J* = 31.5 Hz), 129.9, 125.8 (q, *J* = 3.0 Hz), 123.8 (q, *J* = 271.5 Hz), 105.6, 78.1, 30.2, 28.3. ¹⁹F NMR (564 MHz, CDCl₃) δ -63.10. HRMS (ESI-ion trap): *m/z* [M + H]⁺ calcd for C₁₄H₁₄F₃O: 255.0997; found: 255.0995.

1,3-Diphenylprop-2-yn-1-one (1h). Prepared according to general procedure (I). Intermediate **1h** was obtained as yellow oil (927.3 mg, 90% yield). The ¹H NMR spectral data are in good agreement with the literature data.¹⁶

General procedure (II) for the preparation of intermediate ynones O-methyl oximes (2)

Intermediates **2** were prepared according to a literature procedure.^{3d} To a 50 mL round-bottomed flask were added the alkynones (3.5 mmol), methoxyamine hydrochloride (7.0 mmol, 579 mg), anhydrous Na₂SO₄ (7.0 mmol, 994 mg), pyridine (1.0 mL), and anhydrous methanol (10 mL). The reaction mixture was stirred at room temperature overnight. The mixture was diluted with water (25 mL) and extracted with ethyl acetate (3 × 25 mL). The organic layers were combined, washed with brine, and dried over anhydrous MgSO₄. The solvent was removed under a vacuum, and the residue was purified by flash column chromatography on silica gel (200–300 mesh) using ethyl acetate/petroleum ether as the eluent to afford the desired products **2**.

(Z)-4,4-Dimethyl-1-phenylpent-1-yn-3-one O-methyl oxime (2a). Prepared according to general procedure (II). Intermediate **2a** was obtained as yellow oil (617.5 mg, 82% yield). The ¹H NMR spectral data are in good agreement with the literature data.¹⁹



(Z)-4,4-Dimethyl-1-phenylpent-2-yn-1-one O-methyl oxime (2b). Prepared according to general procedure (II). Intermediate **2b** was obtained as yellow oil (492.7 mg, 70% yield). The ^1H NMR spectral data are in good agreement with the literature data.¹⁹

(Z)-3-Cyclopropyl-1-phenylprop-2-yn-1-one O-methyl oxime (2c). Prepared according to general procedure (II). Intermediate **2c** was obtained as a yellow oil (383.3 mg, 55% yield). The ^1H NMR spectral data are in good agreement with the literature data.²⁰

(Z)-1-Phenyl-2-yn-1-one O-methyl oxime (2d). Prepared according to general procedure (II). Intermediate **2d** was obtained as yellow oil (641.7 mg, 80% yield). ^1H NMR (500 MHz, CDCl_3) δ 7.88–7.82 (m, 2H), 7.40–7.35 (m, 3H), 4.09 (s, 3H), 2.55 (t, J = 7.2 Hz, 2H), 1.72–1.65 (m, 2H), 1.51–1.34 (m, 4H), 0.94 (t, J = 7.3 Hz, 3H). ^{13}C NMR (125 MHz, CDCl_3) δ 140.4, 134.1, 129.6, 128.4, 126.6, 104.1, 71.6, 63.1, 31.2, 28.1, 22.3, 19.9, 14.1. HRMS (ESI-ion trap): m/z $[\text{M} + \text{H}]^+$ calcd for $\text{C}_{15}\text{H}_{20}\text{NO}$: 230.1545; found: 230.1540.

(Z)-4-Methyl-1-phenylpent-1-yn-3-one O-methyl oxime (2e). Prepared according to general procedure (II). Intermediate **2e** was obtained as yellow oil (492.7 mg, 70% yield). The ^1H NMR spectral data are in good agreement with the literature data.²¹

(Z)-1-(4-Methoxyphenyl)-4,4-dimethylpent-2-yn-1-one O-methyl oxime (2f). Prepared according to general procedure (II). Intermediate **2f** was obtained as yellow oil (642.1 mg, 80% yield). ^1H NMR (600 MHz, CDCl_3) δ 7.77 (d, J = 8.8 Hz, 2H), 6.89 (d, J = 8.8 Hz, 2H), 4.05 (s, 3H), 3.82 (s, 3H), 1.38 (s, 9H). ^{13}C NMR (150 MHz, CDCl_3) δ 160.8, 139.9, 128.0, 126.9, 113.8, 111.3, 70.2, 62.8, 55.4, 30.8, 28.6. HRMS (ESI-ion trap): m/z $[\text{M} + \text{H}]^+$ calcd for $\text{C}_{15}\text{H}_{20}\text{NO}_2$: 246.1494; found: 246.1488.

(Z)-4,4-Dimethyl-1-(4-(trifluoromethyl)phenyl)pent-2-yn-1-one O-methyl oxime (2g). Prepared according to general procedure (II). Intermediate **2g** was obtained as yellow oil (792.7 mg, 80% yield). ^1H NMR (600 MHz, CDCl_3) δ 7.95 (d, J = 8.3 Hz, 2H), 7.62 (d, J = 8.4 Hz, 2H), 4.11 (s, 3H), 1.39 (s, 9H). ^{13}C NMR (150 MHz, CDCl_3) δ 139.1, 137.6, 131.3 (q, J = 31.5 Hz), 126.9, 125.4 (q, J = 3.0 Hz), 126.9, 124.3 (q, J = 270.0 Hz), 112.6, 69.8, 63.3, 30.8, 28.8. ^{19}F NMR (564 MHz, CDCl_3) δ –62.70. HRMS (ESI-ion trap): m/z $[\text{M} + \text{H}]^+$ calcd for $\text{C}_{15}\text{H}_{17}\text{F}_3\text{NO}$: 284.1262; found: 284.1258.

(Z)-1,3-Diphenylprop-2-yn-1-one O-methyl oxime (2h). Prepared according to general procedure (II). Intermediate **2h** was obtained as yellow oil (501.9 mg, 61% yield). The ^1H NMR spectral data are in good agreement with the literature data.¹⁹

General procedure (III) for iodocyclization using ICl as a catalyst (3)

To a stirred solution of the appropriate *O*-methyl oxime (3.0 mmol) in CH_2Cl_2 (30 mL), ICl (1 M in CH_2Cl_2 , 1.2 equiv.) was added by dropwise, and then the solution was allowed to stir at room temperature. The reaction was monitored by TLC to establish completion. The excess ICl was removed by washing with a saturated aqueous solution of $\text{Na}_2\text{S}_2\text{O}_3$. The aqueous solution was then extracted with CH_2Cl_2 (3 \times 10 mL). The combined organic layers were dried over anhydrous MgSO_4 and concentrated under a vacuum to yield the crude product, which was purified by flash chromatography on silica gel (200–300 mesh) using ethyl acetate/petroleum ether as the eluent to afford the desired products **3**.

