


 Cite this: *RSC Adv.*, 2020, 10, 33155

Electrochemical sulfonylation of alkenes with sulfonyl hydrazides: a metal- and oxidant-free protocol for the synthesis of (*E*)-vinyl sulfones in water†

 Yin-Long Lai,^{‡a} Yunyan Mo,^{‡a} Shaoxi Yan,^a Shengling Zhang,^a Lejie Zhu,^a Jianmin Luo,^{*a} Huishi Guo,^{*a} Jianpeng Cai^a and Jianhua Liao^{ID} ^{*b}

An efficient electrochemical transformation of a variety of alkenes and sulfonyl hydrazides into vinyl sulfones with a catalytic amount of tetrabutylammonium iodide in water is reported. The reaction proceeds smoothly to afford vinyl sulfones with good selectivities and yields at room temperature under air in an undivided cell. Cyclic voltammograms and control experiments have been performed to provide preliminary insight into the reaction mechanism. The key features of this reaction include using pure water as solvent, transition metal- and oxidant-free conditions, and being easily scaled up to gram-scale synthesis.

 Received 21st August 2020
 Accepted 1st September 2020

DOI: 10.1039/d0ra07212e

rsc.li/rsc-advances

Introduction

To achieve green and sustainable procedures, metal-free strategies have attracted much attention during the past decade.¹ In particular, transition-metal-free couplings in water could provide great opportunities for more sustainable synthetic chemistry.² In addition, the development of transition-metal-free reactions in water enabled by efficient and cleaner techniques could explore novel approaches to construct chemical products in an environmentally benign manner.³

Vinyl sulfones are important and useful building blocks for various organic transformations and exhibit a broad range of biological properties.⁴ As a consequence, various synthetic routes to vinyl sulfones have been developed.^{5,6} In terms of these synthetic methodologies, the cross-coupling of a variety of alkenes with sulfonyl hydrazides has garnered considerable attention for the synthesis of vinyl sulfones.⁶ Despite some great advantages of these reactions, the methods still suffered from certain shortcomings, such as requiring strong oxidants,^{6a-d} employment of transition metal catalysts,^{6e} or high temperature.^{6f} Therefore, it is desirable to synthesize vinyl sulfones directly from styrenes and sulfonyl hydrazides under the metal and oxidant-free conditions.

Organic electrochemistry has been recognized as an atom-economical and eco-friendly benign synthetic strategy, wherein the electric current can be used to replace a stoichiometric amount of a redox agent.⁷ Recently, an elegant example has been devoted to the electrochemistry of vinyl sulfones by Terent'ev and co-workers.⁸ However, the protocol still involved excessive KI and organic solvent. Thus, a more green and efficient strategy for the electrochemistry of (*E*)-vinyl sulfones between styrenes and sulfonyl hydrazides under milder reaction condition is desired. As a benign solvent, water could lead to new reactivity, as well as environmentally.⁹ As part of our ongoing activities in developing electrochemical aqueous-phase reactions,¹⁰ we report here an electrochemical cross-coupling of readily available styrenes and sulfonyl hydrazides using iodide salt as the catalyst with an elegant constant current in water at room temperature under air.

Results and discussion

At the beginning of our investigation, we used styrene **1a** and *p*-toluenesulfonyl hydrazide **2a** as the model substrates to screen the optimized conditions. After some experiments, the optimal reaction conditions were defined as electrolyzing **1a** and **2a** in saturated (NH₄)₂CO₃ aqueous solution using 10 mol% of *n*-Bu₄NI as the catalyst at room temperature in an undivided cell with Pt foils (1.0 × 1.5 cm²). Under these mild conditions, the desired product **3a** was obtained in 88% yield after the reaction mixture had been stirred for 3.0 h (Table 1, entry 1). It was noted that the yield of **3a** increased sharply to 32% when the reaction was run without *n*-Bu₄NI (entry 2). When *n*-Bu₄NI was replaced with some other catalysts, such as NH₄I, PhI(OAc)₂, *n*-Bu₄NBr

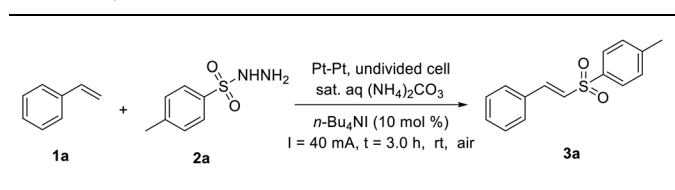
^aCollege of Chemistry and Civil Engineering, Shaoguan University, Shaoguan, 512005, Guangdong Province, P. R. China

^bSchool of Pharmaceutical Sciences, Gannan Medical University, Ganzhou, 341000, Jiangxi Province, P. R. China. E-mail: xxyjlm@163.com; gold0226@126.com; liaojianhua715@163.com

† Electronic supplementary information (ESI) available. See DOI: 10.1039/d0ra07212e

‡ These authors contributed equally.



