


Cite this: *RSC Adv.*, 2023, 13, 9180

Received 19th January 2023  
Accepted 9th March 2023

DOI: 10.1039/d3ra00401e

rsc.li/rsc-advances

# $\alpha$ -Arylsulfonyloxyacrylates: attractive O-centered electrophiles for synthesis of $\alpha$ -substituted acrylates via Pd-catalysed Suzuki reactions†‡

Zhongya Zhang,<sup>a</sup> Li Zhang,<sup>\*d</sup> Ling Huai,<sup>e</sup> Zhentao Wang<sup>\*e</sup> and Yewen Fang<sup>id</sup> <sup>\*abc</sup>

We herein report  $\alpha$ -arylsulfonyloxyacrylates as a kind of useful and attractive O-centered electrophiles for Suzuki cross-coupling reactions. A range of  $\alpha$ -(hetero)aryl substituted acrylates has been prepared *via* the palladium-catalysed C–C cross-coupling reactions between potassium (hetero)aryltrifluoroborates and  $\alpha$ -arylsulfonyloxyacrylates. Moreover,  $\alpha$ -arylsulfonyloxyacrylate could also react with B-alkyl-9-BBN to produce  $\alpha$ -alkyl substituted acrylates. The synthetic application of this new method was demonstrated by the preparation of the intermediate for synthesis of retinoid X receptors-selective retinoids. These Suzuki reaction-based protocols feature broad substrate scope, generality, and mild reaction conditions.

## Introduction

The Suzuki cross-coupling reaction is considered to be one of the most robust methods in modern organic synthesis, providing a rapid and straightforward strategy for constructing C–C bond formation.<sup>1</sup> Taking advantage of the easy availability of coupling partners as well as their stabilities towards air and moisture, the synthetic community would like to choose the Suzuki reaction as their choice for C–C bond formation.<sup>2</sup> Due to the marvelous progress on the supporting ligands<sup>3</sup> and the preparation of organoboron derivatives,<sup>4</sup> protocols based on Suzuki reactions become more reliable and practical. Moreover, the applications of non-noble metal catalysts<sup>5</sup> and the use of continuous-flow reactors for Suzuki reactions meet the requirement of sustainable development of chemistry.<sup>6</sup> Of note, the development of reliable electrophiles has also been the subject of Suzuki cross-coupling reactions.<sup>7</sup> As for the available electrophilic Suzuki coupling partners, the utilization of C–O electrophiles as surrogates for organic halides is especially

attractive due to their flexibility and generality as well as practicality. Compared to the many well-documented methods for synthesis of aromatic halides, the site-specific preparation of alkenyl halides with expected configuration is still a big challenge. Consequently, there has been increasing interest on the Suzuki cross-coupling reactions using enol-based compounds as the coupling electrophiles. Among the many enol-derived electrophiles, alkenyl sulfonates are especially attractive due to their good stability and high reactivity (Fig. 1).<sup>8</sup>

Acrylates and their derivatives are a kind of fundamental monomers and structural motifs. In addition to the wide applications in polymer chemistry,  $\alpha$ -substituted acrylates are useful acceptors for both nucleophiles and nucleophilic radicals.<sup>9</sup> As a result, many efforts have been devoted to their preparation and the further transformations. Among the available strategies, transition-metal-catalysed cross-coupling reactions are undoubtedly indispensable tools. Interestingly, an access to  $\alpha,\beta$ -unsaturated esters has been realized *via* palladium-catalysed reactions using diazo compounds as the coupling partners.<sup>10</sup> Not surprisingly, the Suzuki reaction-based protocols for the preparation of  $\alpha$ -substituted acrylates have

<sup>a</sup>Key Laboratory of Degraded and Unused Land Consolidation Engineering, The Ministry of Land and Resources of China, College of Environmental Science and Engineering, Chang'an University, No. 126 Yanta Road, Xi'an 710054, China

<sup>b</sup>School of Materials and Chemical Engineering, Ningbo University of Technology, No. 201 Fenghua Road, Ningbo 315211, China. E-mail: fang@nbut.edu.cn

<sup>c</sup>Zhejiang Institute of Tianjin University, No. 201 Fenghua Road, Ningbo 315211, China

<sup>d</sup>School of Fundamental Science, Zhejiang Pharmaceutical University, No. 666 Siming Road, Ningbo 315500, China. E-mail: zhangl@zjpu.edu.cn

<sup>e</sup>College of Chemistry and Material Science, Shandong Agricultural University, No. 61 Daizong Road, Tai'an 271018, China. E-mail: wzht423@mail.ustc.edu.cn

† Dedicated to the 40th Anniversary of Ningbo University of Technology.