3-(tert-Butyl)-4-iodo-5-phenylisoxazole (3a). Following general procedure (III), the substrate **3a** was obtained as a colourless

solid (961.4 mg, 98% yield). Mp 80–82 °C. The ^1H NMR spectral data are in good agreement with the literature data.¹⁹

5-(tert-Butyl)-4-iodo-3-phenylisoxazole (3b). Following general procedure (III), the substrate **3b** was obtained as a yellow solid (971.3 mg, 99% yield). Mp 91–93 °C. The ^1H NMR spectral data are in good agreement with the literature data.¹⁹

5-Cyclopropyl-4-iodo-3-phenylisoxazole (3c). Following general procedure (III), the substrate **3c** was obtained as a yellow solid (914.3 mg, 98% yield). Mp 73–75 °C. ^1H NMR (400 MHz, CDCl_3) δ 7.76 (dt, J = 7.4, 3.2 Hz, 2H), 7.51–7.45 (m, 3H), 2.18 (dq, J = 8.4, 5.1 Hz, 1H), 1.25–1.20 (m, 2H), 1.14 (ddd, J = 11.5, 6.9, 4.6 Hz, 2H). ^{13}C NMR (150 MHz, CDCl_3) δ 174.7, 163.1, 130.1, 128.9, 128.8, 128.7, 56.5, 9.4, 8.8. HRMS (ESI-ion trap): m/z $[\text{M} + \text{H}]^+$ calcd for $\text{C}_{12}\text{H}_{11}\text{INO}$: 311.9885; found: 311.9880.

4-Iodo-5-pentyl-3-phenylisoxazole (3d). Following general procedure (III), the substrate **3d** was obtained as yellow oil (992.4 mg, 97% yield). ^1H NMR (500 MHz, CDCl_3) δ 7.85–7.79 (m, 2H), 7.49–7.44 (m, 3H), 2.91–2.83 (m, 2H), 1.82–1.72 (m, 2H), 1.39 (td, J = 7.2, 3.6 Hz, 4H), 0.98–0.89 (m, 3H). ^{13}C NMR (125 MHz, CDCl_3) δ 174.8, 162.6, 129.9, 128.9, 128.6, 128.5, 57.3, 31.2, 27.1, 26.9, 22.3, 13.9. HRMS (ESI-ion trap): m/z $[\text{M} + \text{H}]^+$ calcd for $\text{C}_{14}\text{H}_{17}\text{INO}$: 342.0355; found: 342.0341.

4-Iodo-3-isopropyl-5-phenylisoxazole (3e). Following general procedure (III), the substrate **3e** was obtained as a white solid (901.5 mg, 96% yield). Mp 70–72 °C. ^1H NMR (600 MHz, CDCl_3) δ 8.01 (dd, J = 5.2, 2.8 Hz, 2H), 7.52–7.46 (m, 3H), 3.05 (dt, J = 13.9, 6.9 Hz, 1H), 1.40 (d, J = 7.0 Hz, 6H). ^{13}C NMR (150 MHz, CDCl_3) δ 169.9, 167.6, 130.6, 128.8, 127.7, 127.5, 56.8, 28.1, 20.9. HRMS (ESI-ion trap): m/z $[\text{M} + \text{H}]^+$ calcd for $\text{C}_{12}\text{H}_{12}\text{INO}$: 314.0042; found: 314.0040.

5-(tert-Butyl)-4-iodo-3-(4-methoxyphenyl)isoxazole (3f). Following general procedure (III), the substrate **3f** was obtained as a yellow solid (1017.6 mg, 95% yield). Mp 75–77 °C. ^1H NMR (600 MHz, CDCl_3) δ 7.66–7.61 (m, 2H), 7.02–6.98 (m, 2H), 3.85 (s, 3H), 1.54 (s, 9H). ^{13}C NMR (150 MHz, CDCl_3) δ 177.8, 164.5, 160.9, 130.6, 121.4, 114.1, 55.4, 34.5, 28.4. HRMS (ESI-ion trap): m/z $[\text{M} + \text{H}]^+$ calcd for $\text{C}_{14}\text{H}_{17}\text{INO}$: 358.0304; found: 358.0304.

5-(tert-Butyl)-4-iodo-3-(4-(trifluoromethyl)phenyl)isoxazole (3g). Following general procedure (III), the substrate **3g** was obtained as a yellow solid (1019.1 mg, 86% yield). Mp 99–101 °C. ^1H NMR (600 MHz, CDCl_3) δ 7.82 (d, J = 8.1 Hz, 2H), 7.75 (d, J = 8.2 Hz, 2H), 1.55 (s, 9H). ^{13}C NMR (150 MHz, CDCl_3) δ 163.2, 132.9, 131.9 (q, J = 31.5 Hz), 129.8, 125.6 (q, J = 4.5 Hz), 126.9, 124.1 (q, J = 271.5 Hz), 53.4, 34.7, 28.5. ^{19}F NMR (564 MHz, CDCl_3) δ –62.80. HRMS (ESI-ion trap): m/z $[\text{M} + \text{H}]^+$ calcd for $\text{C}_{14}\text{H}_{14}\text{F}_3\text{INO}$: 396.0072; found: 396.0070.

4-Iodo-3,5-diphenylisoxazole (3h). Following general procedure (III), the substrate **3h** was obtained as a colourless solid (739.1 mg, 71% yield). Mp 176–178 °C. The ^1H NMR spectral data are in good agreement with the literature data.²²

General procedure (IV) for the synthesis of C4-alkynyl isoxazoles (4 or 5)

A 10 mL two-neck round-bottomed flask with a reflux condenser was flame-dried under a stream of nitrogen and cooled to room temperature. **3** (0.3 mmol, 1.0 equiv.), $\text{Pd}(\text{acac})_2$ (4.7 mg,



5 mol%), PPh₃ (7.9 mg, 10 mol%), CuI (5.8 mg, 10 mol%), and Et₂NH (43.9 mg, 2 equiv.) were added, followed by the addition of anhydrous DMF (2.5 mL). The flask was flushed with nitrogen and the terminal acetylene (1.0 M in DMF, 2.0 equiv.) was added gradually by a syringe. The resulting solution was allowed to stir at 60 °C until completion as monitored by thin layer chromatography. After cooling to room temperature, the reaction was poured into 10 mL ethyl acetate and washed three times (3 × 10 mL) with water. The organic layers were combined, dried with anhydrous MgSO₄, and then filtered. The filtrate was concentrated in vacuum, and the resulting residue was purified on silica gel column (200–300 mesh) using ethyl acetate/petroleum ether as eluent to afford the desired products 4 or 5.

3-(*tert*-Butyl)-5-phenyl-4-(phenylethynyl)isoxazole (4a). Following general procedure (IV), the product 4a was obtained as yellow oil (54.2 mg, 60% yield). ¹H NMR (400 MHz, *d*₆-DMSO) δ 8.14–8.11 (m, 2H), 7.60 (dddd, *J* = 6.3, 5.7, 3.3, 1.7 Hz, 5H), 7.49–7.46 (m, 3H), 1.48 (s, 9H). ¹³C NMR (100 MHz, *d*₆-DMSO) δ 170.7, 169.0, 131.2, 130.9, 129.3, 129.0, 126.5, 125.9, 121.7, 96.8, 96.2, 79.4, 33.0, 27.8. HRMS (ESI-ion trap): *m/z* [M + H]⁺ calcd for C₂₁H₂₀NO: 302.1545; found: 302.1542.