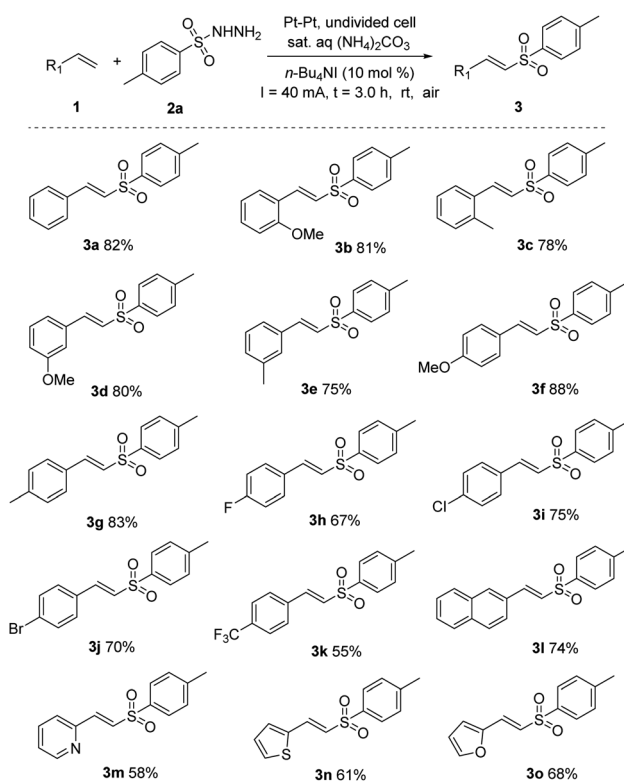
Table 1 Optimization of reaction conditions^a

Entry	Variation from the standard conditions	Yield ^b [%]
1	None	88
2	In the absence of <i>n</i> -Bu ₄ NI	32
3	NH ₄ I instead of <i>n</i> -Bu ₄ NI	77
4	PhI(OAc) ₂ instead of <i>n</i> -Bu ₄ NI	48
5	<i>n</i> -Bu ₄ NBr instead of <i>n</i> -Bu ₄ NI	68
6	I ₂ instead of <i>n</i> -Bu ₄ NI	56
7	Sat. aq. NH ₄ HCO ₃ instead of sat. aq. (NH ₄) ₂ CO ₃	53
8	Sat. aq. CS ₂ CO ₃ instead of sat. aq. (NH ₄) ₂ CO ₃	75
9	Graphite rods as electrodes	72
10 ^c	Reticulated vitreous carbon RVC as electrodes	70
11 ^d	30 mA instead of 40 mA, 4 h	77
12	50 mA instead of 40 mA, 2.4 h	81
13	No electric current	N.R.

^a Standard conditions: the mixture of **1a** (0.5 mmol), **2a** (1.0 mmol), *n*-Bu₄NI (10 mol%) in saturated (NH₄)₂CO₃ aqueous solution (5.0 mL) was electrolyzed at constant current (40 mA) in an undivided cell at room temperature for 3.0 hours, anode and cathode: Pt foil (1.0 × 1.5 cm²). ^b The yield of the product was determined by ¹H NMR spectroscopy; N.R., no reaction. ^c Graphite rods (diameter: 0.5 cm, height: 1.78 cm). ^d Reticulated vitreous carbon RVC (100 PPI, 1.5 cm × 1 cm × 0.2 cm).

and I₂, the yield of the desired product **3a** was reduced (entries 3–6). Among a series of electrolyte (entries 7–8), sat. aq. (NH₄)₂CO₃ gave the optimal result. Subsequently, the electrode material was also screened. When the Pt foil electrodes were replaced by graphite rods or reticulated vitreous carbon rods, the yield of the desired product dropped (entries 9–10). In addition, the electrolysis at lower or higher current density led to a decrease of the yield (entries 11–12). Finally, it was found that no desired product could be obtained without an electric current in this reaction (entry 13).

