



Cite this: *RSC Adv.*, 2019, 9, 31162

Received 24th May 2019  
 Accepted 15th September 2019

DOI: 10.1039/c9ra03921j

[rsc.li/rsc-advances](http://rsc.li/rsc-advances)

# Palladium(II)-catalyzed synthesis of indenones through the cyclization of benzenecarbaldehydes with internal alkynes†

Jajula Kashanna,<sup>a</sup> Rathod Aravind Kumar<sup>b</sup> and Ravada Kishore<sup>c</sup>

The palladium(II)-catalyzed carbocyclization of benzenecarbaldehydes with internal alkynes to afford 2,3-disubstituted indenones was reported. The annulation reaction proceeded through the transmetalation of Pd(II) with an aromatic aldehyde and the insertion of internal alkynes, followed by cyclization *via* the intramolecular nucleophilic addition of intermediate organopalladium(II) species to the aldehyde group. This reaction proceeded in moderate to good yields with high regioselectivity.

## Introduction

The transition metal-catalyzed oxidative C–H activation/carbocyclization of inactivated arene C–H bonds has evolved as a highly efficient route for a wide variety of building blocks.<sup>1,2</sup> In this respect, the direct embodiment of inactivated arene groups in the C–H functionalization reaction is the most excellent synthetic strategy that induces additional features. Mostly, carbocyclization is catalyzed by rhodium<sup>3</sup> or palladium<sup>4</sup> complexes. Palladium<sup>4a–e</sup>-catalyzed carbocyclization of C–H bonds has received enormous attention owing to high efficiency, broad scope and good functional group tolerance. Pd-catalyzed oxidative coupling of arenes with alkynes can result in a broad spectrum of homo and heterocycles such as naphthalenes,<sup>4a</sup> carbolines,<sup>4b</sup> phenanthrenes,<sup>4c</sup> isoquinolones,<sup>4d</sup> and benzazepines.<sup>4e</sup> Some of these methodologies have been successfully applied to the synthesis of natural products.<sup>4f–h</sup> In spite of their success, it is essential to explore the C–H activation of inactivated arenes expedited by directing groups, which not only coordinate to metals but also participate in the subsequent reactions to provide novel tandem transformations. This approach serves not only to broaden the scope of palladium-catalyzed C–H functionalization but also to achieve molecular complexity.

Indenones, which are an important class of carbocyclic compounds, form core moieties of many natural products.<sup>5</sup> They are used as estrogen binding receptors,<sup>5a</sup> pharmaceuticals<sup>5a–e</sup> and fungicides.<sup>5f</sup> Furthermore, they find applications in materials science and photochromic chemistry.<sup>5g</sup> They also serve as useful precursors in the synthesis of a variety of biomolecules such as the C-nor-D-homosteroid ring system,<sup>5h</sup> gibberellins<sup>5i</sup> and indenones.<sup>5j</sup> Liebeskind and South first reported the preparation of indenones from *o*-diiodo benzene and different alkynes employing nickel carbonyl as the catalyst.<sup>6</sup> Later, other transition metals such as iron,<sup>7</sup> palladium<sup>8</sup> and rhodium<sup>9</sup> (Scheme 1, eqn (1)) were utilized as catalysts for the syntheses of indenones using preactivated aldehydes, nitriles, amides, esters or halides as the starting materials;<sup>6–9</sup> among these synthesis methods, Pd-catalyzed annulation of alkynes with *ortho*-functionalized aryl-carbonyl and aryl-nitrile compounds forms a powerful synthetic strategy.<sup>8</sup> In recent times, the direct assembly of indenones *via* rhodium,<sup>10</sup> rhenium,<sup>11</sup> cobalt<sup>12</sup> and ruthenium<sup>13</sup>-catalyzed carbocyclization of benzoyl chlorides, benzimides, benzamides, azomethines, arylnitrones, benzaldehydes, nitrostyrenes<sup>14a</sup> and carboximides<sup>14b</sup> with alkynes and benzaldehydes with haloiodoketones<sup>14c,d</sup> (Scheme 1, eqn (2) and (4)) has been reported. However, these methods have certain drawbacks, which include harsh reaction conditions and the requirement of activated or preactivated arenes normally obtained from limited natural resources. Therefore, to overcome these problems, it is necessary to develop novel, convenient and efficient approaches and readily available starting materials for the synthesis of indenones. With this stated objective in the pursuance of our consistent efforts on the development of new synthetic methodologies,<sup>15</sup> the direct alkynylation of the aromatic rings of benzenecarbaldehydes with the corresponding diaryl alkynes in the presence of a catalytic

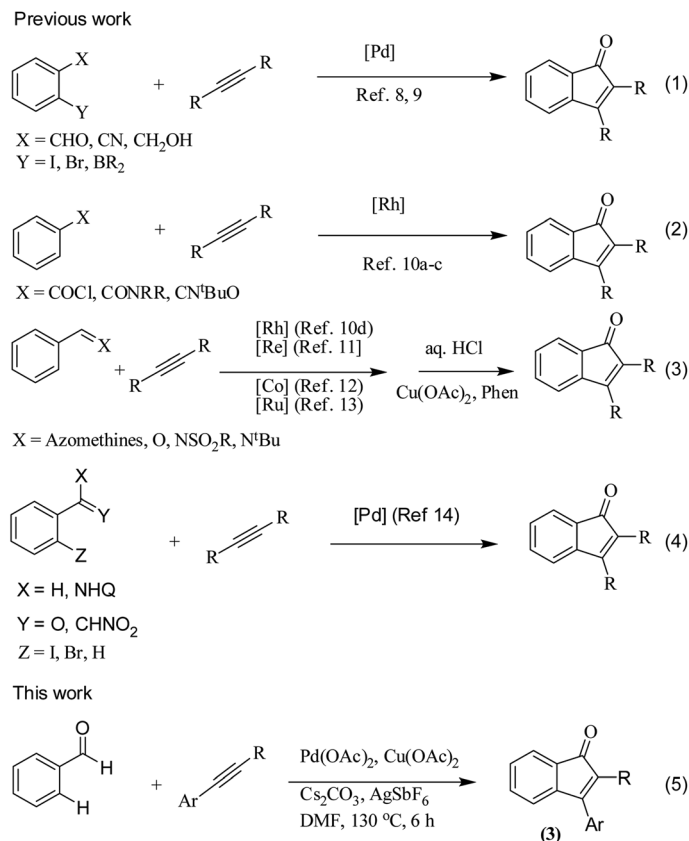
<sup>a</sup>Department of Chemistry, Rajiv Gandhi University of Knowledge Technologies, Basar 504107, India. E-mail: jajulakashanna@yahoo.co.in

<sup>b</sup>Organic Synthesis & Process Chemistry Division, CSIR-Indian Institute of Chemical Technology, Hyderabad 500007, India

<sup>c</sup>Department of Chemistry, GITAM (Deemed to be University), Visakhapatnam 530045, India

† Electronic supplementary information (ESI) available. See DOI: 10.1039/c9ra03921j





Scheme 1 Representative metal-catalyzed synthesis of indenones *via* C–H activation/carbocyclization.

amount of palladium acetate (Scheme 1, eqn (5)) was explored and reported.