3-(*tert*-Butyl)-4-((4-fluorophenyl)ethynyl)-5-phenylisoxazole (4b). Following general procedure (IV), the product 4b was obtained as a white solid (58.4 mg, 61% yield). Mp 81–83 °C. ¹H NMR (500 MHz, CDCl₃) δ 8.17 (d, *J* = 7.5 Hz, 2H), 7.50 (dt, *J* = 15.9, 7.1 Hz, 5H), 7.09 (t, *J* = 8.5 Hz, 2H), 1.54 (s, 9H). ¹³C NMR (125 MHz, CDCl₃) δ 171.5, 169.8, 163.9, 161.9, 133.3, 133.2, 130.7, 129.0, 127.7, 126.5, 119.3, 119.2, 116.2, 116.1, 96.9, 96.0, 80.2, 33.6, 28.3. ¹⁹F NMR (470 MHz, CDCl₃) δ –109.90. HRMS (ESI-ion trap): *m/z* [M + H]⁺ calcd for C₂₁H₁₉FNO: 320.1451; found: 320.1443.

3-(*tert*-Butyl)-5-phenyl-4-(*p*-tolylethynyl)isoxazole (4c). Following general procedure (IV), the product 4c was obtained as a white solid (59.6 mg, 63% yield). Mp 77–79 °C. ¹H NMR (500 MHz, CDCl₃) δ 8.21 (dd, *J* = 8.1, 0.8 Hz, 2H), 7.52–7.42 (m, 5H), 7.21 (d, *J* = 7.9 Hz, 2H), 2.40 (s, 3H), 1.56 (s, 9H). ¹³C NMR (125 MHz, CDCl₃) δ 171.6, 169.5, 139.2, 131.3, 130.6, 129.5, 128.9, 127.8, 126.5, 120.1, 97.4, 97.3, 79.8, 33.6, 28.4, 21.8. HRMS (ESI-ion trap): *m/z* [M + H]⁺ calcd for C₂₂H₂₂NO: 316.1701; found: 316.1694.

5-(*tert*-Butyl)-3-phenyl-4-(phenylethynyl)isoxazole (4d). Following general procedure (IV), the product 4d was obtained as a white solid (87.6 mg, 97% yield). Mp 58–60 °C. ¹H NMR (400 MHz, CDCl₃) δ 8.08 (dd, *J* = 6.5, 3.1 Hz, 2H), 7.51–7.45 (m, 5H), 7.39–7.33 (m, 3H), 1.58 (s, 9H). ¹³C NMR (100 MHz, CDCl₃) δ 182.2, 162.3, 131.1, 130.1, 128.9, 128.8, 128.7, 128.6, 128.0, 123.2, 96.8, 95.9, 79.6, 34.8, 28.5. HRMS (ESI-ion trap): *m/z* [M + H]⁺ calcd for C₂₁H₂₀NO: 302.1545; found: 302.1539.

5-(*tert*-Butyl)-4-((4-fluorophenyl)ethynyl)-3-phenylisoxazole (4e). Following general procedure (IV), the product 4e was obtained as yellow oil (86.2 mg, 90% yield). ¹H NMR (600 MHz, CDCl₃) δ 8.06–8.01 (m, 2H), 7.48 (d, *J* = 4.0 Hz, 3H), 7.43 (dd, *J* = 8.1, 5.7 Hz, 2H), 7.05 (t, *J* = 8.5 Hz, 2H), 1.56 (s, 9H). ¹³C NMR (150 MHz, CDCl₃) δ 182.2, 163.6, 162.4, 162.0, 133.1, 133.0, 132.7, 130.2, 129.4, 128.9, 128.7, 128.6, 128.0, 119.4, 119.3, 116.0, 115.9, 96.6, 94.8, 79.3, 34.8, 28.5. ¹⁹F NMR (564 MHz, CDCl₃) δ –110.30. HRMS (ESI-ion trap): *m/z* [M + H]⁺ calcd for C₂₁H₁₉FNO: 320.1451; found: 320.1449.

5-(*tert*-Butyl)-3-phenyl-4-(*p*-tolylethynyl)isoxazole (4f). Following general procedure (IV), the product 4f was obtained as a white solid

(84.2 mg, 89% yield). Mp 81–83 °C. ¹H NMR (600 MHz, CDCl₃) δ 8.09–8.04 (m, 2H), 7.49–7.47 (m, 3H), 7.36 (d, *J* = 8.1 Hz, 2H), 7.17 (d, *J* = 7.9 Hz, 2H), 2.38 (s, 3H), 1.56 (s, 9H). ¹³C NMR (150 MHz, CDCl₃) δ 182.0, 162.3, 138.9, 132.7, 131.1, 130.1, 129.4, 129.0, 128.7, 128.6, 128.0, 120.2, 96.9, 96.1, 78.9, 34.8, 28.5, 21.7. HRMS (ESI-ion trap): *m/z* [M + H]⁺ calcd for C₂₂H₂₂NO: 316.1701; found: 316.1694.

5-Cyclopropyl-3-phenyl-4-(phenylethynyl)isoxazole (4g). Following general procedure (IV), the product 4g was obtained as yellow oil (82.1 mg, 96% yield). ¹H NMR (400 MHz, CDCl₃) δ 8.07 (dt, *J* = 9.3, 2.8 Hz, 2H), 7.55–7.43 (m, 4H), 7.32 (dd, *J* = 5.0, 3.0 Hz, 1H), 7.18 (dd, *J* = 5.0, 1.0 Hz, 1H), 2.37–2.27 (m, 1H), 1.38–1.32 (m, 2H), 1.21–1.16 (m, 2H). ¹³C NMR (100 MHz, CDCl₃) δ 177.0, 161.6, 131.4, 130.2, 128.9, 128.8, 128.7, 128.6, 127.8, 123.1, 97.5, 94.8, 78.6, 9.0, 8.9. HRMS (ESI-ion trap): *m/z* [M + H]⁺ calcd for C₂₁H₁₈NO: 300.1388; found: 300.1386.

5-Cyclopropyl-4-((4-fluorophenyl)ethynyl)-3-phenylisoxazole (4h). Following general procedure (IV), the product 4h was obtained as a yellow solid (82.8 mg, 91% yield). Mp 85–87 °C. ¹H NMR (500 MHz, CDCl₃) δ 8.11–8.03 (m, 2H), 7.48 (dd, *J* = 7.4, 6.0 Hz, 5H), 7.06 (t, *J* = 8.5 Hz, 2H), 2.37–2.27 (m, 1H), 1.40–1.34 (m, 2H), 1.22–1.15 (m, 2H). ¹³C NMR (125 MHz, CDCl₃) δ 177.0, 163.8, 161.8, 161.6, 133.4, 133.3, 130.2, 128.8, 128.7, 127.8, 119.3, 119.2, 116.0, 115.8, 97.4, 93.7, 78.3, 9.0, 8.9. ¹⁹F NMR (564 MHz, CDCl₃) δ –109.90, –109.91. HRMS (ESI-ion trap): *m/z* [M + H]⁺ calcd for C₂₀H₁₅FNO: 304.1138; found: 304.1130.

5-Cyclopropyl-3-phenyl-4-(*p*-tolylethynyl)isoxazole (4i). Following general procedure (IV), the product 4i was obtained as yellow oil (82.6 mg, 92% yield). ¹H NMR (400 MHz, CDCl₃) δ 8.15–8.06 (m, 2H), 7.53–7.45 (m, 3H), 7.41 (d, *J* = 8.0 Hz, 2H), 7.18 (d, *J* = 7.9 Hz, 2H), 2.39 (s, 3H), 1.40–1.34 (m, 2H), 1.23–1.16 (m, 2H). ¹³C NMR (100 MHz, CDCl₃) δ 176.7, 161.5, 138.9, 131.3, 130.2, 129.3, 128.8, 128.7, 127.7, 120.0, 97.6, 94.9, 77.8, 21.7, 8.9, 8.8. HRMS (ESI-ion trap): *m/z* [M + H]⁺ calcd for C₂₁H₁₈NO: 300.1388; found: 300.1386.