With the optimized reaction conditions in hand, a series of styrene derivatives were further evaluated. As presented in Scheme 1, the reaction proceeded smoothly with various of styrenes to afford the corresponding vinyl sulfones with moderate to good yields (**3a–o**). Notably, *para*-, *meta*-, or *ortho*-substituted aryl alkenes, bearing either electron-donating groups (Me and OMe, **3b–g**) or electron-withdrawing (F, Br, and Cl, **3h–j**) groups on the aryl ring, gave high yields of the desired products. Strong electron-withdrawing groups (CF₃, **3k**) influenced the reaction and delivered lower yields. Moreover, naphthalene derivative (**3l**) was also accommodated in the reaction and afforded the desired product in a yield of 74%. Heteroarene-based styrenes were also good substrates for this process and gave the desired products in moderate yields (**3m–o**). Importantly, excellent *E* selectivity (*E/Z* > 99 : 1) were observed in all product. Notably, alkenes with some functional



Scheme 1 Scope of the reaction with styrene.^{a,b} Reaction conditions: the mixture of **1** (0.5 mmol), **2a** (1.0 mmol), *n*-Bu₄NI (10 mol%) in saturated (NH₄)₂CO₃ aqueous solution (5.0 mL) was electrolyzed at constant current (40 mA) in an undivided cell at room temperature for 3.0 hours, anode and cathode: Pt foil (1.0 × 1.5 cm²). ^b Yields of isolated products.

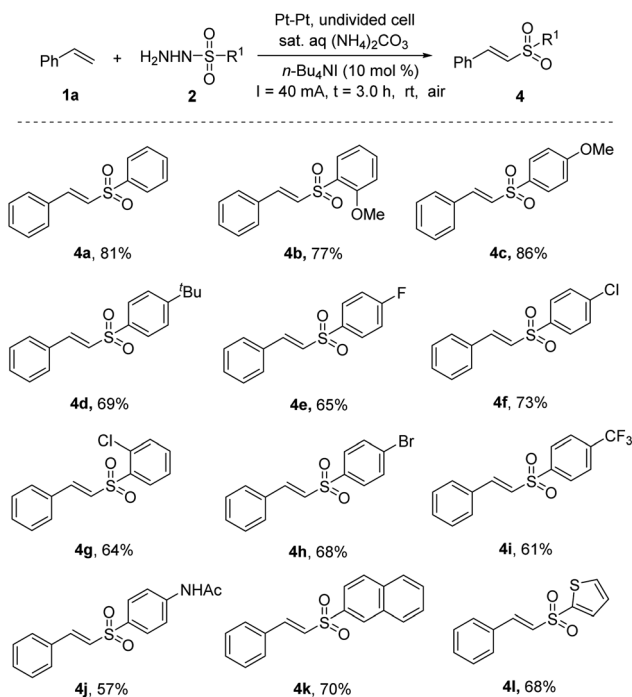
groups-substituted, such as ester, amides, and silyl ethers are not compatible with this electrochemical transformation.

To further examine the scope of this reaction, a range of sulfonyl hydrazides were also used to react with styrene. As shown in Scheme 2, unsubstituted sulfonyl hydrazide afforded the product **4a** with 81% yield. A series of sulfonyl hydrazides bearing electron-donating groups (OMe and ^tBu **4b–d**) and electron-withdrawing (F, Br, Cl, and NHAc, **4e–h**, **4j**) groups produced sulfones in moderate to good yields. The strongly electron-withdrawing group (CF₃, **4i**) led to a slight decrease in yield. Furthermore, sulfonyl hydrazides with a naphthyl group (**4k**) or a thienyl group (**4l**) were examined in this reaction, and the desired products were afforded in yields of 70% and 68%, respectively. It was noteworthy that excellent *E* selectivity (*E/Z* > 99 : 1) was observed in all cases.

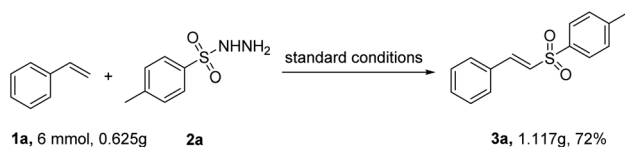
To demonstrate the synthetic utility of this transformation, electrochemical synthesis of the (*E*)-vinyl sulfones in water was performed at a gram scale (Scheme 3). Product **3a** could be prepared in 72% of yield by prolonging the time and changing the size of platinum electrodes, further highlighting the utility of the electrochemical protocol.