## Results and discussion

We focused our studies on the metal-catalyzed direct C–H activation/carbocyclization of inactivated arenes and found that the palladium complexes possessed catalytic activity for the direct C–H activation/carbocyclization of benzenecarbaldehydes with diaryl alkynes. The reaction of the aldehyde (**1a**) with diphenylacetylene (**2a**) in the presence of palladium acetate (10.0 mol%), copper acetate (2.0 equiv.) and cesium carbonate (2.0 equiv.) in DMF (2 mL) at 130 °C for 6 h under a nitrogen atmosphere proceeded to give indenone **3aa**. Magnificently, we obtained 41% yield of the desired product (Table 1, entry 1). The yield of **3aa** improved to 69% when AgSbF<sub>6</sub> was used as the additive. The structure of **3aa** was established on the basis of its <sup>1</sup>H, <sup>13</sup>C NMR and ESI-HRMS results; this structure has been reported in the literature and was obtained by a different route.<sup>16</sup>

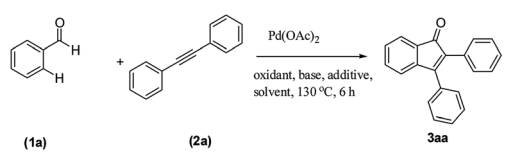
Intrigued by the above optimistic result, the effect of bases, oxidants, additives, solvents and temperatures on the reaction yield was further evaluated and some representative results are shown in Table 1. Various salts including Cu(OAc)<sub>2</sub>, Cu<sub>2</sub>O and CuO were examined; Cu(OAc)<sub>2</sub> was found to be the optimal choice for the carboannulation reaction (Table 1, entries 1 and 4). In the case of Cu<sub>2</sub>O and CuO, the yield was <10% (Table 1, entries 8 and 9). The

Cu(OAc)<sub>2</sub> loading was also evaluated, and the use of 0.5 equiv. of Cu(OAc)<sub>2</sub> led to a significant decrease in the yield (21%, entry 2). The use of Cu(OAc)<sub>2</sub> without Cs<sub>2</sub>CO<sub>3</sub> produced only traces of the product (entry 3). However, the replacement of Cu(OAc)<sub>2</sub> with silver salts such as Ag<sub>2</sub>CO<sub>3</sub>, Ag<sub>2</sub>O, AgOAc and AgF almost resulted in the same yields (entries 11–14). Other bases such as Li<sub>2</sub>CO<sub>3</sub>, Na<sub>2</sub>CO<sub>3</sub>, NaOAc, NaO<sup>t</sup>Bu, Na<sub>3</sub>PO<sub>4</sub>, K<sub>2</sub>CO<sub>3</sub>, KOAc and KO<sup>t</sup>Bu were not suitable for this conversion. A survey of the role of solvents revealed that DMF was the optimal candidate (entries 4–10) as the solvent. To probe the process further, the screening of additives disclosed AgSbF<sub>6</sub> as the most favored one to push the reaction forward, affording the desired product **3aa** in 69% yield (entries 4 and 12). Decreasing the reaction temperature to 100 °C resulted in a lower yield of 49% (entry 15), and no distinct change was detected by raising the reaction temperature (entry 16). When the reaction time was decreased to 3 h, a lower yield of 29% was obtained (entry 17). It may be noted that carboannulation did not proceed in the absence of Pd(OAc)<sub>2</sub> and the use of AgSbF<sub>6</sub> was critical for achieving a high yield.

With the optimized conditions in hand, we further checked for the substrate scope and generality by varying the structures of the alkynes. As shown in Table 2, various valuable indenones can be conveniently and efficiently obtained in moderate to good yields with high regioselectivity by this novel palladium-catalyzed carboannulation reaction, indicating that this method is general and practically useful.



Table 1 Optimization of the reaction conditions



Entry <sup>a</sup>	Oxidant	Additive	Base	Solvent	Yield <sup>b</sup> (%)
1	Cu(OAc) <sub>2</sub>	—	Cs <sub>2</sub> CO <sub>3</sub>	DMF	41
2	Cu(OAc) <sub>2</sub>	—	Cs <sub>2</sub> CO <sub>3</sub>	DMF	21
3	Cu(OAc) <sub>2</sub>	—	—	DMF	Trace
4	Cu(OAc) <sub>2</sub>	AgSbF <sub>6</sub>	Cs <sub>2</sub> CO <sub>3</sub>	DMF	69
5	Cu(OAc) <sub>2</sub>	AgSbF <sub>6</sub>	Cs <sub>2</sub> CO <sub>3</sub>	DCE	32
6	Cu(OAc) <sub>2</sub>	AgSbF <sub>6</sub>	Cs <sub>2</sub> CO <sub>3</sub>	Dioxane	39
7	Cu <sub>2</sub> O	AgSbF <sub>6</sub>	Cs <sub>2</sub> CO <sub>3</sub>	DMF	Trace
8	CuO	AgSbF <sub>6</sub>	Cs <sub>2</sub> CO <sub>3</sub>	DMF	Trace
9	CuI	AgSbF <sub>6</sub>	Cs <sub>2</sub> CO <sub>3</sub>	DMF	Trace
10	Cu(OAc) <sub>2</sub>	AgSbF <sub>6</sub>	Cs <sub>2</sub> CO <sub>3</sub>	Toluene	13
11	Ag <sub>2</sub> CO <sub>3</sub>	—	—	DMF	31
12	Ag <sub>2</sub> CO <sub>3</sub>	AgSbF <sub>6</sub>	Cs <sub>2</sub> CO <sub>3</sub>	DMF	63
13	AgOAc	AgSbF <sub>6</sub>	Cs <sub>2</sub> CO <sub>3</sub>	DMF	56
14	AgF	AgSbF <sub>6</sub>	Cs <sub>2</sub> CO <sub>3</sub>	DMF	48
15	Cu(OAc) <sub>2</sub>	AgSbF <sub>6</sub>	Cs <sub>2</sub> CO <sub>3</sub>	DMF	49
16	Cu(OAc) <sub>2</sub>	AgSbF <sub>6</sub>	Cs <sub>2</sub> CO <sub>3</sub>	DMF	66
17	Cu(OAc) <sub>2</sub>	AgSbF <sub>6</sub>	Cs <sub>2</sub> CO <sub>3</sub>	DMF	29

<sup>a</sup> Reaction conditions: benzaldehyde (**1a**) (0.5 mmol), alkyne (**2a**) (0.6 mmol), Pd(OAc)<sub>2</sub> (0.011 g, 0.05 mmol), oxidant (1 equiv.), additive (20 mol%), base (1 equiv.), solvent (2 mL). <sup>b</sup> Isolated yield after column chromatography.