‡ Electronic supplementary information (ESI) available: Experimental procedures and compound characterisation data. See DOI: <https://doi.org/10.1039/d3ra00401e>

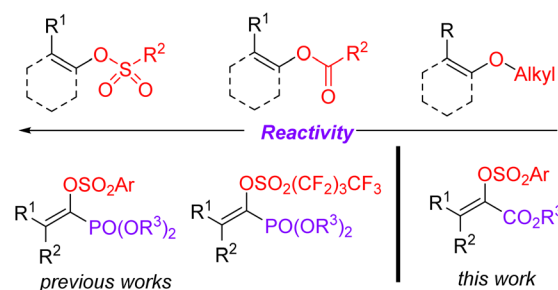
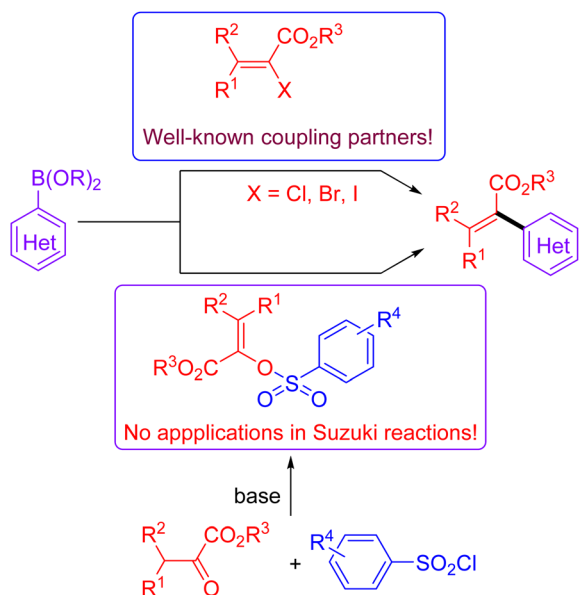


Fig. 1 O-Centered coupling electrophiles.





Scheme 1 Suzuki reactions for synthesis of  $\alpha$ -(hetero)aryl substituted acrylates.

been extensively investigated.<sup>11</sup> In contrast to the applications of  $\alpha$ -halo acrylates in Suzuki reactions, there is still no available reports dealing with the preparation of  $\alpha$ -substituted acrylates using *O*-centered coupling electrophiles (Scheme 1). Inspired by our recent works on the Suzuki cross-coupling reactions using  $\alpha$ -phosphonovinyl arylsulfonates as the electrophilic coupling partners (Fig. 1),<sup>12</sup> we wonder that  $\alpha$ -arylsulfonyloxyacrylates could serve as the *O*-centered electrophile candidate. According to the available reports,  $\alpha$ -arylsulfonyloxyacrylates could be easily prepared from inexpensive aryl sulfonyl chloride with pyruvate derivatives in presence of base. Moreover, in addition to environmentally benign character, the  $\alpha$ -arylsulfonyloxyacrylates would be more stable than  $\alpha$ -haloacrylates coupling partners. We herein report a new protocol for synthesis of  $\alpha$ -(hetero)aryl acrylates *via* the Suzuki reactions between arylsulfonyloxyacrylates and potassium (hetero)aryltrifluoroborates enabled by palladium catalysis.<sup>13</sup> Moreover,  $\alpha$ -alkyl acrylates were also prepared *via* the palladium catalysed C–C cross-coupling reactions of  $\alpha$ -arylsulfonyloxyacrylates with B-alkyl-9-BBN.<sup>14</sup>

## Results and discussion

We began our studies by investigating the Suzuki coupling reaction of potassium phenyltrifluoroborate **2a** with **1a** derived from ethyl pyruvate and 4-fluorobenzenesulfonyl chloride. As outlined in Table 1, a simple survey of experimental parameters led us to identify the optimal reaction conditions (5 mol% Pd(OAc)<sub>2</sub>, 10 mol% SPhos, 1.5 equiv. of K<sub>3</sub>PO<sub>4</sub>, 3 : 1 mixed CH<sub>3</sub>Ph/H<sub>2</sub>O, 60 °C, 24 h) (entry 1).<sup>15</sup> Other Buchwald-type ligands were screened and no better result was observed (entries 2–4). The combination of Pd(OAc)<sub>2</sub> and *rac*-BINAP did not lead to the expected product formation (entry 5). With

Table 1 Reaction optimization<sup>a,b</sup>

Entry	Deviation from standard conditions	Yield of <b>3a</b> (%)
1	None	73
2	RuPhos instead of SPhos	49
3	XPhos instead of SPhos	67
4	BrettPhos instead of SPhos	27
5 <sup>c</sup>	<i>rac</i> -BINAP instead of SPhos	0
6 <sup>c,d</sup>	Cy <sub>3</sub> PH·BF <sub>4</sub> instead of SPhos	36 (12)
7 <sup>c,d</sup>	<i>t</i> -Bu <sub>3</sub> PH·BF <sub>4</sub> instead of SPhos	37 (28)
8 <sup>c,d</sup>	Cs <sub>2</sub> CO <sub>3</sub> instead of K <sub>3</sub> PO <sub>4</sub>	52 (7)
9 <sup>c,d</sup>	K <sub>2</sub> CO <sub>3</sub> instead of K <sub>3</sub> PO <sub>4</sub>	52 (9)
10	<i>t</i> -BuOK instead of K <sub>3</sub> PO <sub>4</sub>	52
11	PdCl <sub>2</sub> instead of Pd(OAc) <sub>2</sub>	62
12	Pd <sub>2</sub> (dba) <sub>3</sub> instead of Pd(OAc) <sub>2</sub>	45
13	<b>1b</b> instead of <b>1a</b>	37
14 <sup>c</sup>	<b>1c</b> instead of <b>1a</b>	0
15 <sup>c,d</sup>	PhB(OH) <sub>2</sub> instead of <b>2a</b>	40 (20)
16 <sup>c,d</sup>	PhBpin instead of <b>2a</b>	31(16)
17	Without base	49
18 <sup>c</sup>	Without ligand	0
19 <sup>c</sup>	Without catalyst	0