To understand the mechanism of this reaction, a series of preliminary mechanistic experiments were performed (Scheme 4). The reaction of **1a** and **2a** was inhibited in the presence of



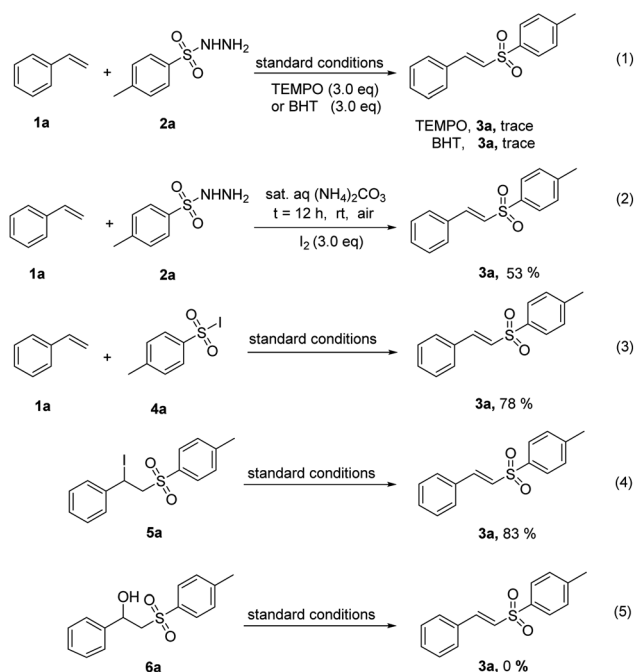


Scheme 2 Scope of the reaction with sulfonyl hydrazides.^{a,b} Reaction conditions: the mixture of **1a** (0.5 mmol), **2** (1.0 mmol), *n*-Bu₄NI (10 mol%) in saturated (NH₄)₂CO₃ aqueous solution (5.0 mL) was electrolyzed at constant current (40 mA) in an undivided cell at room temperature for 3.0 hours, anode and cathode: Pt foil (1.0 × 1.5 cm²). ^bYields of isolated products.



Scheme 3 Gram-scale electrochemical synthesis of **3a**.

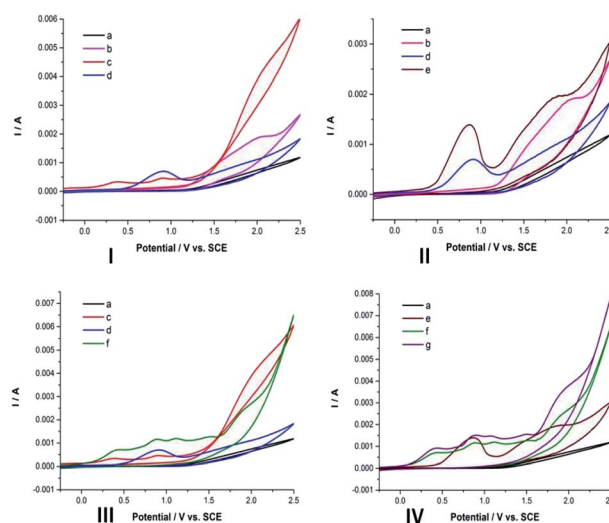
radical inhibitors, such as 2,2,6,6-tetramethyl-1-piperidinyloxy (TEMPO) and 2,6-di-*tert*-butyl-4-methylphenol (BHT) (Scheme 4, eqn (1)) under standard conditions, which supported that the reaction presumably involved a radical pathway. To determine the involvement of molecular iodine, the reaction was carried out in the presence of I₂, the desired product **3a** was afforded in a 53% yield (Scheme 4, eqn (2)). It was proposed that I₂ produced by anode has an effect on the activation of the reaction. In addition, when 4-methylbenzenesulfonyl iodide **4a** was subjected to the reaction with **1a** under standard conditions, a 78% yield of **3a** was obtained (Scheme 4, eqn (3)). Similarly, direct synthesis of desired product **3a** from the β-iodosulfone **5a** under the standard conditions was also successful (Scheme 4, eqn (4)). But when β-hydroxysulfone **6a** was used as the starting material under the standard conditions, no target product **3a** was obtained (Scheme 4, eqn (5)). Thus, it was demonstrated that 4-methylbenzenesulfonyl iodide **4a** and β-iodosulfone **5a** could be active intermediates for this reaction and the



Scheme 4 Preliminary mechanistic studies.

involvement of β-hydroxysulfone **6a** as an intermediate was ruled out.

To gain more insight into this reaction mechanism, cyclic voltammetry (CV) experiments were carried out. As shown in Scheme 5, the oxidation peak of **1a** was observed at $E_p = 1.95$ V vs. SCE (Scheme 5(I), curve b).⁸ Then, the CV of **2a** displayed two