5-Pentyl-3-phenyl-4-(phenylethynyl)isoxazole (4j). Following general procedure (IV), the product 4j was obtained as yellow oil (89.9 mg, 95% yield). ¹H NMR (500 MHz, CDCl₃) δ 8.14–8.06 (m, 2H), 7.52–7.45 (m, 5H), 7.10–7.03 (m, 2H), 2.96 (t, *J* = 7.5 Hz, 2H), 1.86 (p, *J* = 7.3 Hz, 2H), 1.41 (dd, *J* = 7.2, 3.6 Hz, 4H), 0.93 (t, *J* = 6.8 Hz, 3H). ¹³C NMR (125 MHz, CDCl₃) δ 176.9, 163.8, 161.8, 161.3, 133.5, 133.4, 130.2, 128.8, 127.7, 119.1, 116.1, 115.9, 98.7, 93.9, 78.3, 31.3, 26.9, 26.7, 22.4, 14.1. HRMS (ESI-ion trap): *m/z* [M + H]⁺ calcd for C₂₂H₂₂NO: 316.1701; found: 316.1690.

4-((4-Fluorophenyl)ethynyl)-5-pentyl-3-phenylisoxazole (4k). Following general procedure (IV), the product 4k was obtained as yellow oil (91.9 mg, 92% yield). ¹H NMR (500 MHz, CDCl₃) δ 8.13 (td, *J* = 4.2, 2.5 Hz, 2H), 7.51–7.48 (m, 4H), 7.37 (dd, *J* = 4.2, 2.3 Hz, 3H), 3.01–2.91 (m, 2H), 1.87 (p, *J* = 7.3 Hz, 2H), 1.42 (dd, *J* = 4.2, 3.1 Hz, 4H), 0.94 (dt, *J* = 7.0, 3.4 Hz, 3H). ¹³C NMR (125 MHz, CDCl₃) δ 176.9, 161.3, 131.5, 130.2, 128.9, 128.8, 128.7, 128.6, 127.8, 123.1, 98.9, 95.0, 78.6, 31.4, 27.0, 26.7, 22.4, 14.1. ¹⁹F NMR (470 MHz, CDCl₃) δ –110.30. HRMS (ESI-ion trap): *m/z* [M + H]⁺ calcd for C₂₂H₂₁FNO: 334.1607; found: 334.1599.

5-Pentyl-3-phenyl-4-(*p*-tolylethynyl)isoxazole (4l). Following general procedure (IV), the product 4l was obtained as yellow oil (91.9 mg, 98% yield). ¹H NMR (500 MHz, CDCl₃) δ 8.18–8.11 (m, 2H), 7.53–7.46 (m, 3H), 7.42 (d, *J* = 8.0 Hz, 2H), 7.19 (d, *J* =



7.9 Hz, 2H), 2.97 (t, $J = 7.5$ Hz, 2H), 2.39 (s, 3H), 1.86 (dd, $J = 14.7, 7.3$ Hz, 2H), 1.46–1.39 (m, 4H), 0.95 (dd, $J = 10.0, 4.0$ Hz, 3H). ^{13}C NMR (125 MHz, CDCl_3) δ 176.7, 161.2, 138.9, 131.4, 130.1, 129.3, 128.9, 128.7, 127.7, 120.0, 99.0, 95.2, 77.8, 31.3, 26.9, 26.6, 22.4, 21.6, 14.0. HRMS (ESI-ion trap): m/z $[\text{M} + \text{H}]^+$ calcd for $\text{C}_{23}\text{H}_{24}\text{NO}$: 330.1858; found: 330.1852.

3-Isopropyl-5-phenyl-4-(phenylethynyl)isoxazole (4m). Following general procedure (IV), the product **4m** was obtained as yellow oil (77.6 mg, 90% yield). ^1H NMR (600 MHz, CDCl_3) δ 8.23–8.18 (m, 2H), 7.57–7.55 (m, 2H), 7.53–7.46 (m, 3H), 7.42–7.38 (m, 3H), 3.27 (dt, $J = 14.0, 7.0$ Hz, 1H), 1.49 (d, $J = 7.0$ Hz, 6H). ^{13}C NMR (150 MHz, CDCl_3) δ 169.9, 168.8, 131.5, 130.7, 129.0, 128.9, 128.7, 127.6, 126.4, 123.0, 97.6, 96.6, 79.2, 27.1, 20.7. HRMS (ESI-ion trap): m/z $[\text{M} + \text{H}]^+$ calcd for $\text{C}_{20}\text{H}_{18}\text{NO}$: 288.1388; found: 288.1385.

4-((4-Fluorophenyl)ethynyl)-3-isopropyl-5-phenylisoxazole (4n). Following general procedure (IV), the product **4n** was obtained as yellow oil (83.3 mg, 91% yield). ^1H NMR (600 MHz, CDCl_3) δ 8.20–8.14 (m, 2H), 7.54–7.47 (m, 5H), 7.12–7.06 (m, 2H), 3.25 (dt, $J = 14.0, 7.0$ Hz, 1H), 1.48 (d, $J = 7.0$ Hz, 6H). ^{13}C NMR (150 MHz, CDCl_3) δ 169.8, 168.9, 163.7, 162.1, 133.5, 133.4, 130.7, 130.6, 129.0, 128.8, 127.6, 127.5, 126.4, 119.2, 119.1, 116.1, 116.0, 97.5, 95.4, 78.9, 27.1, 20.9, 20.6. ^{19}F NMR (564 MHz, CDCl_3) δ –109.90. HRMS (ESI-ion trap): m/z $[\text{M} + \text{H}]^+$ calcd for $\text{C}_{20}\text{H}_{17}\text{FNO}$: 306.1294; found: 306.1288.

3-Isopropyl-5-phenyl-4-(*p*-tolylethynyl)isoxazole (4o). Following general procedure (IV), the product **4o** was obtained as yellow oil (84.1 mg, 93% yield). ^1H NMR (600 MHz, CDCl_3) δ 8.26–8.17 (m, 2H), 7.52–7.44 (m, 5H), 7.21 (d, $J = 7.9$ Hz, 2H), 3.27 (dt, $J = 13.9, 7.0$ Hz, 1H), 2.40 (s, 3H), 1.49 (dd, $J = 7.0, 1.7$ Hz, 6H). ^{13}C NMR (150 MHz, CDCl_3) δ 169.8, 168.6, 139.1, 131.4, 130.6, 129.4, 128.9, 127.68, 126.4, 119.9, 97.8, 96.8, 78.5, 27.1, 21.7, 20.6. HRMS (ESI-ion trap): m/z $[\text{M} + \text{H}]^+$ calcd for $\text{C}_{21}\text{H}_{20}\text{NO}$: 302.1545; found: 302.1539.

