Chemical Science

ROYAL SOCIETY OF CHEMISTRY

EDGE ARTICLE

View Article Online
View Journal | View Issue

Cite this: *Chem. Sci.*, 2023, **14**, 7648

All publication charges for this article have been paid for by the Royal Society of Chemistry

Construction of pyrroles, furans and thiophenes *via* intramolecular cascade desulfonylative/dehydrogenative cyclization of vinylidenecyclopropanes induced by NXS (X = I or Br)†

Zhe Meng,[a] Jun Yan,[a] Chao Ning,[a] Min Shi *[ab] and Yin Wei *[b]

Received 24th March 2023
Accepted 13th June 2023

DOI: 10.1039/d3sc01542d

rsc.li/chemical-science

Pyrroles, furans, and thiophenes are important structural motifs in biologically active substances, pharmaceuticals and functional materials. In this paper, we disclose an efficient synthetic strategy for the rapid construction of multisubstituted pyrroles, furans, and thiophenes *via* NXS mediated desulfonylative/dehydrogenative cyclization of vinylidenecyclopropanes (VDCPs). The advantages of this method include wide substrate range, high efficiency and synthetic usefulness of the heterocyclic products under metal-free and mild conditions. The derivatization of pyrrole products and the preparation of functional molecules successfully demonstrated the synthetic potential of the products as platform molecules. The reaction mechanism has been investigated on the basis of control experiments and DFT calculations.

Introduction

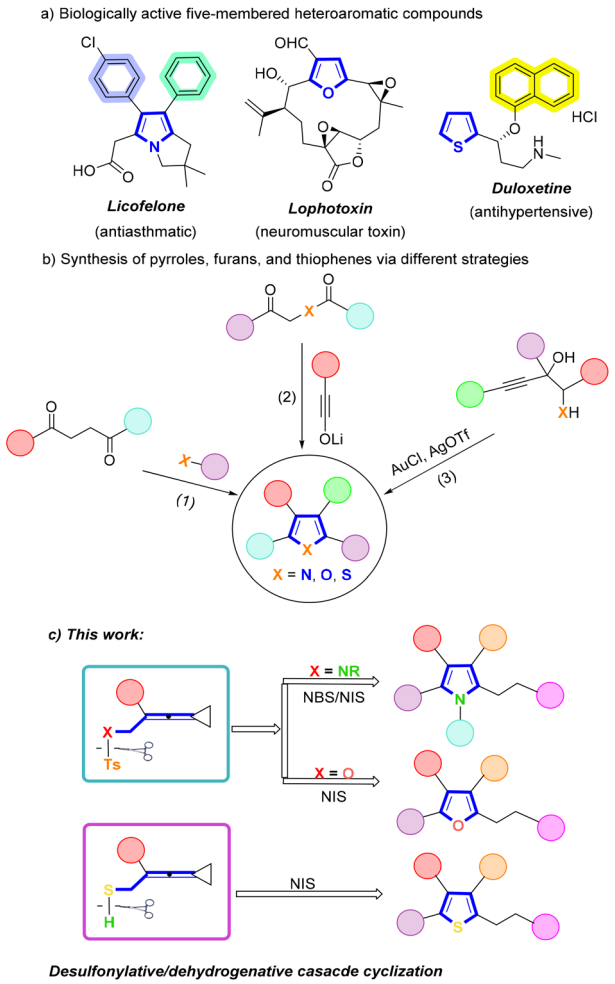
Five-membered heterocycles including pyrroles, furans and thiophenes are widely found in a variety of bioactive molecules, functional and polymeric materials.[1] Moreover, they are also core structural motifs in many natural products and pharmaceuticals. For example, the pyrrole fragment is the key structural unit in licofelone, which possesses significant analgesic, anti-inflammatory, and antiasthmatic activities.[1b] Lophotoxin is a novel neuromuscular toxin that has been isolated from several Pacific gorgonians and contains a furan fragment in its molecular structure.[1e] In addition, thiophene fragment exists in a commercial drug known as duloxetine, which possesses effective antihypertensive activity (Scheme 1a). The synthetic methods of these heterocyclic compounds have been widely reported and are of great concern.[2] To date, the traditional synthetic methods for these heterocycles, including Paal–Knorr condensation,[3] Hantzsch reaction,[4] Feist–Benary reaction,[5] Hinsberg reaction,[6] transition metal-catalyzed cyclizations,[7] and photochemical reactions,[8] have been developed for many years. However, the above reactions frequently employ different synthetic protocols to obtain the starting substrates depending on the required heteroatoms such as N, O, and S. Thus, the development of new strategies that facilitate rapid construction of each of these heterocycles by a single method and provide functionalized pyrroles, furans, and thiophenes in a one-pot manner would be extremely useful and highly desirable. Nonetheless, thus far, only a few methods to access each of these heterocycles by changing the heteroatoms of substrates have been developed (Scheme 1b).[9] For example, Shishido's group reported an efficient strategy for the synthesis of pyrroles, furans and thiophenes utilizing ynolates.[9a] In addition, Marques's group developed the preparation of pyrroles, furans and thiophenes by the gold-catalyzed dehydration and cyclization of heteroatom-substituted propargylic alcohols.[9b] Nevertheless, these synthetic methods usually need harsh reaction conditions, metal catalysts, and prolonged reaction time.