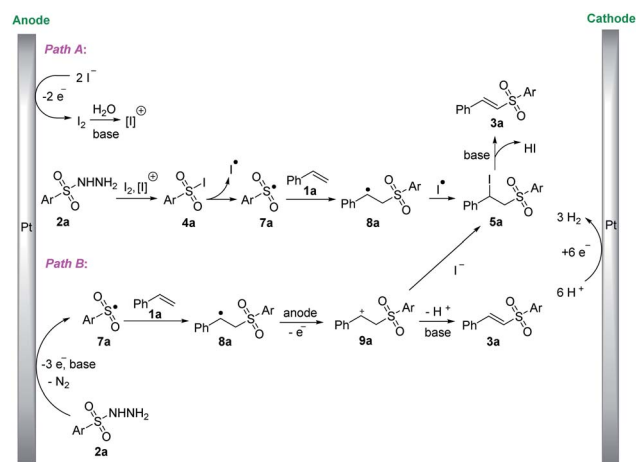


Scheme 5 Cyclic voltammograms experiments.^a Cyclic voltammograms of related compounds in sat. aq. (NH₄)₂CO₃, using a glassy carbon electrode as working electrode (*d* = 3 mm), a Pt wire as counter electrode, and a saturated calomel electrode (SCE) as a reference electrode, at 100 mV s⁻¹ scan rate: (a) none; (b) **1a** (0.005 M); (c) **2a** (0.005 M); (d) *n*-Bu₄NI (0.001 M); (e) **1a** (0.005 M) and *n*-Bu₄NI (0.001 M); (f) **2a** (0.005 M) and *n*-Bu₄NI (0.001 M); (g) **1a** (0.005 M), **2a** (0.005 M) and *n*-Bu₄NI (0.001 M).



oxidation peaks at 0.36 V *vs.* SCE and 0.91 V *vs.* SCE (Scheme 5(I), curve c).^{6b} These results showed that **2a** was oxidized preferentially than **1a** under the standard conditions. Additionally, we found that the pH of the reaction solution remained at 9.34–9.10 throughout the process (Scheme 6), which implied that the oxidation of **2a** could be promoted in basic acidic reaction conditions.¹¹ Next, the role of *n*-Bu₄NI was also studied. The anode potential of *n*-Bu₄NI was observed at 0.90 V *vs.* SCE (Scheme 5(I), curve d), which indicates that iodide ions (I⁻) could be oxidized to molecular iodine (I₂).^{6b,8,12} The CV result of **1a** and *n*-Bu₄NI mixtures showed no obvious new oxidation peaks (Scheme 5(II), curve e), which indicated that *n*-Bu₄NI did not affect compound **1a**. Intriguingly, the addition of *n*-Bu₄NI to **2a** led to two new oxidation peaks at 1.11 V *vs.* SCE and 1.52 V *vs.* SCE (Scheme 5(III), curve f), which indicated that sulfonyl hydrazide **2a** could be oxidized by I₂ or its derivatives in the electrolysis process.¹³ Furthermore, in the mixture solution of **1a**, **2a**, and *n*-Bu₄NI, it did not significantly change the curve (Scheme 5(IV), curve g). Combined with one of the control experiments (Scheme 3, eqn (2)), it suggested that I₂ produced by the electrochemical process is involved in the reaction.

In light of these experimental results and previous works,^{6,8,12–14} two possible mechanisms for this reaction are proposed in Scheme 7. In Path A, the iodide ions were oxidized to molecular iodine at the anode. Under the basic aqueous reaction conditions, molecular iodine can further form electrophilic iodine-containing species [I]⁺. Then, the iodine-containing species (I₂, [I]⁺) reacted with hydrazide **2a** to give the sulfonyl iodide **4a**, which was decomposed to generate sulfonyl radical **7a** and iodine radical. Subsequently, the sulfonyl radical **7a** added to styrene **1a** to afford the benzylic radical **8a**, followed by the reaction with iodine radical to form β-iodosulfone intermediate **5a**. Finally, β-iodosulfone intermediate **5a** was converted into the desired product **3a** through elimination of HI. While in Path B, hydrazide **2a** generated the corresponding sulfonyl radical **7a** *via* preferential deprotonation under the basic condition and three electron oxidation together with the release of molecular nitrogen. The sulfonyl radical **7a** then reacted with styrene **1a** to produce the benzylic radical **8a**, which was further oxidized to benzyl cation **9a** on the anode. The benzyl cation **9a** can generate **3a** directly through



Scheme 7 Proposed mechanism.

liberating H⁺ or react with iodide anion to form β-iodosulfone **5a**, which can lead to **3a** formation through HI elimination.

Conclusions

We developed an efficient electrochemical method for the synthesis of (*E*)-vinyl sulfones from a variety of alkenes and sulfonyl hydrazides with a catalytic amount of iodide salt in water. The reaction proceeded smoothly to afford (*E*)-vinyl sulfones with good selectivities and yields in an undivided cell at room temperature under metal- and external oxidant-free conditions. A satisfactory gram-scale reaction showed the synthetic utility of this process. Further exploration of the synthetic applications is undergoing in our lab.