5-(*tert*-Butyl)-3-(4-methoxyphenyl)-4-(phenylethynyl)isoxazole (4p). Following general procedure (IV), the product **4p** was obtained as yellow oil (89.4 mg, 90% yield). ^1H NMR (600 MHz, CDCl_3) δ 8.04 (d, $J = 8.8$ Hz, 2H), 7.49–7.45 (m, 2H), 7.36 (dd, $J = 5.1, 1.9$ Hz, 3H), 7.01 (d, $J = 8.8$ Hz, 2H), 3.86 (s, 3H), 1.56 (s, 9H). ^{13}C NMR (150 MHz, CDCl_3) δ 182.1, 161.9, 161.1, 131.1, 129.4, 128.6, 123.3, 121.4, 114.1, 96.5, 95.8, 79.9, 55.5, 34.8, 28.4. HRMS (ESI-ion trap): m/z $[\text{M} + \text{H}]^+$ calcd for $\text{C}_{22}\text{H}_{22}\text{NO}_2$: 332.1651; found: 332.1647.

5-(*tert*-Butyl)-4-((4-fluorophenyl)ethynyl)-3-(4-methoxyphenyl)isoxazole (4q). Following general procedure (IV), the product **4q** was obtained as yellow oil (95.3 mg, 91% yield). ^1H NMR (600 MHz, CDCl_3) δ 8.00 (d, $J = 8.7$ Hz, 2H), 7.47–7.41 (m, 2H), 7.06 (t, $J = 8.6$ Hz, 2H), 7.00 (d, $J = 8.7$ Hz, 2H), 3.86 (s, 3H), 1.55 (s, 9H). ^{13}C NMR (150 MHz, CDCl_3) δ 182.1, 163.6, 161.9, 161.1, 133.1, 133.0, 129.3, 121.3, 119.4, 119.3, 116.0, 115.9, 114.1, 96.3, 94.7, 79.6, 55.5, 34.8, 28.4. ^{19}F NMR (564 MHz, CDCl_3) δ –110.34, –110.35, –110.36, –110.37, –110.38, –110.39, –110.40. HRMS (ESI-ion trap): m/z $[\text{M} + \text{H}]^+$ calcd for $\text{C}_{22}\text{H}_{22}\text{FNO}_2$: 350.1556; found: 350.1552.

5-(*tert*-Butyl)-3-(4-methoxyphenyl)-4-(*p*-tolylethynyl)isoxazole (4r). Following general procedure (IV), the product **4r** was obtained as yellow oil (95.3 mg, 92% yield). ^1H NMR (600 MHz, CDCl_3) δ 8.07–8.01 (m, 2H), 7.37 (d, $J = 8.1$ Hz, 2H), 7.17 (d, $J =$

7.9 Hz, 2H), 7.01–6.98 (m, 2H), 3.86 (s, 3H), 2.38 (s, 3H), 1.55 (s, 9H). ^{13}C NMR (150 MHz, CDCl_3) δ 181.8, 161.9, 161.1, 138.8, 131.1, 129.5, 129.4, 121.5, 120.2, 114.1, 96.6, 95.9, 79.2, 55.5, 34.7, 28.4, 21.7. HRMS (ESI-ion trap): m/z $[\text{M} + \text{H}]^+$ calcd for $\text{C}_{23}\text{H}_{24}\text{NO}_2$: 346.1807; found: 346.1798.

5-(*tert*-Butyl)-4-(phenylethynyl)-3-(4-(trifluoromethyl)phenyl)isoxazole (4s). Following general procedure (IV), the product **4s** was obtained as yellow oil (107.5 mg, 97% yield). ^1H NMR (600 MHz, CDCl_3) δ 8.21 (d, $J = 8.2$ Hz, 2H), 7.76 (d, $J = 8.3$ Hz, 2H), 7.51–7.45 (m, 2H), 7.41–7.34 (m, 3H), 1.58 (s, 9H). ^{13}C NMR (150 MHz, CDCl_3) δ 182.8, 161.1, 132.5, 132.1, 131.8, 131.2, 129.7, 129.0, 128.7, 128.3, 125.7 (q, $J = 4.5$ Hz), 125.1, 123.2, 122.9, 96.9, 96.4, 78.9, 34.9, 28.5. ^{19}F NMR (564 MHz, CDCl_3) δ –62.80. HRMS (ESI-ion trap): m/z $[\text{M} + \text{H}]^+$ calcd for $\text{C}_{22}\text{H}_{19}\text{F}_3\text{NO}$: 370.1419; found: 370.1416.

5-(*tert*-Butyl)-4-((4-fluorophenyl)ethynyl)-3-(4-(trifluoromethyl)phenyl)isoxazole (4t). Following general procedure (IV), the product **4t** was obtained as a yellow solid (110.4 mg, 95% yield). Mp 77–79 °C. ^1H NMR (400 MHz, CDCl_3) δ 8.18 (d, $J = 8.2$ Hz, 2H), 7.75 (d, $J = 8.3$ Hz, 2H), 7.44 (dd, $J = 8.7, 5.4$ Hz, 2H), 7.07 (t, $J = 8.6$ Hz, 2H), 1.57 (s, 9H). ^{13}C NMR (150 MHz, CDCl_3) δ 182.8, 163.8, 162.2, 161.1, 133.2, 133.1, 132.4, 132.1, 131.9, 128.3, 127.2, 125.7 (q, $J = 3$ Hz), 125.1, 123.2, 119.0, 118.9, 116.2, 116.0, 96.7, 95.3, 78.7, 34.9, 29.0, 28.4. ^{19}F NMR (564 MHz, CDCl_3) δ –62.80, –109.80. HRMS (ESI-ion trap): m/z $[\text{M} + \text{H}]^+$ calcd for $\text{C}_{22}\text{H}_{19}\text{F}_4\text{NO}$: 388.1325; found: 388.1319.

5-(*tert*-Butyl)-4-(*p*-tolylethynyl)-3-(4-(trifluoromethyl)phenyl)isoxazole (4u). Following general procedure (IV), the product **4u** was obtained as a yellow solid (111.4 mg, 97% yield). Mp 83–85 °C. ^1H NMR (600 MHz, CDCl_3) δ 8.22 (d, $J = 8.2$ Hz, 2H), 7.75 (d, $J = 8.2$ Hz, 2H), 7.37 (d, $J = 8.1$ Hz, 2H), 7.19 (d, $J = 7.9$ Hz, 2H), 2.39 (s, 3H), 1.58 (s, 9H). ^{13}C NMR (150 MHz, CDCl_3) δ 182.5, 161.1, 139.2, 132.5, 132.2, 132.0, 131.8, 131.6, 131.1, 129.5, 128.3, 126.8, 125.7 (q, $J = 3$ Hz), 123.2, 121.4, 119.8, 97.1, 96.6, 78.3, 34.9, 28.4, 21.7. ^{19}F NMR (564 MHz, CDCl_3) δ –62.80. HRMS (ESI-ion trap): m/z $[\text{M} + \text{H}]^+$ calcd for $\text{C}_{23}\text{H}_{21}\text{F}_3\text{NO}$: 384.1575; found: 384.1571.

3,5-Diphenyl-4-(phenylethynyl)isoxazole (5a). Following general procedure (IV), the product **5a** was obtained as a yellow solid (90.6 mg, 94% yield). Mp 90–92 °C. ^1H NMR (400 MHz, CDCl_3) δ 8.30 (dd, $J = 8.1, 1.4$ Hz, 2H), 8.21–8.14 (m, 2H), 7.61–7.51 (m, 8H), 7.41 (dd, $J = 6.4, 2.7$ Hz, 3H). ^{13}C NMR (100 MHz, CDCl_3) δ 170.0, 162.6, 131.5, 130.9, 130.4, 129.1, 129.0, 128.8, 128.7, 128.6, 128.0, 127.4, 126.5, 122.8, 97.5, 96.6, 79.9. HRMS (ESI-ion trap): m/z $[\text{M} + \text{H}]^+$ calcd for $\text{C}_{23}\text{H}_{16}\text{NO}$: 322.1232; found: 322.1229.