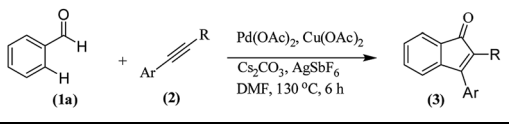
In general, both electron-rich and electron-deficient aromatic diaryl alkynes were suitable for this method, and a wide range of groups such as methyl, fluoro, chloro, methoxy, trifluoromethyl, and hydrogen were tolerated under the reaction conditions (**3aa–3am**). We further checked the generality of both electron-rich and electron-deficient aromatic disubstituted diaryl alkynes. In general, electron-rich disubstituted diaryl alkynes underwent carboannulation smoothly and gave moderate yields, whereas electron-deficient aromatic disubstituted diaryl alkynes were not suitable for this conversion. Unsymmetrical alkynes also underwent carbocyclization smoothly and gave moderate yields with high regioselectivity. Besides the fact that no traces of regioisomers were detected by *in situ* <sup>1</sup>H NMR analysis in all the annulations, the results demonstrated that this novel Pd-catalyzed carboannulation reaction exhibited high regioselectivity.

We further checked for the substrate scope and generality by varying the structures of benzaldehyde, as shown in Table 3. In general, both electron-rich and electron-deficient compounds were used to prepare different indenones following the above method. The electron-withdrawing groups containing benzenecarbaldehydes underwent C–H annulations smoothly and gave good yields, whereas the electron-rich benzenecarbaldehydes gave low yields of indenones and required a comparatively longer time.

## Plausible pathway

On the basis of the current information,<sup>8,17</sup> a plausible mechanism for conversion is shown in Scheme 2. The formation of indenone **3aa** apparently started with the palladation of an

Table 2 Substrate scope of alkynes



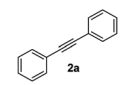
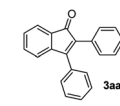
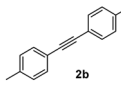
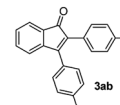
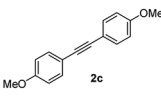
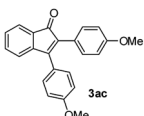
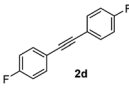
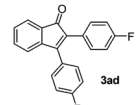
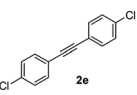
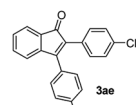
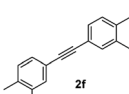
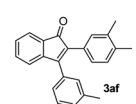
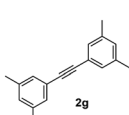
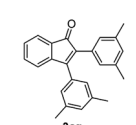
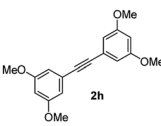
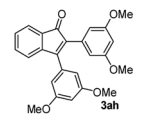
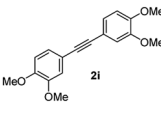
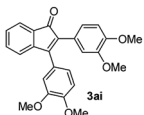
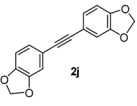
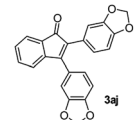
Entry <sup>a</sup>	Alkyne ( <b>2</b> )	Product ( <b>3</b> )	Yield <sup>b</sup> (%)
1			69
2			71
3			73
4			59
5			55
6			77
7			75
8			78
9			75
10			59



Table 2 (Contd.)

Entry <sup>a</sup>	Alkyne (2)	Product (3)	Yield <sup>b</sup> (%)
11			45
12			40

<sup>a</sup> Reaction conditions: benzaldehyde (1) (0.074 g, 0.5 mmol), alkyne (2) (0.6 mmol), Pd(OAc)<sub>2</sub> (0.011 g, 0.05 mmol), Cu(OAc)<sub>2</sub> (0.090 g, 0.5 mmol), Cs<sub>2</sub>CO<sub>3</sub> (0.162 g, 0.5 mmol), AgSbF<sub>6</sub> (0.034 g, 0.1 mmol), DMF (2 mL). <sup>b</sup> Isolated yield after column chromatography.

aromatic aldehyde by Pd(OAc)<sub>2</sub> to yield the palladium complex 4. *Syn*-addition of 4 to the triple bond of diphenylacetylene 2 yielded the palladium species 5. This was followed by intramolecular cyclization, which would lead to 6; it further underwent reductive elimination to yield the indenone 3aa. AgSbF<sub>6</sub> may be speculated to facilitate the removal of an acetate anion by exchange with [SbF<sub>6</sub>]<sup>-</sup>, which could propel the forward reaction. In case of unsymmetrical alkynes, the *syn* addition of complex 4 to alkyne 2 occurred in such a way that the alkyne carbon bearing the bulky group coupled with the complex 4 to give 5 by possibly avoiding steric hindrance when annulating with the carbaldehyde carbon.

Finally, to express the practical applicability of this protocol on a preparative scale, some reactions were carried out on the gram scale (20 mmol) using the following combinations of substrates: 1a with 2a and 1a with 2g. As per our expectations, the reactions proceeded smoothly to afford the target compounds in high yields as obtained in similar reactions on the milligram scale (entries 1 and 7, Table 2), which demonstrated the practical utility of this method.

## Conclusions

In conclusion, we developed one-pot palladium-catalyzed carboannulation between benzaldehyde and internal alkynes for the synthesis of indenones. The reaction involved challenging nucleophilic addition of an organopalladium species to benzaldehyde. With this protocol, generally, high regioselective addition across unsymmetrically substituted alkynes was achievable.

## Experimental procedure

### Materials and method

Solvents were dried according to known methods as appropriate. <sup>1</sup>H, <sup>13</sup>C spectra (<sup>1</sup>H, 400 MHz; <sup>13</sup>C, 100 MHz) were

Table 3 Substrate scope of benzaldehydes

Entry <sup>a</sup>	Benzaldehyde (1)	Product (3)	Yield <sup>b</sup> (%)
1			43
2			49
3			55
4			51
5			55
6			57
7			53