In view of the aforementioned research circumstances, we attempted to introduce heteroatoms into vinylidenecyclopropanes (VDCPs)[10] and assumed that these heteroatomic VDCPs could be excellent candidates for exploiting new methods in cyclization for the rapid construction of heteroaromatics due to their multiple reaction sites. Herein, we describe an intramolecular desulfonylative/dehydrogenative cyclization reaction that proceeds effectively under mild and metal-free conditions, providing functionalized pyrroles, furans, and thiophenes in good yields (Scheme 1c).

[a]*Key Laboratory for Advanced Materials and Institute of Fine Chemicals, School of Chemistry & Molecular Engineering, East China University of Science and Technology, 130 Meilong Road, Shanghai 200237, China*

[b]*State Key Laboratory of Organometallic Chemistry, Center for Excellence in Molecular Synthesis, Shanghai Institute of Organic Chemistry, University of Chinese Academy of Sciences, Chinese Academy of Sciences, 345 Lingling Road, Shanghai 200032, China. E-mail: mshi@mail.sioc.ac.cn; weiyin@sioc.ac.cn*

† Electronic supplementary information (ESI) available: Experimental procedures, characterization data of new compounds. CCDC 2083431 and 2142800. For ESI and crystallographic data in CIF or other electronic format see DOI: https://doi.org/10.1039/d3sc01542d

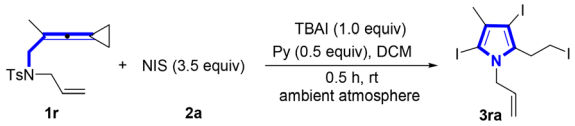


Scheme 1 (a) Representative biologically active five-membered heteroaromatic compounds; (b) previous reports on pyrroles, furans and thiophenes synthesis; (c) this work.