<sup>a</sup> Standard reaction conditions: a reaction mixture of **1a** (0.2 mmol), **2a** (0.26 mmol), Pd(OAc)<sub>2</sub> (5 mol%), SPhos (10 mol%), K<sub>3</sub>PO<sub>4</sub> (0.3 mmol), and CH<sub>3</sub>Ph/H<sub>2</sub>O (3.0 mL/1.0 mL) was stirred at 60 °C for 24 h. <sup>b</sup> Yield of the isolated product **3a**. <sup>c</sup> NMR yield (500 MHz) was reported by use of *p*-nitroacetophenone as an internal standard. <sup>d</sup> NMR yields of the **3aa** were reported in the brackets.

tricyclohexylphosphine as the supporting ligand, a mixture of **3a** and **3aa** was observed (entry 6). Possibly, the side product **3aa** would be formed when the  $\beta$ -hydride elimination pathway took place ahead of transmetalation process.<sup>16</sup> Again, we found that a mixture of **3a** and **3aa** was achieved using Pd(OAc)<sub>2</sub>, *t*-Bu<sub>3</sub>PH·BF<sub>4</sub>, and K<sub>3</sub>PO<sub>4</sub> (entry 7). Other inorganic bases such as Cs<sub>2</sub>CO<sub>3</sub>, K<sub>2</sub>CO<sub>3</sub>, and *t*-BuOK gave inferior results (entries 8–10). Moreover, no better results were observed using other palladium catalysts (entries 11 and 12). As for the electrophiles,  $\alpha$ -tosyloxyacrylate **1b** could serve as the alternative, albeit in low yield (entry 13). However, no desired product could be observed using  $\alpha$ -ethylsulfonyloxyacrylate **1c** as the coupling partner (entry 14). With phenylboronic acid instead of **2a** as the nucleophilic coupling partner, the desired product **3a** was contaminated by the formation of **3aa** (entry 15). Similar result was achieved using phenylboronic acid pinacol ester as the coupling



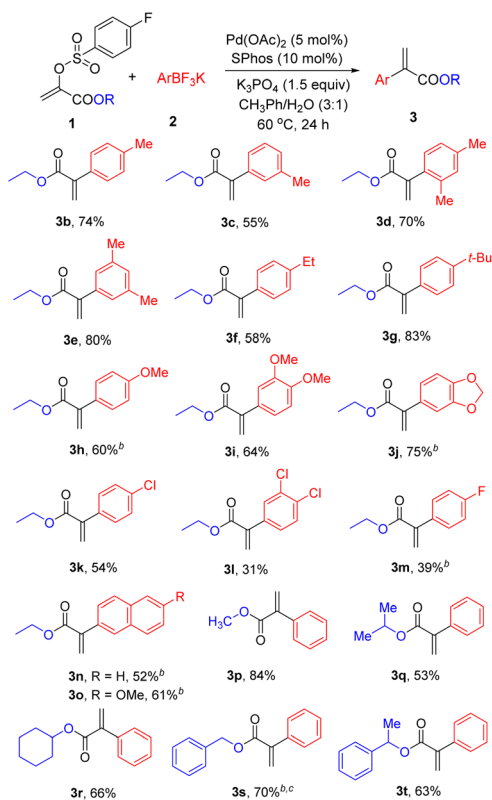
partner (entry 16). In the absence of base, treatment of **1a** with **2a** under the palladium catalysed reaction conditions gave **3a** in 49% yield (entry 17). Control experiments confirmed that both ligand and catalyst were required for this transformation (entries 18 and 19).

After the optimal reaction conditions were established for this Pd-catalysed Suzuki reactions, the scope of aryl trifluoroborates and  $\alpha$ -arylsulfonyloxyacrylates was initially tested (Table 2). A range of potassium aryltrifluoroborate was firstly investigated. Generally, both electron-rich and electron-deficient aryl trifluoroborates proved viable coupling partners, giving **3b–3o** in 31–83% yields. Notably, steric variance on the phenyl ring did not lead to an obvious influence on the reaction efficiency. The aryl trifluoroborates having *para*- (**3b**), *meta*- (**3c**, **3e**), or *ortho*- (**3d**) substituents were all eligible to forge the desired ethyl  $\alpha$ -aryl acrylates. Pleasingly, the cross-coupling reactions of substituted aryl trifluoroborates (-ethyl, -*tert*-butyl, and -methoxyl) worked well to give the desired products **3f–3j** in 58–83% yields. Noticeably, chloro substituent is well tolerated in this reaction conditions (**3k** and **3l**), which is advantageous for the further decoration. Likewise, potassium 4-fluorophenyltrifluoroborate could be coupled with **1a** using this new protocol, obtaining **3m** in moderate yield. Moreover, aryl trifluoroborates bearing a naphthalene ring can be transformed to the corresponding

products **3n** and **3o** in 52% and 61% yields, respectively. After the evaluation of scope of aryl trifluoroborates, various alkyl  $\alpha$ -phenylacrylates were prepared under the standard cross-coupling reaction conditions. In addition to efficient access to methyl and iso-propyl  $\alpha$ -phenylacrylates (**3p**, **3q**), cyclohexyl  $\alpha$ -phenylacrylate (**3r**) could be nicely prepared in 66% yield. Additionally, benzyl  $\alpha$ -phenylacrylates (**3s**, **3t**) were also successfully prepared in efficient manner.