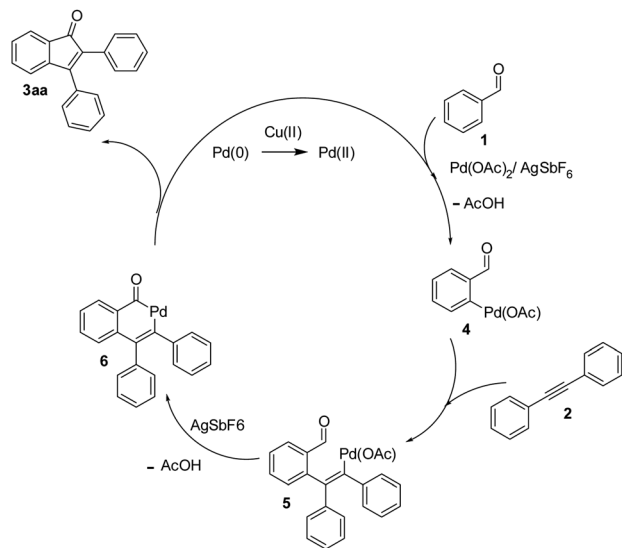
<sup>a</sup> Reaction conditions: benzaldehyde (1) (0.5 mmol), alkyne (2) (0.6 mmol), Pd(OAc)<sub>2</sub> (0.011 g, 0.05 mmol), Cu(OAc)<sub>2</sub> (0.090 g, 0.5 mmol), Cs<sub>2</sub>CO<sub>3</sub> (0.162 g, 0.5 mmol), AgSbF<sub>6</sub> (0.034 g, 0.1 mmol), DMF (2 mL). <sup>b</sup> Isolated yield after column chromatography.

recorded using a 400 MHz spectrometer in CDCl<sub>3</sub> with shifts referenced to SiMe<sub>4</sub> (δ = 0). IR spectra were recorded on an FTIR spectrophotometer. Elemental analyses were carried out on a CHN analyzer. Mass spectra were recorded using LC-MS and HRMS (ESI-TOF analyzer) equipment. Column chromatography was performed on silica gel (250–400 mesh) using ethyl acetate (EtOAc)/hexane mixture.

### General procedure for the synthesis of indenones

Benzaldehyde (0.053 g, 0.5 mmol), Pd(OAc)<sub>2</sub> (0.011 g, 0.05 mmol), Cu(OAc)<sub>2</sub> (0.090 g, 0.5 mmol), AgSbF<sub>6</sub> (0.034 g, 0.1 mmol), Cs<sub>2</sub>CO<sub>3</sub> (0.162 g, 0.5 mmol), DMF (2 mL) and diaryl acetylene (0.6 mmol) were charged into an oven-dried 25 mL round bottomed flask under nitrogen. The mixture was stirred at 130 °C for 6 h. After cooling to room temperature and extracting with EtOAc (3 × 25 mL). The combined ethyl acetate





Scheme 2 A plausible pathway for the formation of **3aa**.

extract was washed with brine (75 mL), dried over anhydrous  $\text{Na}_2\text{SO}_4$  and filtered. The solvent was removed under vacuum and the resulting crude product was purified by silica gel chromatography using hexane/ethyl acetate mixture to afford compounds **3aa–3al**. The details on the yields for all the compounds are presented in Tables 2 and 3

**2,3-Diphenyl-1-indenone (3aa)**. A mixture of benzaldehyde **1a** (0.053 g, 0.5 mmol) and 1,2-diphenylethyne (0.6 mmol) was stirred at 130 °C for 6 h. The residue was purified by flash chromatography over silica gel (hexane/ethyl acetate, 99 : 1) to afford the desired product **3aa** as a red solid. IR (KBr,  $\text{cm}^{-1}$ ) 2911, 1704, 1605, 1447;  $^1\text{H}$  NMR (400 MHz,  $\text{CDCl}_3$ )  $\delta$  7.60 (d,  $J = 5.4$  Hz, 1H), 7.42–7.35 (m, 6H), 7.30–7.21 (m, 6H), 7.17 (d,  $J = 5.4$  Hz, 1H);  $^{13}\text{C}$  NMR (100 MHz,  $\text{CDCl}_3$ )  $\delta$  196.4, 153.3, 145.2, 133.2, 132.7, 132.4, 130.7, 129.9, 129.2, 128.9, 128.7, 128.5, 128.0, 127.7, 122.9, 121.2; (HRMS (ESI) Calcd for  $\text{C}_{21}\text{H}_{15}\text{O}$  [ $\text{M} + \text{H}$ ]:  $m/z$  283.1124. Found: 283.1123).

**2,3-Bis(4-methylphenyl)-1-indenone (3ab)**. A mixture of benzaldehyde **1a** (0.053 g, 0.5 mmol) and 1,2-bis(4-methylphenyl)ethyne (0.6 mmol) was stirred at 130 °C for 6 h. The residue was purified by flash chromatography over silica gel (hexane/ethyl acetate, 99 : 1) to afford the desired product **3ab** as a red solid. IR (KBr,  $\text{cm}^{-1}$ ) 2914, 1703, 1601, 1450;  $^1\text{H}$  NMR (400 MHz,  $\text{CDCl}_3$ )  $\delta$  7.59 (d,  $J = 7.3$  Hz, 1H), 7.39 (td,  $J = 7.3$  and 1.2 Hz, 3H), 7.27–7.15 (m, 5H), 7.09 (d,  $J = 8.4$  Hz, 2H), 2.42 (s, 3H), 2.34 (s, 3H);  $^{13}\text{C}$  NMR (100 MHz,  $\text{CDCl}_3$ )  $\delta$  196.7, 154.7, 145.5, 139.3, 137.5, 133.2, 132.0, 130.9, 129.9, 129.8, 129.4, 128.8, 128.7, 128.4, 127.9, 122.7, 121.1, 21.5, 21.3; (HRMS (ESI) Calcd for  $\text{C}_{23}\text{H}_{19}\text{O}$  [ $\text{M} + \text{H}$ ]:  $m/z$  311.1436. Found: 311.136)

**2,3-Bis(4-methoxyphenyl)-1-indenone (3ac)**. A mixture of benzaldehyde **1a** (0.053 g, 0.5 mmol) and 1,2-bis(4-methoxyphenyl)ethyne (0.6 mmol) was stirred at 130 °C for 6 h. The residue was purified by flash chromatography over silica gel (hexane/ethyl acetate, 99 : 1) to afford the desired product **3ac** as a red solid. IR (KBr,  $\text{cm}^{-1}$ ) 2911, 1701, 1605, 1439;  $^1\text{H}$  NMR (400 MHz,  $\text{CDCl}_3$ )  $\delta$  7.59 (d,  $J = 7.0$  Hz, 1H), 7.39

(d,  $J = 8.1$  Hz, 3H), 7.36–7.29 (m, 3H), 7.22 (d,  $J = 8.1$  Hz, 1H), 6.97 (d,  $J = 8.1$  Hz, 2H), 6.85 (d,  $J = 8.1$  Hz, 2H), 3.88 (s, 3H), 3.82 (s, 3H);  $^{13}\text{C}$  NMR (100 MHz,  $\text{CDCl}_3$ )  $\delta$  197.0, 159.1, 133.2, 131.2, 131.0, 130.2, 128.6, 125.1, 122.7, 120.9, 114.2, 113.6, 55.3, 55.2; (HRMS (ESI) Calcd for  $\text{C}_{23}\text{H}_{19}\text{O}_3$  [ $\text{M} + \text{H}$ ]:  $m/z$  343.1335. Found: 343.1335).