4-((4-Fluorophenyl)ethynyl)-3,5-diphenylisoxazole (5b). Following general procedure (IV), the product **5b** was obtained as a white solid (96.6 mg, 96% yield). Mp 100–102 °C. ^1H NMR (500 MHz, CDCl_3) δ 8.26 (d, $J = 7.3$ Hz, 2H), 8.17–8.11 (m, 2H), 7.56–7.49 (m, 8H), 7.09 (t, $J = 8.5$ Hz, 2H). ^{13}C NMR (125 MHz, CDCl_3) δ 170.1, 163.9, 162.7, 162.0, 133.5, 133.4, 130.9, 130.4, 129.1, 128.8, 128.6, 128.0, 127.5, 126.6, 119.0, 118.9, 116.2, 116.0, 97.3, 95.5, 79.7. ^{19}F NMR (470 MHz, CDCl_3) δ –109.62. HRMS (ESI-ion trap): m/z $[\text{M} + \text{H}]^+$ calcd for $\text{C}_{23}\text{H}_{15}\text{FNO}$: 340.1138; found: 340.1130.

3,5-Diphenyl-4-(*p*-tolylethynyl)isoxazole (5c). Following general procedure (IV), the product **5c** was obtained as a white solid (95.5 mg, 95% yield). Mp 106–108 °C. ^1H NMR (400 MHz, CDCl_3)



δ 8.31 (d, $J = 6.9$ Hz, 2H), 8.23–8.15 (m, 2H), 7.58–7.43 (m, 8H), 7.22 (d, $J = 7.9$ Hz, 2H), 2.41 (s, 3H). ^{13}C NMR (100 MHz, CDCl_3) δ 169.8, 162.6, 139.2, 131.4, 130.8, 130.3, 129.4, 129.0, 128.8, 128.7, 128.0, 127.5, 126.5, 119.8, 97.6, 96.8, 79.2, 21.7. HRMS (ESI-ion trap): m/z $[\text{M} + \text{H}]^+$ calcd for $\text{C}_{24}\text{H}_{18}\text{NO}$: 336.1388; found: 336.1382.

3,5-Diphenyl-4-(*m*-tolylethynyl)isoxazole (5d). Following general procedure (IV), the product **5d** was obtained as a yellow solid (92.5 mg, 92% yield). Mp 95–97 °C. ^1H NMR (600 MHz, CDCl_3) δ 8.29 (d, $J = 7.5$ Hz, 2H), 8.22–8.12 (m, 2H), 7.57–7.51 (m, 6H), 7.36 (d, $J = 5.9$ Hz, 2H), 7.29 (t, $J = 7.8$ Hz, 1H), 7.21 (d, $J = 7.6$ Hz, 1H), 2.39 (s, 3H). ^{13}C NMR (150 MHz, CDCl_3) δ 170.1, 162.7, 138.5, 132.1, 130.9, 130.4, 129.9, 129.1, 128.8, 128.7, 128.6, 128.1, 127.5, 126.6, 122.7, 97.6, 96.9, 79.5, 21.5. HRMS (ESI-ion trap): m/z $[\text{M} + \text{H}]^+$ calcd for $\text{C}_{24}\text{H}_{18}\text{NO}$: 336.1388; found: 336.1381.

3,5-Diphenyl-4-(*p*-propylphenylethynyl)isoxazole (5e). Following general procedure (IV), the product **5e** was obtained as a yellow solid (102.4 mg, 94% yield). Mp 97–99 °C. ^1H NMR (400 MHz, CDCl_3) δ 8.31 (d, $J = 6.8$ Hz, 2H), 8.19 (dd, $J = 6.4, 2.8$ Hz, 2H), 7.53 (ddd, $J = 25.3, 12.3, 7.4$ Hz, 8H), 7.22 (d, $J = 8.0$ Hz, 2H), 2.64 (t, $J = 7.6$ Hz, 2H), 1.68 (dd, $J = 15.0, 7.5$ Hz, 2H), 0.98 (t, $J = 7.3$ Hz, 3H). ^{13}C NMR (100 MHz, CDCl_3) δ 169.8, 162.6, 144.0, 131.4, 130.8, 130.3, 129.0, 128.9, 128.8, 128.7, 128.0, 127.5, 126.5, 120.1, 97.7, 96.9, 79.2, 38.1, 24.5, 13.9. HRMS (ESI-ion trap): m/z $[\text{M} + \text{H}]^+$ calcd for $\text{C}_{26}\text{H}_{22}\text{NO}$: 364.1701; found: 364.1690.

4-(*t*-butylphenylethynyl)-3,5-diphenylisoxazole (5f). Following general procedure (IV), the product **5f** was obtained as a yellow solid (105.3 mg, 93% yield). Mp 115–117 °C. ^1H NMR (600 MHz, CDCl_3) δ 8.29 (d, $J = 7.8$ Hz, 2H), 8.17 (d, $J = 7.6$ Hz, 2H), 7.52 (dd, $J = 14.2, 7.5$ Hz, 8H), 7.43 (d, $J = 8.2$ Hz, 2H), 1.35 (s, 9H). ^{13}C NMR (150 MHz, CDCl_3) δ 169.9, 162.7, 152.5, 131.4, 130.9, 130.8, 130.4, 130.3, 129.2, 129.1, 128.9, 128.8, 128.7, 128.1, 127.9, 127.6, 126.6, 125.8, 119.9, 97.7, 96.9, 79.2, 35.1, 31.4. HRMS (ESI-ion trap): m/z $[\text{M} + \text{H}]^+$ calcd for $\text{C}_{27}\text{H}_{24}\text{NO}$: 378.1858; found: 378.1849.

4-(*p*-methoxyphenylethynyl)-3,5-diphenylisoxazole (5g). Following general procedure (IV), the product **5g** was obtained as a white solid (90.6 mg, 89% yield). Mp 114–116 °C. ^1H NMR (600 MHz, CDCl_3) δ 8.32–8.26 (m, 2H), 8.21–8.13 (m, 2H), 7.56–7.45 (m, 8H), 6.92 (d, $J = 8.7$ Hz, 2H), 3.85 (s, 3H). ^{13}C NMR (150 MHz, CDCl_3) δ 169.6, 162.6, 160.2, 133.1, 130.8, 130.4, 129.1, 128.9, 128.8, 128.1, 127.6, 126.5, 115.1, 114.4, 97.8, 96.7, 78.6, 55.6. HRMS (ESI-ion trap): m/z $[\text{M} + \text{H}]^+$ calcd for $\text{C}_{22}\text{H}_{19}\text{F}_4\text{NO}$: 352.1338; found: 352.1334.