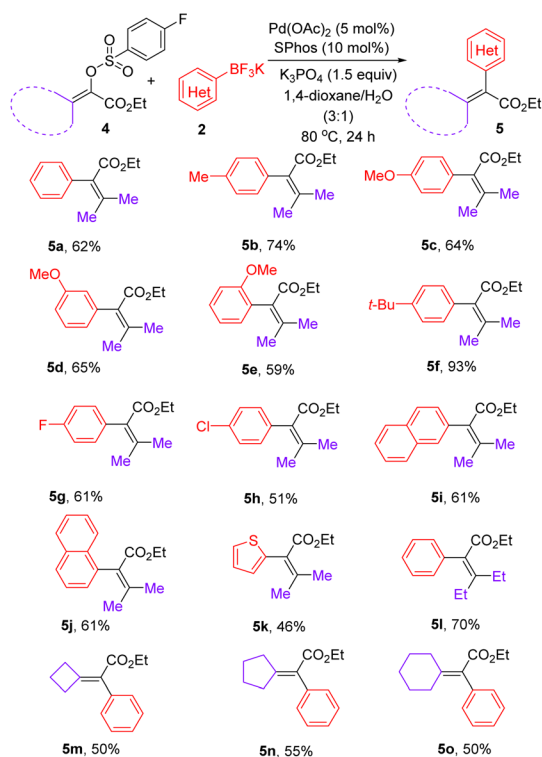
After realizing the synthesis of  $\alpha$ -aryl acrylates, we set out to prepare tetrasubstituted  $\alpha,\beta$ -unsaturated esters under the above optimized catalyst system. As shown in Table 3, a range of  $\beta,\beta$ -disubstituted- $\alpha$ -aryl acrylates could be synthesized *via* the reactions between  $\beta,\beta$ -disubstituted- $\alpha$ -arylsulfonyloxyacrylates and aryl trifluoroborates enabled by palladium catalysis. Due to the possible steric effect, increasing the reaction temperature to 80 °C was required for preparation of tetrasubstituted olefins using mixed 1,4-dioxane/H<sub>2</sub>O as the solvent. Notably, aryl trifluoroborates bearing a methoxyl group at *ortho*-, *meta*-, or *para*-positions on the phenyl ring, were well-tolerated, giving the corresponding products **5c–5e** in 59–65% yields. In addition to aryl trifluoroborates bearing electron-neutral and electron-donating substituents, fluoro and chloro substituents were well both accommodated, furnishing the expected products **5g** and **5h** in 61% and 51% yields, respectively. In addition to the smooth reaction of potassium (2-naphthalene)trifluoroborate

Table 2 Arylations of  $\alpha$ -arylsulfonyloxyacrylates **1**<sup>a</sup>



<sup>a</sup> Reaction conditions: see entry 1, Table 1. Isolated yields. <sup>b</sup> A mixture of 1,4-dioxane/H<sub>2</sub>O (3.0 mL/1.0 mL) was used. <sup>c</sup> The reaction temperature was 80 °C.

Table 3 Synthesis of tetrasubstituted olefins **5**<sup>a</sup>



<sup>a</sup> Reaction conditions: a reaction mixture of **4** (0.2 mmol), **2** (0.3 mmol), Pd(OAc)<sub>2</sub> (5 mol%), SPhos (10 mol%), K<sub>3</sub>PO<sub>4</sub> (0.3 mmol), and 1,4-dioxane/H<sub>2</sub>O (3.0 mL/1.0 mL) was stirred at 80 °C for 24 h.



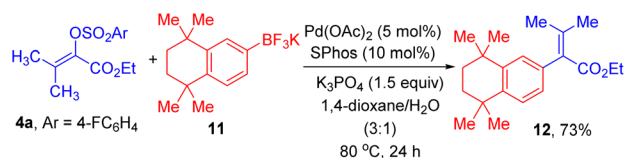
with **4a**, a sterically demanding potassium (1-naphthalene)tri-fluoroborate was compatible in this reaction, furnishing **5j** in 61% yield. Gratifyingly, potassium 2-thienyltrifluoroborate could undergo coupling reaction with **4a** to afford **5k** in 46% yield. After the successful synthesis of various ethyl 3-methyl-2-aryl-2-butenates **5a–5k**,  $\beta,\beta$ -diethyl substituted  $\alpha$ -phenyl acrylate **5l** could be expectedly prepared in 70% yield. To our delight, a range of exocyclic olefins **5m–5o** could be obtained in 50–55% yields.

Next, the stereoselective cross-coupling of  $\alpha$ -arylsulfonyloxyacrylate **6** with potassium phenyltrifluoroborate **2a** was briefly investigated. As shown in Scheme 2, full conversion could be achieved and no trace of the alkene geometry erosion was observed, producing (*E*)-ethyl 2-phenyl-2-butenate **7** in 81% yield. The results listed in Tables 2, 3 and Scheme 2 nicely demonstrated the generality of (hetero)arylation of arylsulfonyloxyacrylates.