**2,3-Bis(4-fluorophenyl)-1-indenone (3ad)**. A mixture of benzaldehyde **1a** (0.053 g, 0.5 mmol) and 1,2-bis(4-fluorophenyl)ethyne (0.6 mmol) was stirred at 130 °C for 6 h. The residue was purified by flash chromatography over silica gel (hexane/ethyl acetate, 99 : 1) to afford the desired product **3ad** as a red solid. IR (KBr,  $\text{cm}^{-1}$ ) 2989, 1714, 1608, 1440;  $^1\text{H}$  NMR (400 MHz,  $\text{CDCl}_3$ )  $\delta$  7.60 (d,  $J = 7.0$  Hz, 1H), 7.44 (t,  $J = 8.1$  and 1.0 Hz, 3H), 7.41–7.30 (m, 3H), 7.19 (t,  $J = 8.1$  and 1.0 Hz, 3H), 7.15–6.90 (m, 2H);  $^{13}\text{C}$  NMR (100 MHz,  $\text{CDCl}_3$ )  $\delta$  196.2, 164.1, 162.1 (d,  $J_{\text{C-F}} = 244.0$  Hz), 154.1 (d,  $J_{\text{C-F}} = 244.0$  Hz), 144.8 (d,  $J_{\text{C-F}} = 8.0$  Hz), 133.6, 131.7 (d,  $J_{\text{C-F}} = 8.0$  Hz), 131.5, 130.5 (d,  $J_{\text{C-F}} = 8.0$  Hz), 129.2, 128.4, 126.5 (d,  $J_{\text{C-F}} = 8.0$  Hz), 123.4, 121.1, 116.3, 116.1, 115.4, 115.2; (HRMS (ESI) Calcd for  $\text{C}_{21}\text{H}_{12}\text{F}_2\text{O}_2$  [ $\text{M} + \text{H}$ ]:  $m/z$  319.0935. Found: 319.0959).

**2,3-Bis(4-chlorophenyl)-1-indenone (3ae)**. A mixture of benzaldehyde **1a** (0.053 g, 0.5 mmol) and 1,2-bis(4-chlorophenyl)ethyne (0.6 mmol) was stirred at 130 °C for 6 h. The residue was purified by flash chromatography over silica gel (hexane/ethyl acetate, 99 : 1) to afford the desired product **3ae** as a red solid. IR (KBr,  $\text{cm}^{-1}$ ) 2915, 1700, 1605, 1446;  $^1\text{H}$  NMR (400 MHz,  $\text{CDCl}_3$ )  $\delta$  7.59 (d,  $J = 7.0$  Hz, 1H), 7.43–7.36 (m, 3H), 7.34–7.29 (m, 3H), 7.26–7.23 (m, 2H), 7.20–7.18 (m, 2H), 7.11 (d,  $J = 7.0$  Hz, 1H);  $^{13}\text{C}$  NMR (100 MHz,  $\text{CDCl}_3$ )  $\delta$  196.1, 154.3, 144.6, 135.3, 134.1, 133.6, 131.4, 131.3, 130.9, 130.4, 129.9, 129.4, 128.7, 128.4, 123.3, 121.1; (HRMS (ESI) Calcd for  $\text{C}_{21}\text{H}_{12}\text{Cl}_2\text{O}_2$  [ $\text{M} + \text{H}$ ]:  $m/z$  351.0235. Found: 351.0247).

**2,3-Bis(3,4-dimethylphenyl)-1-indenone (3af)**. A mixture of benzaldehyde **1a** (0.053 g, 0.5 mmol) and 1,2-bis(3,4-dimethylphenyl)ethyne (0.6 mmol) was stirred at 130 °C for 6 h. The residue was purified by flash chromatography over silica gel (hexane/ethyl acetate, 99 : 1) to afford the desired product **3af** as a red solid. IR (KBr,  $\text{cm}^{-1}$ ) 2915, 1704, 1600, 1446;  $^1\text{H}$  NMR (400 MHz,  $\text{CDCl}_3$ )  $\delta$  7.56 (d,  $J = 5.0$  Hz, 1H), 7.34 (dt,  $J = 5.6$  and 0.8 Hz, 1H), 7.27 (dt,  $J = 5.7$ , 0.6 Hz, 1H), 7.22 (brs, 1H), 7.16 (brs, 2H), 7.15 (brs, 1H), 7.09 (d,  $J = 5.8$  Hz, 1H), 7.00 (d,  $J = 5.8$  Hz, 1H), 6.95 (d,  $J = 5.8$  Hz, 1H), 2.32 (s, 3H), 2.28 (s, 3H), 2.24 (s, 3H), 2.22 (s, 3H);  $^{13}\text{C}$  NMR (100 MHz,  $\text{CDCl}_3$ )  $\delta$  197.0, 154.8, 145.6, 137.9, 136.8, 136.1<sub>9</sub>, 136.1<sub>1</sub>, 133.2, 132.0, 131.0, 130.9, 130.3, 129.9, 129.3, 129.2, 128.6, 128.4, 127.3, 122.6, 121.1, 19.8, 19.6; (HRMS (ESI) Calcd For  $\text{C}_{25}\text{H}_{22}\text{ONa}$  [ $\text{M} + \text{Na}$ ]:  $m/z$  361.1568. Found: 361.1570).

**2,3-Bis(3,5-dimethylphenyl)-1-indenone (3ag)**. A mixture of benzaldehyde (0.053 g, 0.5 mmol) and 1,2-bis(3,5-dimethylphenyl)ethyne (0.140 g, 0.6 mmol) was stirred at 130 °C for 6 h. The residue was purified by flash chromatography over silica gel (hexane/ethyl acetate, 99 : 1) to afford the desired product **3ag** as a red solid. IR (KBr,  $\text{cm}^{-1}$ ) 2915, 1709, 1600, 1457;  $^1\text{H}$  NMR (400 MHz,  $\text{CDCl}_3$ )  $\delta$  7.58 (d,  $J = 2.6$  Hz, 1H), 7.37 (dt,  $J = 5.9$ , 0.9 Hz, 1H), 7.28 (dt,  $J = 5.8$ , 0.6 Hz, 1H), 7.14 (d,  $J = 5.8$  Hz, 1H), 7.05 (brs, 1H), 7.00 (brs, 2H), 6.91 (brs, 2H), 6.89 (brs, 1H), 2.31 (s, 6H), 2.23 (s, 6H);  $^{13}\text{C}$  NMR (100 MHz,  $\text{CDCl}_3$ )



$\delta$  196.9, 156.4, 145.6, 138.8, 138.1, 137.2, 136.6, 133.3, 132.7, 132.3, 130.8, 130.6, 129.4, 128.7, 127.6, 126.0, 122.7, 121.2, 21.34, 21.32; HRMS (ESI) Calcd for  $C_{25}H_{22}ONa$  [M + Na]:  $m/z$  361.1568. Found: 361.1567.