4-(*1,1'*-biphenyl)-4-ylethynyl)-3,5-diphenylisoxazole (5h). Following general procedure (IV), the product **5h** was obtained as a white solid (59.6 mg, 50% yield). Mp 120–122 °C. ^1H NMR (600 MHz, CDCl_3) δ 8.33–8.29 (m, 2H), 8.18 (dd, $J = 7.7, 1.8$ Hz, 2H), 7.65–7.60 (m, 6H), 7.55 (qdd, $J = 6.6, 4.2, 2.2$ Hz, 6H), 7.48 (dd, $J = 10.5, 4.9$ Hz, 2H), 7.41–7.38 (m, 1H). ^{13}C NMR (150 MHz, CDCl_3) δ 170.1, 162.7, 141.8, 140.3, 132.1, 131.0, 130.4, 129.2, 129.1, 128.9, 128.7, 128.1, 128.0, 127.5, 127.4, 127.2, 126.6, 121.7, 97.6, 96.5, 80.6. HRMS (ESI-ion trap): m/z $[\text{M} + \text{H}]^+$ calcd for $\text{C}_{29}\text{H}_{20}\text{NO}$: 398.1545; found: 398.1540.

3,5-Diphenyl-4-(thiophen-3-ylethynyl)isoxazole (5i). Following general procedure (IV), the product **5i** was obtained as a white solid (89.3 mg, 91% yield). Mp 133–135 °C. ^1H NMR (400 MHz, CDCl_3) δ 8.27 (dd, $J = 7.9, 1.4$ Hz, 2H), 8.15 (dd, $J = 6.6, 3.1$ Hz,

2H), 7.60–7.48 (m, 7H), 7.36 (dd, $J = 4.9, 3.0$ Hz, 1H), 7.23 (dd, $J = 5.0, 0.6$ Hz, 1H). ^{13}C NMR (100 MHz, CDCl_3) δ 170.1, 162.7, 130.9, 130.3, 129.7, 129.3, 129.2, 129.1, 128.9, 128.6, 128.0, 127.4, 126.9, 126.5, 125.9, 121.8, 97.4, 91.9, 79.3. HRMS (ESI-ion trap): m/z $[\text{M} + \text{H}]^+$ calcd for $\text{C}_{21}\text{H}_{14}\text{NOS}$: 328.0796; found: 328.0790.

4-(Cyclohex-1-en-1-ylethynyl)-3,5-diphenylisoxazole (5j). Following general procedure (IV), the product **5j** was obtained as yellow oil (88.8 mg, 91% yield). ^1H NMR (400 MHz, CDCl_3) δ 8.27–8.20 (m, 2H), 8.12 (dd, $J = 6.2, 2.7$ Hz, 2H), 7.56–7.44 (m, 6H), 6.28–6.21 (m, 1H), 2.30–2.24 (m, 2H), 2.21–2.15 (m, 2H), 1.74–1.63 (m, 4H). ^{13}C NMR (100 MHz, CDCl_3) δ 169.3, 162.5, 136.1, 130.6, 130.2, 128.9, 128.8, 128.7, 127.9, 127.6, 126.4, 120.7, 98.7, 97.9, 28.8, 25.9, 22.3, 21.6. HRMS (ESI-ion trap): m/z $[\text{M} + \text{H}]^+$ calcd for $\text{C}_{23}\text{H}_{20}\text{NO}$: 326.1545; found: 326.1540.

4-(Cyclohexylethynyl)-3,5-diphenylisoxazole (5k). Following general procedure (IV), the product **5k** was obtained as a white solid (96.2 mg, 98% yield). Mp 97–99 °C. ^1H NMR (600 MHz, CDCl_3) δ 8.27–8.23 (m, 2H), 8.12 (dd, $J = 6.6, 3.0$ Hz, 2H), 7.50 (dd, $J = 8.2, 5.1$ Hz, 5H), 2.83–2.63 (m, 1H), 1.97–1.90 (m, 2H), 1.78 (dt, $J = 12.8, 5.2$ Hz, 2H), 1.65–1.57 (m, 3H), 1.45–1.37 (m, 3H). ^{13}C NMR (150 MHz, CDCl_3) δ 169.4, 162.7, 130.6, 130.2, 129.1, 128.8, 128.6, 127.9, 127.7, 126.3, 102.2, 98.0, 71.0, 32.4, 30.2, 26.0, 24.9. HRMS (ESI-ion trap): m/z $[\text{M} + \text{H}]^+$ calcd for $\text{C}_{23}\text{H}_{22}\text{NO}$: 328.1701; found: 328.1696.

4-(3-methoxyprop-1-yn-1-yl)-3,5-diphenylisoxazole (5l). Following general procedure (IV), the product **5l** was obtained as a white solid (69.4 mg, 80% yield). Mp 68–70 °C. ^1H NMR (600 MHz, CDCl_3) δ 8.20 (dd, $J = 7.9, 1.5$ Hz, 2H), 8.09–8.03 (m, 2H), 7.56–7.46 (m, 6H), 4.41 (s, 2H), 3.46 (s, 3H). ^{13}C NMR (150 MHz, CDCl_3) δ 170.7, 162.9, 131.1, 130.4, 129.1, 128.8, 128.5, 128.1, 127.3, 126.6, 96.8, 92.8, 76.9, 60.7, 58.1. HRMS (ESI-ion trap): m/z $[\text{M} + \text{H}]^+$ calcd for $\text{C}_{19}\text{H}_{16}\text{NO}_2$: 290.1181; found: 290.1180.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

We gratefully thank the National Natural Science Foundation of China (21172081, 21372090), the Natural Science Foundation of Guangdong Province (S2013020013091) and the City of Guangzhou Science and Technology Plan Projects (201510010054) for financial support.

References

- (a) R. G. Micetich and R. Raap, *J. Med. Chem.*, 1968, **11**, 159; (b) J. J. Talley, *Prog. Med. Chem.*, 1999, **36**, 201; (c) M. P. Giovannoni, C. Vergelli, C. Ghelardini, N. Galeotti, A. Bartolini and V. Dal Piaz, *J. Med. Chem.*, 2003, **46**, 1055; (d) M. Dougados, P. Emery, E. M. Lemmel, A. F. Zerbini, S. Brin and P. Van Rie, *Ann. Rheum. Dis.*, 2005, **64**, 44; (e) S. Naud, I. M. Westwood, A. Faisal, P. Sheldrake, V. Bavetsias, B. Atrash, K. M. J. Cheung, M. J. Liu, A. Hayes, J. Schmitt, A. Wood, V. Chi, K. Boxall, J. Mak, M. Gurden, M. Valenti, A. D. H. Brandon, A. Henley,