Conflicts of interest

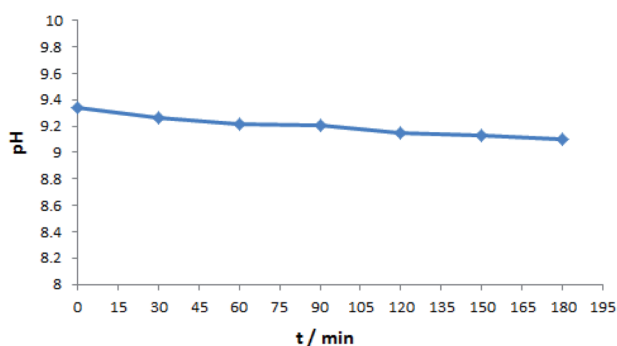
There are no conflicts to declare.

Acknowledgements

The authors thank the Innovation Projects of Department of Education of Guangdong Province (2018KQNCX236, 2019KTSCX162), the Science and Technology Project of Guangdong Province (408-99000213), the Science and Technology Project of Shaoguang city (2018sn047, 2019sn055), Shaoguan University (408-9900416, 408-99000618), National undergraduate innovation and entrepreneurship project (201810576016), National Natural Science Foundation of China (21961002), and the emergency project of Gannan Medical University (YJ202027) for financial support.

Notes and references

- For examples, see: (a) A. Bhunia, S. R. Yetra and A. T. Biju, *Chem. Soc. Rev.*, 2012, **41**, 3140; (b) S. Roscales and A. G. Csaky, *Chem. Soc. Rev.*, 2014, **43**, 8215; (c) A. B. Cuenca, R. Shishido, H. Ito and E. Fernandez, *Chem. Soc. Rev.*, 2017, **46**, 415.



Scheme 6 pH value during the process of the reaction.^a The pH value was measured every 30 minutes.