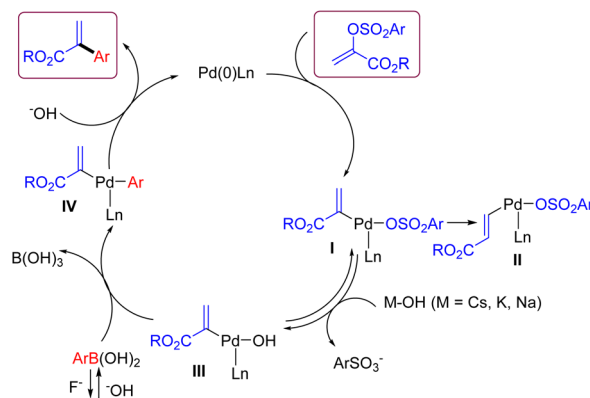
As an extension, the B-alkyl Suzuki cross coupling reactions have been demonstrated with  $\alpha$ -arylsulfonyloxyacrylates as the electrophilic coupling partners. As shown in Scheme 3,<sup>15e</sup> the hydroboration of styrene **8** with 9-BBN (THF, rt) afforded the corresponding B-phenylethyl-9-BBN, which was *in situ* treated with  $\text{Cs}_2\text{CO}_3$  and **1a** in the presence of  $\text{Pd}(\text{OAc})_2$  and SPhos in THF at 50 °C for 24 hours, producing the desired cross-coupled product **9** in 86% yield. Likewise, tetrasubstituted alkene **10** could be prepared in 90% yield *via* the reactions of B-phenylethyl-9-BBN with **4a**.

Lastly, a demonstration of the synthetic value of this method is given by the preparation of **12**, which is an important intermediate for synthesis of retinoid X receptors-selective retinoids.<sup>17</sup> As displayed in Scheme 4, efficient C–C cross-coupling reaction for formation of **12** could take place between **4a** and aryl trifluoroborate **11** under the standard reaction conditions.

According to the literature reports and our results,<sup>18</sup> a plausible reaction mechanism for this Suzuki cross-coupling reaction between  $\alpha$ -arylsulfonyloxyacrylate and aryl trifluoroborate is depicted in Scheme 5. The oxidative addition of  $\alpha$ -



Scheme 4 Synthetic demonstration.



Scheme 5 Proposed mechanistic pathway.

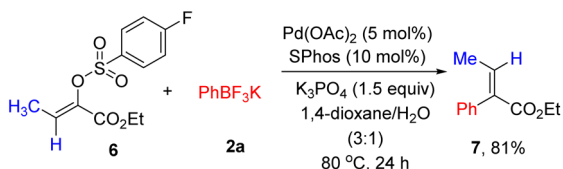
arylsulfonyloxyacrylate onto a ligated  $\text{Pd}(0)$  species generates arylpalladium(II) complex **I**. At this stage, a side intermediate **II** for the formation of alkyl cinnamate would be formed *via* a competitive pathway involving  $\beta$ -H elimination of **I** followed by reinsertion of  $\text{Pd-H}$  species.<sup>16</sup> As for the expected pathway, the more reactive organopalladium hydroxide **III** is formed from the **I** *via* the displacement of arylsulfonyloxy ion with  $\text{HO}^-$  anion. Then transmetalation with arylboronic acid takes place to give intermediate **IV**. Finally, reductive elimination of **IV** affords the coupling product and regenerates the  $\text{Pd}(0)$  species with the aid of base.

## Conclusions

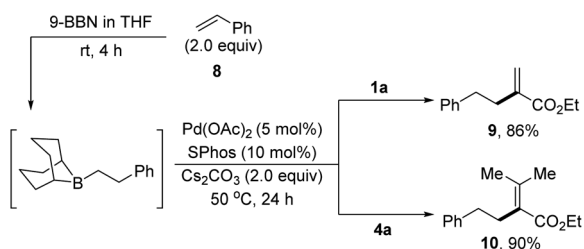
In summary, we have reported  $\alpha$ -arylsulfonyloxyacrylates as the useful *O*-centered electrophiles for the  $\text{Pd}$ -catalysed Suzuki cross-coupling reactions. Using functionalized potassium (hetero)aryltrifluoroborates as the nucleophilic coupling partners, a list of  $\alpha$ -(hetero)aryl substituted acrylates could be modularly prepared *via* the C–C cross-coupling reactions. Moreover,  $\alpha$ -alkyl substituted acrylates could be also efficiently accessed *via* palladium-catalyzed reactions of  $\alpha$ -arylsulfonyloxyacrylate with B-alkyl-9-BBN. We anticipate that these new developed  $\alpha$ -arylsulfonyloxyacrylates could find more application for the synthesis of functionalized  $\alpha,\beta$ -unsaturated esters *via* various C–C cross-coupling reactions enabled by transition-metal catalysis and beyond.

## Author contributions

YF, LZ, and ZW conceived the idea and designed the research. ZZ and LH performed the research. ZZ, LH, and YF analyzed the



Scheme 2 Stereoselective cross-coupling reaction.



Scheme 3 B-alkyl Suzuki cross-coupling reactions.





data. YF and ZZ wrote the original manuscript. YF and LZ reviewed the manuscript and suggested improvements.

## Conflicts of interest

There are no conflicts to declare.

## Acknowledgements

This work was supported by the National Natural Science Foundation of China (No. 22271168 and 21801190), the Natural Science Foundation of Ningbo (No. 2021J140), the Science and Technology Innovation 2025 Major Project of Ningbo (No. 2019B10112), and the Scientific Research Fund of Zhejiang Provincial Education Department (No. Y202147855).