- R. Baker, C. McAndrew, B. Matijssen, R. Burker, S. Hoelder, S. A. Eccles, F. I. Raynaud, S. Linardopoulos, R. L. M. V. Montfort and J. L. Blagg, *J. Med. Chem.*, 2013, **56**, 10045; (f) J.-J. Feng and J. Zhang, *ACS Catal.*, 2016, **6**, 6651; (g) Q.-Q. Cheng, Y. Yu, J. Yedoyan and M. P. Doyle, *ChemCatChem*, 2018, **10**, 488.
- 2 (a) F. Himmo, T. Lovell, R. Hilgraf, V. V. Rostovtsev, L. Noodleman, K. B. Sharpless and V. V. Fokin, *J. Org. Chem.*, 2005, **70**, 7761; (b) T. V. Hansen, P. Wu and V. V. Fokin, *J. Org. Chem.*, 2005, **70**, 7761; (c) H. Li, L. Yu, X. Zhang, W. L. Johnson, R. Figueroa and R. P. Hsung, *Heterocycles*, 2007, **74**, 553; (d) M. Meldal and C. W. Tornøe, *Chem. Rev.*, 2008, **108**, 2952; (e) S. Grecian and V. V. Fokin, *Angew. Chem., Int. Ed.*, 2008, **47**, 8285; (f) J. S. Oakdale, R. K. Sit and V. V. Fokin, *Chem.–Eur. J.*, 2014, **20**, 11101; (g) J.-X. Li, M. Hu, C.-S. Li, C. Li, J.-W. Li, W.-Q. Wu and H.-F. Jiang, *Adv. Synth. Catal.*, 2018, **360**, 2707.
- 3 (a) K. Maeda, T. Hosokawa, S. Murahashi and I. Moritani, *Tetrahedron Lett.*, 1973, 5075; (b) T. Hosokawa, N. Shimo, K. Maeda, A. Sonoda and S. Murahashi, *Tetrahedron Lett.*, 1976, 383; (c) J. P. Waldo and R. C. Larock, *Org. Lett.*, 2005, **7**, 5203; (d) J. P. Waldo and R. C. Larock, *J. Org. Chem.*, 2007, **72**, 9643; (e) T. Okitsu, K. Sato, T. M. Potewar and A. Wada, *J. Org. Chem.*, 2011, **76**, 3438; (f) I. Cikotiene, *Eur. J. Org. Chem.*, 2012, 2766; (g) C. R. Reddy, J. Vijaykumar, E. Jithender, G. P. K. Reddy and R. Gree, *Eur. J. Org. Chem.*, 2012, 5767; (h) L. Zhang, Q. Zeng, A. Mao, Z. Wu, T. Luo, Y. Xiao and J. Zhang, *J. Org. Biomol. Chem.*, 2014, **12**, 8942.
- 4 (a) T. T. Dang, U. Albrecht and P. Langer, *Synthesis*, 2006, 2515; (b) S. Tang, J. He, Y. Sun, L. He and X. She, *Org. Lett.*, 2009, **11**, 3982; (c) S. Tang, J. He, Y. Sun, L. He and X. She, *J. Org. Chem.*, 2010, **75**, 1961; (d) D. Xiang, X. Xin, X. Liu, R. Zhang, J. Yang and D. Dong, *Org. Lett.*, 2012, **14**, 644; (e) S. Samai, T. Chanda, H. Ila and M. S. Singh, *Eur. J. Org. Chem.*, 2013, 4026; (f) B. Raghava, G. Parameshwarappa, Y. Acharya, T. R. Swaroop, K. S. Rangappa and H. Ila, *Eur. J. Org. Chem.*, 2014, 1882.
- 5 F. Hu and M. Szostak, *Adv. Synth. Catal.*, 2015, **357**, 2583.
- 6 (a) H. Yamanaka, M. Shiraiwa, E. Yamamoto and T. Sakamoto, *Chem. Pharm. Bull.*, 1981, **29**, 3543; (b) N. Nakamura, Y. Tajima and K. Saki, *Heterocycles*, 1982, **17**, 235; (c) H. Kromann, F. A. Slok, T. N. Johansen and P. Krosggaard-Larsen, *Tetrahedron*, 2001, **57**, 2195; (d) H. A. Chiong and O. Daugulis, *Org. Lett.*, 2007, **9**, 1449; (e) J. P. Waldo, S. Mehta, B. Neuenswander, G. H. Lushington and R. C. Larock, *J. Comb. Chem.*, 2008, **10**, 658; (f) Y. Fall, C. Reynaud, H. Doucet and M. Santelli, *Eur. J. Org. Chem.*, 2009, 4041; (g) I. I. F. Boogaerts and S. P. Nolan, *J. Am. Chem. Soc.*, 2010, **132**, 8858; (h) B. Chappell, N. Dedman and S. Wheeler, *Tetrahedron Lett.*, 2011, **52**, 3223; (i) D. Roy, S. Mom, S. Royer, D. Lucas, J. C. Hierso and H. Doucet, *ACS Catal.*, 2012, **2**, 1033; (j) D. Hay, O. Fedorov, P. Filippakopoulos, S. Martin, M. Philpott, D. S. Hewings, S. Uttakar, T. D. Heightman, S. Conway, S. Knapp and P. E. Brennan, *Med. Chem. Commun.*, 2013, **4**, 140; (k) X.-C. Wang, Y. Hu, S. Bonacorsi, Y. Hong, R. Burrell and J.-Q. Yu, *J. Am. Chem. Soc.*, 2013, **135**, 10326; (l) J. Sun, C. Lin, X.-C. Qin, X.-P. Dong, Z.-C. Tu, F. Tang, C.-N. Chen and J.-C. Zhang, *Bioorg. Med. Chem. Lett.*, 2015, **25**, 3129.
- 7 C. C. C. Johansson Seechurn, M. Q. Kitching, T. J. Colacot and V. Snieckus, *Angew. Chem., Int. Ed.*, 2012, **51**, 5062.
- 8 R. Chinchilla and C. Nájera, *Chem. Rev.*, 2007, **107**, 874.
- 9 Y.-W. Guo, X.-J. Wang, Z.-T. Zhu, J.-N. Zhang and Y.-M. Wu, *Synlett*, 2016, **27**, 2259.
- 10 K. C. Coffman, T. A. Palazzo, P. Z. Hartley, J. C. Fettinger, D. J. Tantilo and M. Kurth, *J. Org. Lett.*, 2013, **15**, 2062.
- 11 T. Morita, S. Fukuhara, S. Fuse and H. Nakamura, *Org. Lett.*, 2018, **20**, 433.
- 12 A. de Meijere and F. Diederich, *Metal-Catalyzed Cross-Coupling Reactions*, Wiley-VCH, Weinheim, 2nd edn, 2004.
- 13 D. A. Alonso, C. Najera and M. C. Pacheco, *J. Org. Chem.*, 2004, **69**, 1615.
- 14 W. Kim, K. Park, A. Park, J. Choe and S. Lee, *Org. Lett.*, 2013, **15**, 1654.
- 15 S. Tang, L. Zeng, Y.-C. Liu and A.-W. Lei, *Angew. Chem., Int. Ed.*, 2015, **54**, 15850.
- 16 A. Park, K. Park, Y. Kim and S. Lee, *Org. Lett.*, 2011, **13**, 944.
- 17 Y. Zhu, B. Zhao and Y. Shi, *Org. Lett.*, 2013, **15**, 992.
- 18 B. Liang, M. Huang, Z. You, K. Lu, R. Fathi, J. Chen and Z. Yang, *J. Org. Chem.*, 2005, **70**, 6097.
- 19 J. P. Waldo and R. C. Larock, *Org. Lett.*, 2005, **7**, 5203.
- 20 D. D. Dolliver, B. T. Bhattarai, A. Pandey, M. L. Lanier, A. S. Bordelon, S. Adhikari, J. A. Dinser, P. F. Flowers, V. S. Wills and C. L. Scheier, *J. Org. Chem.*, 2013, **78**, 3676.
- 21 W. Kaewsri, C. Thongsornlleeb, J. Tummatorn and S. Ruchirawat, *RSC Adv.*, 2016, **6**, 48666.
- 22 R. A. Day, J. A. Blake and C. E. Stephens, *Synthesis*, 2003, 1586.