**2,3-Bis(3,5-dimethoxyphenyl)-1-indenone (3ah).** A mixture of benzaldehyde **1a** (0.053 g, 0.5 mmol) and 1,2-bis(3,5-dimethoxyphenyl)ethyne (0.178 g, 0.6 mmol) was stirred at 130 °C for 6 h. The residue was purified by flash chromatography over silica gel (hexane/ethyl acetate, 95 : 5) to afford the desired product **3ah** as a red solid. IR (KBr,  $cm^{-1}$ ) 2913, 1709, 1594, 1452;  $^1H$  NMR (400 MHz,  $CDCl_3$ )  $\delta$  7.56 (d,  $J = 5.6$  Hz, 1H), 7.37 (dt,  $J = 0.9, 5.9$  Hz, 1H), 7.28 (dt,  $J = 0.6, 5.8$  Hz, 1H), 7.17 (d,  $J = 5.8$  Hz, 1H), 6.52 (d,  $J = 1.8$  Hz, 2H), 6.49 (t,  $J = 1.8$  Hz, 1H), 6.47 (d,  $J = 1.8$  Hz, 2H), 6.36 (t,  $J = 1.8$  Hz, 1H), 3.71 (s, 6H), 3.65 (s, 6H);  $^{13}C$  NMR (100 MHz,  $CDCl_3$ )  $\delta$  196.2, 161.0, 160.2, 155.6, 145.0, 134.5, 133.5, 132.4, 132.2, 130.6, 129.0, 122.9, 121.4, 107.8, 106.3, 101.4, 100.8, 55.4, 55.2; HRMS (ESI) Calcd for  $C_{25}H_{22}O_5Na$  [M + Na]:  $m/z$  425.1365. Found: 425.1362.

**2,3-Bis(3,4-dimethoxyphenyl)-1-indenone (3ai).** A mixture of benzaldehyde **1a** (0.053 g, 0.5 mmol) and 1,2-bis(3,4-dimethoxyphenyl)ethyne (0.178 g, 0.6 mmol) was stirred at 130 °C for 6 h. The residue was purified by flash chromatography over silica gel (hexane/ethyl acetate, 95 : 5) to afford the desired product **3ai** as a red solid. IR (KBr,  $cm^{-1}$ ) 2915, 1693, 1632, 1452;  $^1H$  NMR (400 MHz,  $CDCl_3$ )  $\delta$  7.57 (d,  $J = 5.4$  Hz, 1H), 7.39 (dt,  $J = 6.0, 0.8$  Hz, 1H), 7.29 (dt,  $J = 5.9, 0.6$  Hz, 1H), 7.21 (d,  $J = 5.8$  Hz, 1H), 7.08 (dd,  $J = 6.6, 1.5$  Hz, 1H), 6.95 (d,  $J = 6.7$  Hz, 2H), 6.88 (dd,  $J = 9.9$  Hz and  $J = 1.5$  Hz, 2H), 6.81 (d,  $J = 6.7$  Hz, 1H), 3.95 (s, 3H), 3.88 (s, 3H), 3.73 (s, 3H), 3.70 (s, 3H);  $^{13}C$  NMR (100 MHz,  $CDCl_3$ )  $\delta$  196.8, 153.9, 149.9, 149.1, 148.7, 148.4, 145.3, 133.3, 131.3, 131.0, 128.7, 125.4, 123.6, 123.0, 122.7, 121.6, 120.9, 113.1, 111.9, 111.3, 110.9, 55.9, 55.8, 55.6; HRMS (ESI) Calcd for  $C_{25}H_{22}O_5Na$  [M + Na]:  $m/z$  425.1365. Found: 425.1363.

**2,3-Bis(3,4-dimethoxymethylenephenyl)-1-indenone (3aj).** A mixture of benzaldehyde **1a** (0.053 g, 0.5 mmol) and 1,2-bis(3,4-dimethoxymethylenephenyl)ethyne (0.159 g, 0.6 mmol) was stirred at 130 °C for 6 h. The residue was purified by flash chromatography over silica gel (hexane/ethyl acetate, 99 : 1) to afford the desired product as a red solid. IR (KBr,  $cm^{-1}$ ) 2914, 1699, 1630, 1499;  $^1H$  NMR (400 MHz,  $CDCl_3$ )  $\delta$  7.56 (d,  $J = 7.0$  Hz, 1H), 7.38 (dt,  $J = 7.5, 1.1$  Hz, 1H), 7.28 (dt,  $J = 7.7, 0.9$  Hz, 1H), 7.17 (d,  $J = 7.2$  Hz, 1H), 6.95 (dd,  $J \sim 8.1, J = 1.7$  Hz, 1H), 6.86 (d,  $J = 8.0$  Hz, 1H), 6.84 (dd,  $J \sim 8.4$  Hz and  $J = 1.6$  Hz, 2H), 6.79–6.77 (m, 2H), 6.05 (s, 2H), 5.96 (s, 2H);  $^{13}C$  NMR (100 MHz,  $CDCl_3$ )  $\delta$  196.5, 154.1, 148.5, 148.0, 147.4, 147.3, 145.2, 133.4, 131.6, 130.8, 128.8, 126.4, 124.6, 124.2, 122.9, 121.1, 110.2, 108.9, 108.8, 108.4, 101.4, 101.0; HRMS (ESI) Calcd for  $C_{23}H_{15}O_5$  [M + H]:  $m/z$  371.0919. Found: 371.0917.

**2-Propyl,3-phenyl-1-indenone (3ak).** A mixture of benzaldehyde **1a** (0.053 g, 0.5 mmol) and 1-phenylbutyne (0.6 mmol) was stirred at 130 °C for 6 h. The residue was purified by flash chromatography over silica gel (hexane/ethyl acetate, 99 : 1) to afford the desired product **3ak** as a red solid. IR (KBr,  $cm^{-1}$ ) 2914, 1703, 1615, 1447;  $^1H$  NMR (400 MHz,  $CDCl_3$ )  $\delta$  7.59–7.41 (v(m, 6H), 7.39–7.18 (m, 2H), 7.12 (d,  $J = 7.0$  Hz, 1H), 2.72–2.31 (m, 2H), 1.56–1.48 (m, 2H), 0.90 (t,  $J = 7.0$  and 2.1 Hz, 3H);  $^{13}C$

NMR (100 MHz,  $CDCl_3$ )  $\delta$  198.3, 155.2, 145.9, 135.3, 133.1, 132.9, 130.9, 129.0, 128.1, 122.4, 120.5, 120.5, 25.3, 22.6, 14.2; HRMS (ESI) Calcd for  $C_{17}H_{15}O$  [M + H]:  $m/z$  235.1124. Found: 235.1100.