Results and discussion

We began our investigation by exploring the model reaction between vinylidenecyclopropane (VDCP) **1r** (0.2 mmol, 1.0 equiv.) and *N*-iodosuccinimide (NIS) **2a** (0.7 mmol, 3.5 equiv.), pyridine (Py, 0.5 equiv.) as an organic base and TBAI (0.2 mmol, 1.0 equiv.) as an additive in dichloromethane (DCM) (2.0 mL) at room temperature in an ambient atmosphere for 30 min, affording the desired product **3ra** in 95% NMR yield and 93% isolated yield (Table 1, entry 1). The optimization of the reaction conditions indicated that there was a significant decrease in reaction efficiency when TBAI was not added into the reaction mixture (Table 1, entry 2). In addition, we also optimized the reaction conditions in the absence of TBAI to obtain **3ra** in 76% yield (see Table S1 in the ESI† for more details). An investigation of base effect revealed that DMAP and Cs_2CO_3 turned out to be less efficient (Table 1, entries 3 and 4) (see Table S2 in the ESI† for more details). The screening of solvent effect demonstrated that DCM was more suitable than others such as toluene, DMF and MeCN (Table 1, entries 5–7) (see Table S3 in the ESI† for more information). However, by increasing the employed amount of pyridine to 2.0 equiv. or without the addition of pyridine, the reaction efficiency was reduced (Table 1, entries 8 and 9) (see Table S4 in the ESI† for more information). Moreover, we observed that on prolonging the reaction time to 1.0 h or 12.0 h, the yield of **3ra** decreased to 82% and 50%, respectively, indicating that **3ra** was labile in the reaction system (Table 1, entries 10 and 11) (see Table S5 in the ESI† for more information). The use of other sources of iodine reagents, such as IPy_2BF_4 and I_2, afforded **3ra** in 43% and 15% yields, respectively (Table 1, entries 12 and 13). It was worthy to note that NBS could also be used to react with **1r**, giving brominated pyrrole in 44% yield (Table 1, entry 14). However, when NCS was utilized in the reaction, none of the desired products was produced (Table 1, entry 15).

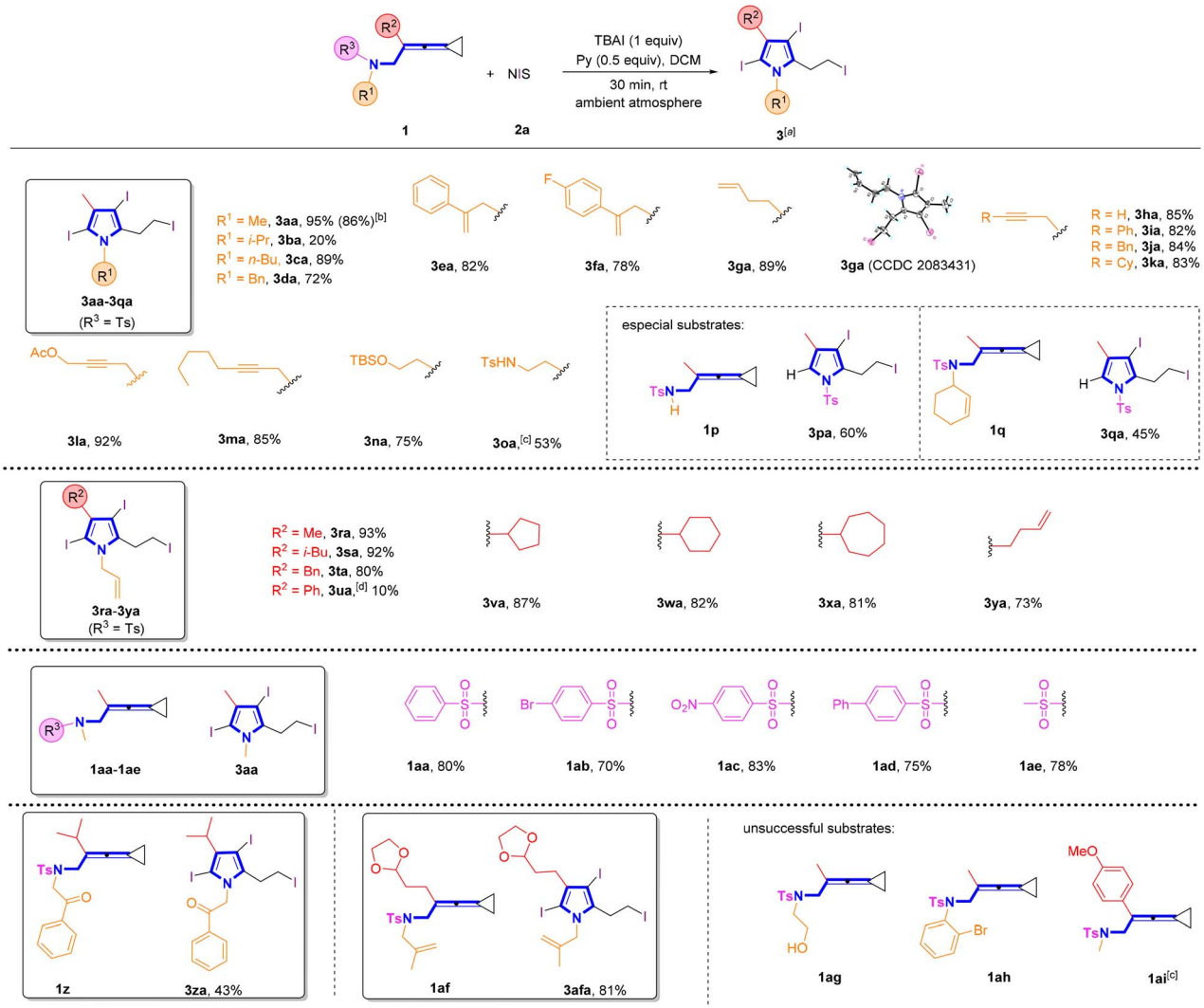
Table 1 Optimization of reaction conditions[a]