## Notes and references

- (a) N. Miyaura, K. Yamada and A. Suzuki, A new stereospecific cross-coupling by the palladium-catalyzed reaction of 1-alkenylboranes with 1-alkenyl or 1-alkynyl halides, *Tetrahedron Lett.*, 1979, **20**, 3437–3440; (b) N. Miyaura and A. Suzuki, Stereoselective Synthesis of Arylated (*E*)-Alkenes by the Reaction of Alk-1-enylboranes with Aryl Halides in the Presence of Palladium Catalyst, *J. Chem. Soc., Chem. Commun.*, 1979, 866–867; (c) N. Miyaura and A. Suzuki, Palladium-Catalyzed Cross-Coupling Reactions of Organoboron Compounds, *Chem. Rev.*, 1995, **95**, 2457–2483.
- (a) C. C. Johansson Seechurn, M. O. Kitching, T. J. Colacot and V. Snieckus, Palladium-Catalyzed Cross-Coupling: A Historical Contextual Perspective to the 2010 Nobel Prize, *Angew. Chem., Int. Ed.*, 2012, **51**, 5062–5086; (b) K. C. Nicolaou, P. G. Bulger and D. Sarlah, Palladium-Catalyzed Cross-Coupling Reactions in Total Synthesis, *Angew. Chem., Int. Ed.*, 2005, **44**, 4442–4489; (c) A. J. J. Lennox and G. C. Lloyd-Jones, Selection of boron reagents for Suzuki–Miyaura coupling, *Chem. Soc. Rev.*, 2014, **43**, 412–443.
- (a) R. Martin and S. L. Buchwald, Palladium-Catalyzed Suzuki–Miyaura Cross-Coupling Reactions Employing Dialkylbiaryl Phosphine Ligands, *Acc. Chem. Res.*, 2008, **41**, 1461–1473; (b) N. Marion and S. P. Nolan, Well-Defined N-Heterocyclic Carbenes–Palladium(II) Precatalysts for Cross-Coupling Reactions, *Acc. Chem. Res.*, 2008, **41**, 1440–1449.
- (a) F. W. Friese and A. Studer, New avenues for C–B bond formation via radical intermediates, *Chem. Sci.*, 2019, **10**, 8503–8518; (b) E. C. Neeve, S. J. Geier, I. A. I. Mkhalid, S. A. Westcott and T. B. Marder, Diboron(4) Compounds: From Structural Curiosity to Synthetic Workhorse, *Chem. Rev.*, 2016, **116**, 9091–9161; (c) J. Li, A. S. Grillo and M. D. Burke, From Synthesis to Function via Iterative Assembly of *N*-Methyliminodiacetic Acid Boronate Building Blocks, *Acc. Chem. Res.*, 2015, **48**, 2297–2307; (d) I. A. I. Mkhalid, J. H. Barnard, T. B. Marder, J. M. Murphy and J. F. Hartwig, C–H Activation for the Construction of C–B Bonds, *Chem. Rev.*, 2010, **110**, 890–931; (e) D. M. Volochnyuk, A. O. Gorlova and O. O. Grygorenko, Saturated Boronic Acids, Boronates, and Trifluoroborates: An Update on Their Synthetic and Medicinal Chemistry, *Chem.–Eur. J.*, 2021, **27**, 15277–15326; (f) D. G. Hall, *Boronic acids. Preparation and applications in organic synthesis, medicine and materials*, WILEY-VCH, Weinheim, 2nd edn, 2011.
- T. Mesganaw and N. K. Garg, Ni- and Fe-Catalyzed Cross-Coupling Reactions of Phenol Derivatives, *Org. Process Res. Dev.*, 2013, **17**, 29–39.
- (a) T. Noël, S. Kuhn, A. J. Musacchio, K. F. Jensen and S. L. Buchwald, Suzuki–Miyaura Cross-Coupling Reactions in Flow: Multistep Synthesis Enabled by a Microfluidic Extraction, *Angew. Chem., Int. Ed.*, 2011, **50**, 5943–5946; (b) A. Fihri, M. Bouhrara, B. Nekoueishahraki, J.-M. Bassett and V. Polshettiwar, Nanocatalysts for Suzuki cross-coupling reactions, *Chem. Soc. Rev.*, 2011, **40**, 5181–5203.
- (a) D.-G. Yu, B.-J. Li and Z.-J. Shi, Exploration of New C–O Electrophiles in Cross-Coupling Reactions, *Acc. Chem. Res.*, 2010, **43**, 1486–1495; (b) C. M. So and F. Y. Kwong, Palladium-catalyzed cross-coupling reactions of aryl mesylates, *Chem. Soc. Rev.*, 2011, **40**, 4963–4972; (c) J. Cornella, C. Zarate and R. Martin, Metal-catalyzed activation of ethers via C–O bond cleavage: a new strategy for molecular diversity, *Chem. Soc. Rev.*, 2014, **43**, 8081–8097; (d) B. M. Rosen, K. W. Quasdorf, D. A. Wilson, N. Zhang, A.-M. Resmerita, N. K. Garg and V. Percec, Nickel-Catalyzed Cross-Couplings Involving Carbon–Oxygen Bonds, *Chem. Rev.*, 2011, **111**, 1346–1416; (e) J. Yamaguchi, K. Muto and K. Itami, Recent Progress in Nickel-Catalyzed Biaryl Coupling, *Eur. J. Org. Chem.*, 2013, 19–30.
- B.-J. Li, D.-G. Yu, C.-L. Sun and Z.-J. Shi, Activation of “Inert” Alkenyl/Aryl C–O Bond and Its Application in Cross-Coupling Reactions, *Chem.–Eur. J.*, 2011, **17**, 1728–1759.
- (a) T. Guo, L. Zhang, Y. Fang, X. Jin, Y. Li, R. Li, X. Li, W. Cen, X. Liu and Z. Tian, Visible-Light-Promoted Decarboxylative Giese Reactions of  $\alpha$ -Aryl Ethenylphosphonates and the Application in the Synthesis of Fosmidomycin Analogue, *Adv. Synth. Catal.*, 2018, **360**, 1352–1357; (b) T. Guo, L. Zhang, X. Liu, Y. Fang, X. Jin, Y. Yang, Y. Li, B. Chen and M. Ouyang, Visible-Light-Promoted Redox-Neutral Cyclopropanation Reactions of  $\alpha$ -Substituted Vinylphosphonates and Other Michael Acceptors with Chloromethyl Silicate as Methylene Transfer Reagent, *Adv. Synth. Catal.*, 2018, **360**, 4459–4463; (c) W. Luo, Y. Yang, Y. Fang, X. Zhang, X. Jin, G. Zhao, L. Zhang, Y. Li, W. Zhou, T. Xia and B. Chen, Photoredox-Catalyzed Cyclopropanation of 1,1-Disubstituted Alkenes via Radical-Polar Crossover Process, *Adv. Synth. Catal.*, 2019, **361**, 4215–4221; (d) W. Luo, Y. Fang, L. Zhang, T. Xu, Y. Liu, Y. Li, X. Jin, J. Bao, X. Wu and Z. Zhang, Bromomethyl Silicate: A Robust Methylene Transfer Reagent for Radical-Polar Crossover Cyclopropanation of Alkenes, *Eur. J. Org. Chem.*, 2020, 1778–1781; (e) L. Zhang, Y. Fang, X. Jin, T. Guo, R. Li, Y. Li, X. Li, Y. Yang, M. Yuan and Z. Tian, Efficient synthesis of  $\alpha$ -substituted ethylphosphonates via