- 2 (a) E. Nakamura and K. Sato, *Nat. Mater.*, 2011, **10**, 158; (b) C.-L. Sun and Z.-J. Shi, *Chem. Rev.*, 2014, **114**, 9219; (c) W. Liu, L. Li and C.-J. Li, *Nat. Commun.*, 2015, **6**, 6526.
- 3 (a) A. Albini and M. Fagnoni, *Green Chem.*, 2004, **6**, 1; (b) Y. Yuan and A. Lei, *Nat. Commun.*, 2020, **11**, 802.
- 4 For examples, see: (a) G. Wang, U. Mahesh, G. Y. J. Chen and S. Q. Yao, *Org. Lett.*, 2003, **5**, 737; (b) B. A. Frankel, M. Bentley, R. G. Kruger and D. G. McCafferty, *J. Am. Chem. Soc.*, 2004, **126**, 3404; (c) F. Hof, A. Schutz, C. Fah, S. Meyer, D. Bur, J. Liu, D. E. Goldberg and E. Diederich, *Angew. Chem., Int. Ed.*, 2006, **45**, 2138; (d) D. C. Meadows, T. Sanchez, N. Neamati, T. W. North and J. Gervay-Hague, *Bioorg. Med. Chem.*, 2007, **15**, 1127; (e) M. Uttamchandani, K. Liu, R. C. Panicker and S.-Q. Yao, *Chem. Commun.*, 2007, 1518.
- 5 For examples, see: (a) S. Chodroff and W. F. Whitmore, *J. Am. Chem. Soc.*, 1950, **72**, 1073; (b) I. C. Popoff, J. L. Dever and G. R. Leader, *J. Org. Chem.*, 1969, **34**, 1128; (c) J. M. Baskin and Z. Wang, *Org. Lett.*, 2002, **4**, 4423; (d) Y. Xu, X. Tang, W. Hu, W. Wu and H. Jiang, *Green Chem.*, 2014, **16**, 3720; (e) A. U. Meyer, S. Jäger, D. Prasad Hari and B. König, *Adv. Synth. Catal.*, 2015, **357**, 2050; (f) R. Singh, B. K. Allam, N. Singh, K. Kumari, S. K. Singh and K. N. Singh, *Org. Lett.*, 2015, **17**, 2656; (g) S. Cai, Y. Xu, D. Chen, L. Li, Q. Chen, M. Huang and W. Weng, *Org. Lett.*, 2016, **18**, 2990; (h) Y. Fang, Z. Luo and X. Xu, *RSC Adv.*, 2016, **6**, 59661; (i) L. Kadari, R. K. Palakodety and L. P. Yallapragada, *Org. Lett.*, 2017, **19**, 2580; (j) H. Yue, C. Zhu and M. Rueping, *Angew. Chem., Int. Ed.*, 2018, **57**, 1371; (k) Q. Gui, K. Han, Z. Liu, Z. Su, X. He, H. Jiang, B. Tian and Y. Li, *Org. Biomol. Chem.*, 2018, **16**, 5748; (l) S. Kumar, R. Singh and K. N. Singh, *Asian J. Org. Chem.*, 2018, **7**, 359.
- 6 (a) X. Li, X. Xu and C. Zhou, *Chem. Commun.*, 2012, **48**, 12240; (b) S. Tang, Y. Wu, W.-Q. Liao, R.-P. Bai, C. Liu and A. W. Lei, *Chem. Commun.*, 2014, **50**, 4496; (c) B. Aegurla and R. K. Peddinti, *Asian J. Org. Chem.*, 2018, **7**, 946; (d) W.-H. Bao, W.-W. Ying, X.-D. Xu, G.-D. Zhou, X.-X. Meng, W.-T. Wei, Y.-Y. Liu and Q. Li, *Tetrahedron Lett.*, 2019, **60**, 55; (e) X.-W. Li, Y.-L. Xu, W.-Q. Wu, C. Jiang, C.-R. Qi and H.-F. Jiang, *Chem.-Eur. J.*, 2014, **20**, 7911; (f) Z. Zhan, H. Ma, D. Wei, J. Pu, Y. Zhang and G. Huang, *Tetrahedron Lett.*, 2018, **59**, 1446; (g) M. Pramanik, K. Choudhuri and P. Mal, *Asian J. Org. Chem.*, 2019, **8**, 144.
- 7 For recent representative reviews about electrosynthesis, see: (a) M. Yan, Y. Kawamata and P. S. Baran, *Chem. Rev.*, 2017, **117**, 13230; (b) Y. Jiang, K. Xu and C.-C. Zeng, *Chem. Rev.*, 2018, **118**, 4485; (c) J.-I. Yoshida, A. Shimizu and R. Hayashi, *Chem. Rev.*, 2018, **118**, 4702; (d) K. Liu, C. L. Song and A. Lei, *Org. Biomol. Chem.*, 2018, **16**, 2375; (e) A. Wiebe, T. Gieshoff, S. Mçhle, E. Rdrigo, M. Zirbes and S. R. Waldvogel, *Angew. Chem., Int. Ed.*, 2018, **57**, 5594; (f) S. Mçhle, M. Zirbes, E. Rodrigo, T. Gieshoff, A. Wiebe and S. R. Waldvogel, *Angew. Chem., Int. Ed.*, 2018, **57**, 6018; (g) G. S. Sauer and S. Lin, *ACS Catal.*, 2018, **8**, 5175; (h) K. D. Moeller, *Chem. Rev.*, 2018, **118**, 4817; (i) N. Sauermann, T. H. Meyer, Y. A. Qiu and L. Ackermann, *ACS Catal.*, 2018, **8**, 7086; (j) C. Ma, P. Fang and T.-S. Mei, *ACS Catal.*, 2018, **8**, 7179; (k) M. D. Kärkäs, *Chem. Soc. Rev.*, 2018, **47**, 5786; (l) S. R. Waldvogel, S. Lips, M. Selt, B. Riehl and C. J. Kampf, *Chem. Rev.