Entry[a]	Variation from the standard condition	**3ra**, yield[b] [%]
1	None	95 (93)[c]
2	Without TBAI	76
3	DMAP instead of Py	70
4	Cs_2CO_3 instead of Py	60
5	Toluene instead of DCM	55
6	DMF instead of DCM	29
7	MeCN instead of DCM	85
8	Py (2.0 equiv.) instead of Py (0.5 equiv.)	55
9	Py (0 equiv.) instead of Py (0.5 equiv.)	40
10	1.0 h instead of 0.5 h	82
11	12.0 h instead of 0.5 h	50
12	IPy_2BF_4 instead of NIS	43
13	I_2 instead of NIS	15
14	NBS instead of NIS	44[d]
15	NCS instead of NIS	0

[a] The reaction was carried out with **1r** (0.2 mmol, 1.0 equiv.), **2a** (3.5 equiv.) in the presence of an organic or inorganic base and the solvent (2.0 mL). [b] ^{1}H NMR yield using 1,3,5-trimethoxybenzene as an internal standard. [c] Isolated yield. [d] Brominated pyrrole.

With the optimal reaction conditions established, we next explored the substrate scope for the synthesis of pyrroles (Scheme 2). It was found that most of the substrates successfully underwent these reactions, providing the desired products in good to excellent yields. Utilizing VDCP substrates **1a–1d** (R^1 = alkyl group, R^2 = Me), the desired products **3aa–3da** were obtained in 20–95% yields. It is worth noting that increase of the steric hindrance of the alkyl group decreased the yield of **3** such as substrate **1b** bearing an isopropyl group. A gram-scale reaction was conducted by employing 0.55 g (2.0 mmol) of **1a** and NIS (3.5 mmol, 1.58 g), delivering the desired product **3aa** in 86% yield (0.86 g) under the standard conditions. Substrates **1e–1m** (R^2 = Me) having an alkenyl or an alkynyl unit in R^1 were all tolerated in this reaction, delivering the corresponding



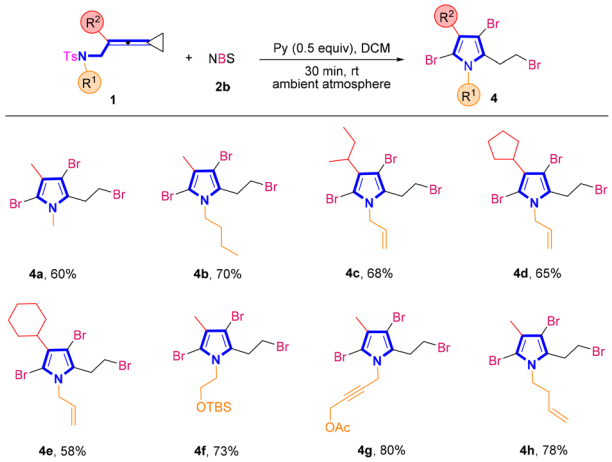
Scheme 2 (a) Standard conditions: substrate **1** (0.2 mmol, 1.0 equiv.), **2a** (3.5 equiv.), TBAI (1.0 equiv.) and pyridine (0.5 equiv.) in DCM (2 mL), ambient atmosphere, 30 min, rt. (b) Gram scale reaction, **1a** (2.0 mmol, 0.55 g), **2a** (7.0 mmol, 1.58 g), TBAI (2.0 mmol), pyridine (0.8 mL), DCM (10 mL). (c) A byproduct **3oa′** was afforded in 45% yield (see Fig. S5 on page S182 in the ESI† for more information). (d) 80 °C, 12 h.