- CuH-catalyzed conjugate reduction of terminal alkenylphosphonate, *Tetrahedron Lett.*, 2017, **58**, 4538–4541.
- 10 (a) J. Barluenga, P. Moriel, C. Valdés and F. Aznar, *N*-Tosylhydrazones as Reagents for Cross-Coupling Reactions: A Route to Polysubstituted Olefins, *Angew. Chem., Int. Ed.*, 2007, **46**, 5587–5590; (b) J. Barluenga, M. Tomás-Gamasa, F. Aznar and C. Valdés, Synthesis of 2-Arylacrylates from Pyruvate by Tosylhydrazide-Promoted Pd-Catalyzed Coupling with Aryl Halides, *Chem.-Eur. J.*, 2010, **16**, 12801–12803; (c) C. Peng, Y. Wang and J. Wang, Palladium-Catalyzed Cross-Coupling of  $\alpha$ -Diazocarbonyl Compounds with Arylboronic Acids, *J. Am. Chem. Soc.*, 2008, **130**, 1566–1567; (d) C. Peng, G. Yan, Y. Wang, Y. Jiang, Y. Zhang and J. Wang, Palladium-Catalyzed Coupling Reaction of  $\alpha$ -Diazocarbonyl Compounds with Aromatic Boronic Acids or Halides, *Synthesis*, 2010, 4154–4168; (e) L. Zhou, Y. Liu, Y. Zhang and J. Wang, Pd-catalyzed coupling of  $\beta$ -hydroxy  $\alpha$ -diazocarbonyl compounds with aryl iodides: a migratory insertion/ $\beta$ -hydroxy elimination sequence, *Chem. Commun.*, 2011, **47**, 3622–3624; (f) R. J. Sullivan, G. P. R. Freure and S. G. Newman, Overcoming Scope Limitations in Cross-Coupling of Diazo Nucleophiles by Manipulating Catalyst Speciation and Using Flow Diazo Generation, *ACS Catal.*, 2019, **9**, 5623–5630.
  - 11 (a) F. Berthiol, H. Doucet and M. Santelli, Suzuki Coupling of 2-Chloroacrylonitrile, Methyl 2-Chloroacrylate, or 2-Chloroprop1-en-3-ol with Arylboronic Acids Catalyzed by a Palladium-Tetraphosphine Complex, *Synth. Commun.*, 2006, **36**, 3019–3027; (b) F. Berthiol, H. Doucet and M. Santelli, Synthesis of Polysubstituted Alkenes by Heck Vinylation or Suzuki Cross-Coupling Reactions in the Presence of a Tetraphosphane-Palladium Catalyst, *Eur. J. Org. Chem.*, 2003, 1091–1096.
  - 12 (a) Y. Fang, L. Zhang, J. Li, X. Jin, M. Yuan, R. Li, R. Wu and J. Fang, Applications of  $\alpha$ -Phosphonovinyl Tosylates in the Synthesis of  $\alpha$ -Arylethenylphosphonates via Suzuki-Miyaura Cross-Coupling Reactions, *Org. Lett.*, 2015, **17**, 798–801; (b) M. Yuan, Y. Fang, L. Zhang, X. Jin, M. Tao, Q. Ye, R. Li, J. Li, H. Zheng and J. Gu, Pd-Catalyzed Synthesis of  $\alpha$ -Aryl Vinylphosphonates via Suzuki Arylation of  $\alpha$ -Phosphonovinyl Nonaflates, *Chin. J. Chem.*, 2015, **33**, 1119–1123; (c) Y. Fang, L. Zhang, X. Jin, J. Li, M. Yuan, R. Li, T. Wang, T. Wang, H. Hu and J. Gu,  $\alpha$ -Phosphonovinyl Arylsulfonates: An Attractive Partner for the Synthesis of  $\alpha$ -Substituted Vinylphosphonates through Palladium-Catalyzed Suzuki Reactions, *Eur. J. Org. Chem.*, 2016, 1577–1587; (d) L. Zhang, Y. Fang, X. Jin, T. Guo, R. Li, Y. Li, X. Li, Q. Ye and X. Luo, Palladium-catalysed coupling of  $\alpha$ -halo vinylphosphonate and  $\alpha$ -phosphonovinyl sulfonate with alkylzincs: straightforward and versatile synthesis of  $\alpha$ -alkyl vinylphosphonates, *Org. Chem. Front.*, 2018, **5**, 1457–1461.