## Conflicts of interest

There are no conflicts to declare.

## Acknowledgements

We thank UGC-DSK (New Delhi) for the Dr D. S. Kothari fellowship. JK also thank to Prof. K. C. Kumaraswamy for his expert suggestions. RK acknowledges to the DST for the financial support under the early career research award scheme (project no. ECR/2018/000637). We also thank Director CSIR-IICT for the support (IICT/Pubs/2019/352).

## Notes and references

- (a) F. Kakiuchi and S. Murai, *Acc. Chem. Res.*, 2002, **35**(10), 826–834; (b) G. Zeni and R. C. Larock, *Chem. Rev.*, 2006, **106**(11), 4644–4680; (c) C.-H. Jun, E.-A. Jo and J.-W. Park, *Eur. J. Org. Chem.*, 2007, 1869–1881; (d) D. Kalyani and M. S. Sanford, *Top. Organomet. Chem.*, 2007, **24**, 85–116; (e) L. Ackermann, *Top. Organomet. Chem.*, 2007, **24**, 35–60; (f) Y. J. Park, J.-W. Park and C.-H. Jun, *Acc. Chem. Res.*, 2008, **41**(2), 222–234; (g) D. A. Colby, R. G. Bergman and J. A. Ellman, *Chem. Rev.*, 2010, **110**(2), 624–655; (h) T. W. Lyons and M. S. Sanford, *Chem. Rev.*, 2010, **110**(2), 1147–1169; (i) R. Chinchilla and C. Nájera, *Chem. Rev.*, 2014, **114**(3), 1783–1826.
- (a) V. Ritleng, C. Sirlin and M. Pfeffer, *Chem. Rev.*, 2002, **102**(5), 1731–1770; (b) F. Kakiuchi and N. Chatani, *Adv. Synth. Catal.*, 2003, **345**(9–10), 1077–1101; (c) K. Godula and D. Sames, *Science*, 2006, **312**(5770), 67–72; (d) F. Kakiuchi, *Top. Organomet. Chem.*, 2007, **24**, 1–33; (e) T. Satoh and M. Miura, *Top. Organomet. Chem.*, 2007, **24**, 61–84; (f) I. V. Seregin and V. Gevorgyan, *Chem. Soc. Rev.*, 2007, **36**, 1173–1193; (g) D. Alberico, M. E. Scott and M. Lautens, *Chem. Rev.*, 2007, **107**(1), 174–238; (h) J. C. Lewis, R. G. Bergman and J. A. Ellman, *Acc. Chem. Res.*, 2008, **41**(8), 1013–1025; (i) P. Thansandote and M. Lautens, *Chem.–Eur. J.*, 2009, **15**(24), 5874–5883; (j) M. C. Willis, *Chem. Rev.*, 2010, **110**(2), 725–748; (k) T. W. Lyons and M. S. Sanford, *Chem. Rev.*, 2010, **110**(2), 1147–1169; (l) C.-L. Sun, B.-J. Li and Z.-J. Shi, *Chem. Commun.*, 2010, **46**, 677–685; (m) R. Jazzar, J. Hitce, A. Renaudat, J. S. Kreuzer and O. Baudoin, *Chem.–Eur. J.*, 2010, **16**(9), 2654–2672; (n) L. Ackermann, *Chem. Rev.*, 2011, **111**(3), 1315–1345.
- (a) S. Mochida, N. Umeda, K. Hirano, T. Satoh and M. Miura, *Chem. Lett.*, 2010, **39**(7), 744–746; (b) T. K. Hyster and T. Rovis, *J. Am. Chem. Soc.*, 2010, **132**(30), 10565–10569; (c) S. Rakshit, C. Grohmann, T. Besset and F. Glorius, *J. Am. Chem. Soc.*, 2011, **133**(8), 2350–2353; (d) F. W. Patureau, T. Besset and F. Glorius, *Angew. Chem., Int. Ed.*, 2011, **50**(5), 1064–1067; (e) C. Zhu and J. R. Falck, *Chem.*