products **3ea–3ma** in 78–92% yields. The structure of **3ga** was unambiguously determined by X-ray crystallographic analysis and its ORTEP drawing is shown in Scheme 2. Notably, substrate **1n** having a protected hydroxy group and substrate **1o** containing a protected amino group were both well compatible, giving the desired products **3na** and **3oa** in 53% and 75% yields, respectively. However, for substrate **1p** having a TsNH moiety, pyrrole **3pa** with the tosyl group was afforded presumably due to the easier departure of H^+ than that of the tosyl group. In addition, as for the cyclohexene-substituted substrate **1q**, the pyrrole product **3qa** with the sulfonyl group was also obtained in 45% yield perhaps because during the reaction, the cyclohexenyl group connected with the NT unit was nucleophilically attacked by I^-, causing the release of this functional group. It was noteworthy that the N atom in products **3pa** and **3qa** was connected with the electron-withdrawing Ts group to reduce the activity of pyrrole, resulting in the inability to undergo further halogenation reaction under the standard conditions. Next, we shifted our attention to examine the R^2 group in VDCPs **1** (R^1 = allyl) and found that introducing alkyl, cycloalkyl and alkenyl substituents in the R^2 group of VDCPs **1r–1t** and **1v–1y** gave the desired products **3ra–3ta** and **3va–3ya** in 73–93% yields. When **1u** was used as a substrate under room temperature conditions, only a small amount of product spots was observed on the TLC plate. The desired product **3ua** was furnished in 10% yield, when the reaction was carried out at 80 °C, presumably due to the electronic effect. Moreover, the removable R^3 sulfonyl group was also exploited under the standard conditions and we identified that substrates **1aa–1ae** with a variety of sulfonated groups in R^3 all provided the desired pyrrole in good yields. Further investigation revealed that this reaction also tolerated carbonyl group and acetal group containing VDCPs, giving the corresponding products **3za** and **3afa** in 43% and 81% yields, respectively. However, substrate **1ag** with an unprotected hydroxy group could not deliver the desired product **3aga**. The hydroxy group in **1ag** was involved in

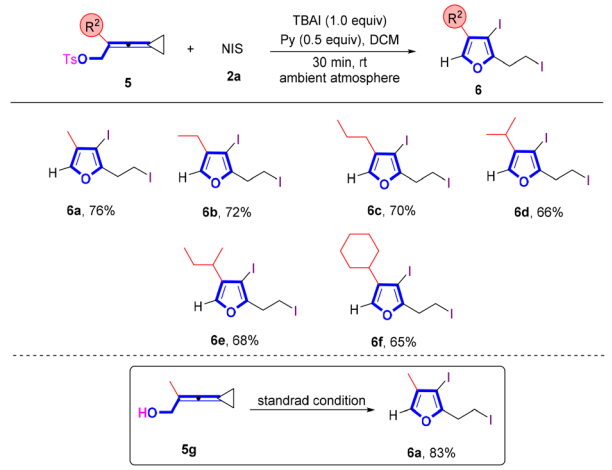
the reaction and the desired pyrrole product was not obtained. Moreover, we observed that the reactions did not proceed when **1ah** and **1ai** were employed as substrates (see Fig. S1on page S14 in the ESI†).