  - 13 (a) G. A. Molander, Organotrifluoroborates: Another Branch of the Mighty Oak, *J. Org. Chem.*, 2015, **80**, 7837–7848; (b) G. A. Molander and N. Ellis, Organotrifluoroborates: Protected Boronic Acids That Expand the Versatility of the Suzuki Coupling Reaction, *Acc. Chem. Res.*, 2007, **40**, 275–286; (c) S. Darses and J.-P. Genet, Potassium Organotrifluoroborates: New Perspectives in Organic Synthesis, *Chem. Rev.*, 2008, **108**, 288–325.
  - 14 (a) G. Seidel and A. Fürstner, Suzuki reactions of extended scope: the '9-MeO-9-BBN variant' as a complementary format for cross-coupling, *Chem. Commun.*, 2012, **48**, 2055–2070; (b) J. El-Maiss, T. M. El Dine, C.-S. Lu, I. Karamé, A. Kanj, K. Polychronopoulou and J. Shaya, Recent Advances in Metal-Catalyzed Alkyl-Boron ( $C(sp^3)$ )-(C( $sp^2$ )) Suzuki-Miyaura Cross-Couplings, *Catalysts*, 2020, **10**, 296–320.
  - 15 (a) L. Zhang, Y. Fang, X. Jin, H. Xu, R. Li, H. Wu, B. Chen, Y. Zhu, Y. Yang and Z. Tian, Pd-Catalysed Suzuki coupling of  $\alpha$ -bromoethenylphosphonates with organotrifluoroborates: a general protocol for the synthesis of terminal  $\alpha$ -substituted vinylphosphonates, *Org. Biomol. Chem.*, 2017, **15**, 8985–8989; (b) Y. Fang, M. Yuan, J. Zhang, L. Zhang, X. Jin, R. Li and J. Li, An efficient and straightforward route to terminal vinyl sulfones via palladium-catalyzed Suzuki reactions of  $\alpha$ -bromoethenylsulfones, *Tetrahedron Lett.*, 2016, **57**, 1460–1463; (c) Y. Fang, L. Zhang, X. Jin, J. Li, M. Yuan, R. Li, H. Gao, J. Fang and Y. Liu, Expedient Synthesis of Terminal Vinylphosphonates by Palladium-Catalyzed C-C Cross-Coupling Reactions of (1-Halovinyl)phosphonates, *Synlett*, 2015, **26**, 980–984; (d) L. Zhang, Modular Synthesis of  $\alpha$ -Substituted Alkenyl Acetals by a Palladium-Catalyzed Suzuki Reaction of  $\alpha$ -Haloalkenyl Acetals with Organoboranes, *Synlett*, 2021, **32**, 723–727; (e) L. Zhang, J. Shi and Y. Fang, An Alternative to the Arbuzov Reaction: Generation and Transformation of  $\alpha$ -Dialkyl-Substituted Methylphosphonate Carbanions via an SET Reduction Process, *Synthesis*, 2023, **55**, 907–918.
  - 16 E. M. Woerly, J. E. Miller and M. D. Burke, (1-Bromovinyl)-MIDA boronate: a readily accessible and highly versatile building block for small molecule synthesis, *Tetrahedron*, 2013, **69**, 7732–7740.
  - 17 M. I. Dawson, L. Jong, P. D. Hobbs, J. F. Cameron, W.-R. Chao, M. Pfahl, M.-O. Lee, B. Shroot and M. Pfahl, Conformational Effects on Retinoid Receptor Selectivity. 2. Effects of Retinoid Bridging Group on Retinoid X Receptor Activity and Selectivity, *J. Med. Chem.*, 1995, **38**, 3368–3383.
  - 18 (a) C. Amatore, G. Le Duc and A. Jutand, Mechanism of Palladium-Catalyzed Suzuki-Miyaura Reactions: Multiple and Antagonistic Roles of Anionic "Bases" and Their Counteractions, *Chem.-Eur. J.*, 2013, **19**, 10082–10093; (b) L. Zhang, C. Yang, X. Guo and F. Mo, Research Progress of Suzuki-Miyaura Cross-Coupling Reaction Mechanism, *Chin. J. Org. Chem.*, 2021, **41**, 3492–3510.