*, 2018, **118**, 6706; (m) R. Francke and D. Little, *ChemElectroChem*, 2019, **6**, 4373; (n) C. Song, K. Liu, X. Dong, C.-W. Chiang and A. Lei, *Synlett*, 2019, **30**, 1149; (o) T. Noël, Y. Cao and G. Laudadio, *Acc. Chem. Res.*, 2019, **52**, 2858; (p) P. Xiong and H.-C. Xu, *Acc. Chem. Res.*, 2019, **52**, 3339; (q) F. Marken and J. D. Wadhawan, *Acc. Chem. Res.*, 2019, **52**(12), 3325; (r) M. Elsherbini and T. Wirth, *Acc. Chem. Res.*, 2019, **52**(12), 3287; (s) Y. Yuan and A. Lei, *Acc. Chem. Res.*, 2019, **52**(12), 3309; (t) J. Chen, S. Lv and S. Tian, *ChemSusChem*, 2019, **12**, 115; (u) X. Han, K. Wang, W. Gao and J. Chen, *Adv. Synth. Catal.*, 2019, **361**, 2804; (v) S. Lv, G. Zhang, J. Chen and W. Gao, *Adv. Synth. Catal.*, 2019, **362**, 462; (w) M. C. Leech and K. Lam, *Acc. Chem. Res.*, 2020, **53**(1), 121; (x) K.-J. Jiao, Y.-K. Xing, Q.-L. Yang, H. Qiu and T.-S. Mei, *Acc. Chem. Res.*, 2020, **53**(2), 300; (y) T. Fuchigami and T. Fuchigami, *Acc. Chem. Res.*, 2020, **53**, 322.
- 8 A. O. Terent'ev, O. M. Mulina, D. A. Pirgach, A. I. Ilovaisky, M. A. Syroeshkin, N. I. Kapustina and G. I. Nikishin, *Tetrahedron*, 2017, **73**, 6871.
- 9 For examples, see: (a) R. Breslow, *Acc. Chem. Res.*, 1991, **24**, 159; (b) U. M. Lindström, *Chem. Rev.*, 2002, **102**, 2751; (c) M. C. Pirrung and K. D. Sarma, *J. Am. Chem. Soc.*, 2004, **126**, 444; (d) R. Breslow, *Acc. Chem. Res.*, 2004, **37**, 471; (e) S. Narayan, J. Muldoon, M. G. Finn, V. V. Fokin, H. C. Kolb and K. B. Sharpless, *Angew. Chem., Int. Ed.*, 2005, **44**, 3275; (f) C. J. Li and L. Chen, *Chem. Soc. Rev.*, 2006, **35**, 68; (g) N. Mase, Y. Nakai, N. Ohara, H. Yoda, K. Takabe, F. Tanaka and C. F. Barbas III, *J. Am. Chem. Soc.*, 2006, **128**, 734; (h) Z.-L. Shen, S.-Y. Wang, Y.-K. Chok, Y.-H. Xu and T.-P. Loh, *Chem. Rev.*, 2013, **113**, 271; (i) M. B. Gawande, V. D. B. Bonifacio, R. Luque, P. S. Branco and R. S. Varma, *Chem. Soc. Rev.*, 2013, **42**, 5522; (j) B. Li and P. H. Dixneuf, *Chem. Soc. Rev.*, 2013, **42**, 5744; (k) A. Dhakshinamoorthy, A. M. Asiri and H. Garcia, *Chem. Commun.*, 2014, **50**, 12800.
- 10 (a) Y.-L. Lai and J.-M. Huang, *Org. Lett.*, 2017, **19**, 2022; (b) Y.-L. Lai, J.-S. Ye and J.-M. Huang, *Chem.-Eur. J.*, 2016, **22**, 5425.
- 11 Y. Zhao, Y.-L. Lai, K.-S. Du, D.-Z. Lin and J.-M. Huang, *J. Org. Chem.*, 2017, **82**, 9655.
- 12 (a) X. Gao, G. Yuan, H. Chen, H. Jiang, Y. Li and C. Qi, *Electrochem. Commun.*, 2013, **34**, 242; (b) H. Huang, G. Yuan, X. Li and H. Jiang, *Tetrahedron Lett.*, 2013, **54**, 7156; (c) G. Yuan, Z. Zhu, X. Gao and H. Jiang, *RSC Adv.*, 2014, **4**, 24300.
- 13 (a) O. M. Mulina, N. V. Zhironkina, S. A. Paveliev, D. V. Demchuk and A. O. Terent'ev, *Org. Lett.*, 2020, **22**, 1818; (b) H.-D. Zuo, W.-J. Hao, C.-F. Zhu, C. Guo, S.-J. Tu and B. Jiang, *Org. Lett.*, 2020, **22**, 4471.
- 14 (a) S. Yamada, D. Morizono and K. Yamamoto, *Tetrahedron Lett.*, 1992, **33**, 4329; (b) Y.-C. Luo, X.-J. Pan and G.-Q. Yuan, *Tetrahedron*, 2015, **71**, 2119; (c) Y. Yuan, Y. Cao, Y. Lin, Y. Li, Z. Huang and A. Lei, *ACS Catal.*, 2018, **8**, 10871; (d) Z.-Y. Mo, T. R. Swaroop, W. Tong, Y.-Z. Zhang, H.-T. Tang, Y.-M. Pan, H.-B. Sun and Z.-F. Chen, *Green*



Chem., 2018, **20**, 4428; (e) Y.-Z. Zhang, Z.-Y. Mo, H.-S. Wang, X.-A. Wen, H.-T. Tang and Y.-M. Pan, *Green Chem.*, 2019, **21**, 3807; (f) Y. J. Kim and D. Y. Kim, *Tetrahedron Lett.*, 2019, **60**, 1287; (g) K. Mahanty, D. Maiti and S. D. Sarkar, *J. Org. Chem.*,

2020, **85**, 3699; (h) T.-J. He, W.-Q. Zhong and J.-M. Huang, *Chem. Commun.*, 2020, **56**, 2735; (i) Z.-Y. Mo, Y.-Z. Zhang, G.-B. Huang, X.-Y. Wang, Y.-M. Pan and H.-T. Tang, *Adv. Synth. Catal.*, 2020, **362**, 2160.