In order to further demonstrate the generality of this synthetic strategy, we then turned our attention to examining the substrate scope of brominated pyrroles **4** in the presence of NBS **2b** (Scheme 3). Similarly, using VDCPs **1** as the substrates, the desired brominated pyrrole products **4a–4h** were produced in moderate to good yields ranging from 58% to 80%. In VDCPs **1**, R^1 could be an alkyl, an allyl, an alkyl group bearing a protected hydroxy group, a propargyl group or a homoallyl group and R^2 could be an alkyl or a cycloalkyl group, smoothly delivering the desired products **4** under the standard conditions.

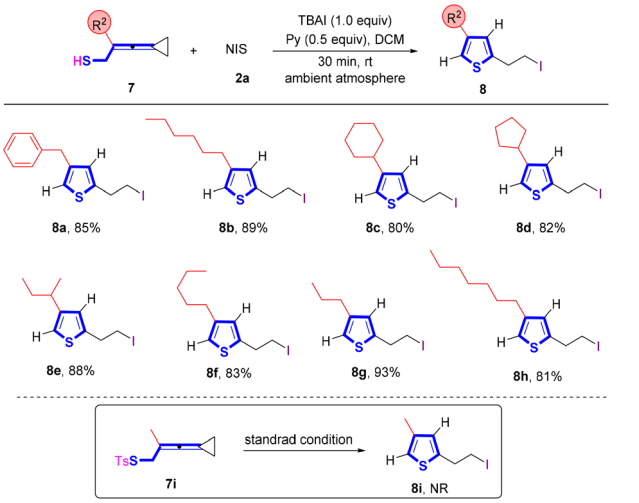
When VDCPs **5**, in which the VDCP moiety is connected with a tosylated oxygen atom, were utilized as substrates to react with NIS under the standard conditions, the corresponding iodinated furan products **6** were obtained in moderate yields (Scheme 4). A variety of VDCPs **5a–5f** bearing an alkyl or a cycloalkyl group were tolerated, giving furans **6a–6f** in 65–76% yields. Substrate **5g**, replacing the OT moiety with the hydroxy group, could also afford the desired product **6a** in 83% yield.



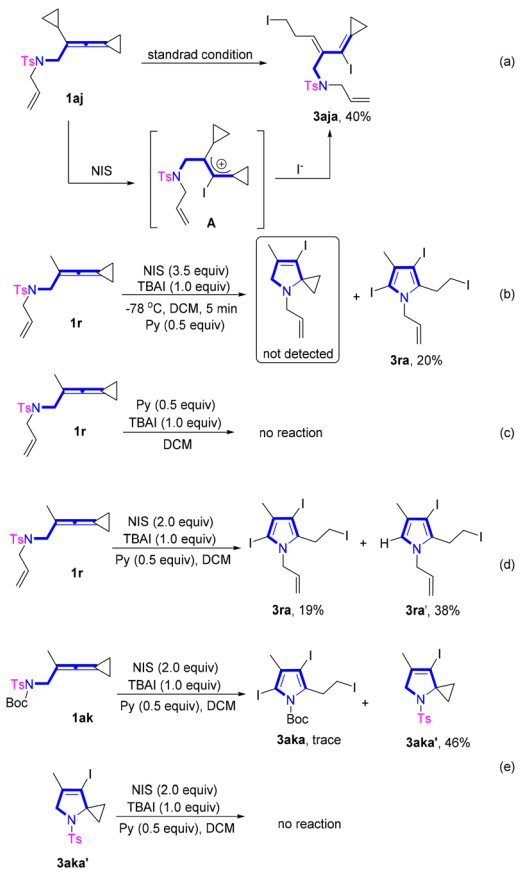
Scheme 3 Standard conditions: substrate **1** (0.2 mmol, 1.0 equiv.), **2b** (3.5 equiv.) and pyridine (0.5 equiv.) in DCM (2 mL), ambient atmosphere, 30 min, rt.



Scheme 4 Standard conditions: substrate **5** (0.2 mmol, 1.0 equiv.), **2a** (3.5 equiv.) and pyridine (0.5 equiv.) in DCM (2 mL), ambient atmosphere, 30 min, rt.