- Commun.*, 2012, **48**, 1674–1676; (f) F. Wang, G. Song, Z. Du and X. J. Li, *J. Org. Chem.*, 2011, **76**(8), 2926–2932; (g) J. Willwacher, S. Rakshit and F. Glorius, *Org. Biomol. Chem.*, 2011, **9**, 4736–4740.
- 4 (a) Y.-T. Wu, K.-H. Huang, C.-C. Shin and T.-C. Wu, *Chem.-Eur. J.*, 2008, **14**(22), 6697–6703; (b) S. Ding, Z. Shi and N. Jiao, *Org. Lett.*, 2010, **12**(7), 1540–1543; (c) C. Wang, S. Rakshit and F. Glorius, *J. Am. Chem. Soc.*, 2010, **132**(40), 14006–14008; (d) H. Zhong, D. Yang, S. Wang and J. Huang, *Chem. Commun.*, 2012, **48**, 3236–3238; (e) L. Wang, J. Huang, S. Peng, H. Liu, X. Jiang and J. Wang, *Angew. Chem., Int. Ed.*, 2013, **52**(6), 1768–1772; (f) H. Yokoyama, K. Otaya, H. Kobayashi, M. Miyazawa, S. Yamaguchi and H. Hirai, *Org. Lett.*, 2000, **2**(16), 2427–2429; (g) X. Xie, X. Lu, Y. Liu and W. Xu, *J. Org. Chem.*, 2001, **66**(20), 6545–6550; (h) A. L. Bowie and D. Trauner, *J. Org. Chem.*, 2009, **74**(4), 1581–1586; (i) K. Anderson, K. Calo, T. Pfaffeneder, A. J. P. White and A. G. M. Barrett, *Org. Lett.*, 2011, **13**(21), 5748–5750; (j) G. Ji, Y. Duan, S. Zhang and Y. Yang, *Catal. Today*, 2019, **330**(11), 101–108.
- 5 (a) G. M. Anstead, J. L. Ensign, C. S. Peterson and J. A. Katzenellenbogen, *J. Org. Chem.*, 1989, **54**(7), 1485–1491; (b) R. E. McDevitt, M. S. Malamas, E. S. Manas, R. J. Unwalla, Z. B. Xu, C. P. Miller and H. A. Harris, *Bioorg. Med. Chem. Lett.*, 2005, **15**(12), 3137–3142; (c) H. Gao, J. A. Katzenellenbogen, R. Garg and C. Hansch, *Chem. Rev.*, 1999, **99**(3), 723–744; (d) J. H. Ahn, M. S. Shin, S. H. Jung, S. K. Kang, K. R. Kim, S. D. Rhee, W. H. Jung, S. D. Yang, S. J. Kim, J. R. Woo, J. H. Lee, H. G. Cheon and S. S. Kim, *J. Med. Chem.*, 2006, **49**(15), 4781–4784; (e) W. M. Clark, A. M. Tickner-Eldridge, G. Kris Huang, L. N. Pridgen, M. A. Olsen, R. J. Mills, I. Lantos and N. H. Baine, *J. Am. Chem. Soc.*, 1998, **120**(18), 4550–4551; (f) G. P. Jourdan, B. A. Dreikorn, R. E. Hackler, H. R. Hall and W. R. Arnold, in *Synthesis and Chemistry of Agrochemicals II*, ACS Symposium Series, American Chemical Society, Washington, DC, 1991, p. 566; (g) E. F. Ullmann and W. A. J. Henderson, *J. Am. Chem. Soc.*, 1966, **88**(21), 4942–4960; (h) A. Chatterjee and S. Banerjee, *Tetrahedron*, 1970, **26**(11), 2599–2608; (i) H. O. Hose and J. K. Larson, *J. Org. Chem.*, 1968, **33**(1), 448–451; (j) E. N. Alessio, D. G. Tombari, A. F. Ibanez, G. Y. MoltrasioIdesias and J. M. Aguirre, *Can. J. Chem.*, 1991, **69**, 1166–1170; (k) B. VenkatRamulu and G. Satyanarayana, *RSC Adv.*, 2015, **5**, 70972–70976.
- 6 L. S. Liebeskind and M. S. South, *J. Org. Chem.*, 1980, **45**(26), 5426–5429.
- 7 I. R. Butler, *Can. J. Chem.*, 1990, **68**, 1979–1987.
- 8 (a) W. Tao, L. J. Silverberg, A. L. Rheingold and R. F. Heck, *Organometallics*, 1989, **8**(11), 2550–2559; (b) R. C. Larock, Q. Tian and A. A. Pletnev, *J. Am. Chem. Soc.*, 1999, **121**(13), 3238–3239; (c) A. A. Pletnev, Q. Tian and R. C. Larock, *J. Org. Chem.*, 2002, **67**(26), 9276–9287; (d) H. Tsukamoto and Y. Kondo, *Org. Lett.*, 2007, **9**(21), 4227–4230; (e) J. Zhang, F. Yang and Y. Wu, *Appl. Organomet. Chem.*, 2011, **25**(9), 675–679; (f) F. Yang, J. Zhang and Y. Wu, *Tetrahedron*, 2011, **67**(16), 2969–2973; (g) N. Wu, A. Messinis, A. S. Batsanov, Z. Yang, A. Whiting and T. B. Marder, *Chem. Commun.*, 2012, **48**, 9986–9988; (h) X. Chen, Q. He, Y. Xie and C. Yang, *Org. Biomol. Chem.*, 2013, **11**, 2582–2585; (i) R. C. Larock and M. J. Doty, *J. Org. Chem.*, 1993, **58**(17), 4579–4583; (j) M. L. N. Rao and R. J. Dhanorkar, *Tetrahedron*, 2014, **70**(43), 8067–8078; (k) J. Feng, G. Lu, M. Lv and C. Cai, *J. Org. Chem.*, 2014, **79**(21), 10561–10567.
- 9 (a) A. Padwa, K. E. Krumpe, Y. Gareau and U. Chiacchio, *J. Org. Chem.*, 1991, **56**(7), 2523–2530; (b) T. Miura and M. Murakami, *Org. Lett.*, 2005, **7**(15), 3339–3341; (c) Y. Harada, J. Nakanishi, H. Fujihara, M. Tobisu, Y. Fukumoto and N. Chatani, *J. Am. Chem. Soc.*, 2007, **129**(17), 5766–5771; (d) T. Morimoto, K. Yamasaki, A. Hirano, K. Tsutsumi, N. Kagawa, K. Kakiuchi, Y. Harada, Y. Fukumoto, N. Chatani and T. Nishioka, *Org. Lett.*, 2009, **11**(8), 1777–1780.
- 10 (a) K. Kokubo, K. Matsumasa, M. Miura and M. Nomura, *J. Org. Chem.*, 1996, **61**(20), 6941–6946; (b) B. J. Li, H. Y. Wang, Q. L. Zhu and Z. J. Shi, *Angew. Chem., Int. Ed.*, 2012, **51**(16), 3948–3952; (c) Z. Qi, M. Wang and X. Li, *Org. Lett.*, 2013, **15**(21), 5440–5443; (d) Y. Chen, F. Wang, W. Zhen and X. Li, *Adv. Synth. Catal.*, 2013, **355**(2–3), 353–359; (e) S. Chen, J. Yu, Y. Jiang, F. Chen and J. Cheng, *Org. Lett.*, 2013, **15**(18), 4754–4757.
- 11 Y. Kuninobu, T. Matsuki and K. Takai, *Org. Lett.*, 2010, **12**(13), 2948–2950.
- 12 K. Gao and N. Yoshikai, *Chem. Commun.*, 2012, **48**, 4305–4307.
- 13 P. Zhao, F. Wang, K. Han and X. Li, *Org. Lett.*, 2012, **14**(21), 5506–5509.
- 14 (a) J. Kashanna, K. Nagaraju and K. C. Kumara Swamy, *Tetrahedron Lett.*, 2016, **57**(14), 1576–1581; (b) A. Ilies, Y. Arslanoglu, T. Matsubara and E. Nakamura, *Asian J. Org. Chem.*, 2018, **7**(7), 1327–1329; (c) K. Ramesh and G. Satyanarayana, *Eur. J. Org. Chem.*, 2018, 4135–4146; (d) B. Suchand and G. Satyanarayana, *J. Org. Chem.*, 2017, **82**(1), 372–381.
- 15 (a) J. Kashanna, R. A. Kumar, R. Kishore and D. N. Kumar, *Chem. Biodiversity*, 2018, **15**, e1800277; (b) R. A. Kumar, N. Salvanna, B. Das and J. Kashanna, *World Res. J. Appl. Med. Chem.*, 2019, **4**(1), 14–18; (c) A. S. Kumar, R. A. Kumar, E. P. Reddy, V. Satyanarayana, J. Kashanna, B. J. M. Reddy, B. V. Subba Reddy and J. S. Yadav, *Nat. Prod. Commun.*, 2018, **13**(5), 599.
- 16 (a) K. J. Jens and E. Weiss, *Chem. Ber.*, 1984, **117**(7), 2469–2478; (b) W. H. Watson and A. Nagl, *Acta Crystallogr., Sect. C: Cryst. Struct. Commun.*, 1987, **43**, 2444–2445; (c) M. Hussain, N. T. Hung, R. A. Khera, A. Villinger and P. Langer, *Tetrahedron Lett.*, 2011, **52**(2), 184–187.
- 17 H. Ohmiya, Y. Makida, D. Li, M. Tanabe and M. J. Sawamura, *J. Am. Chem. Soc.*, 2010, **132**(2), 879–889.