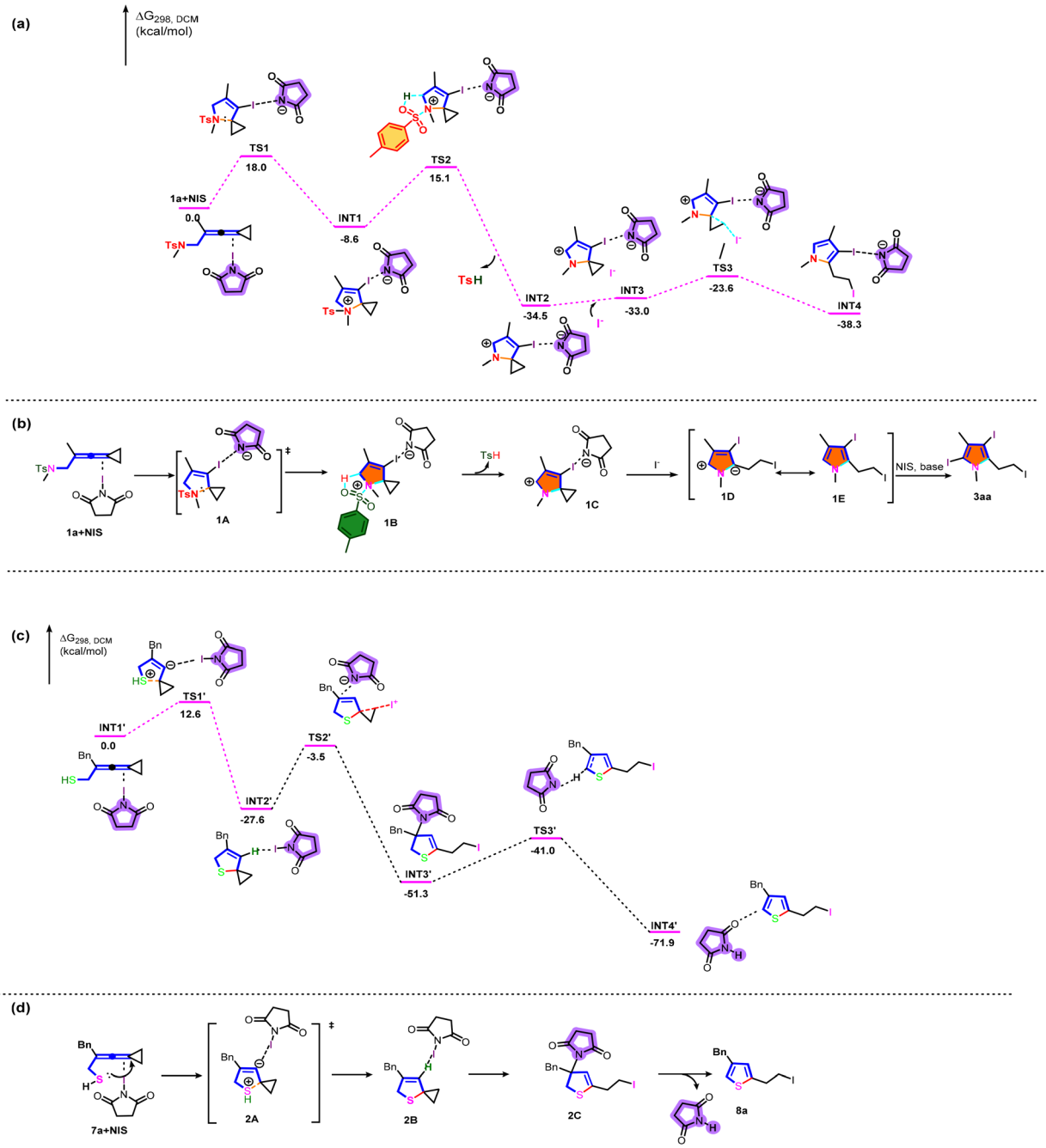
Scheme 5 Standard conditions: substrate **7** (0.2 mmol, 1.0 equiv.), **2a** (1.0 equiv.) and pyridine (0.5 equiv.) in DCM (2 mL), ambient atmosphere, 30 min, rt.



Scheme 6 Control experiments.

To synthesize thiophene derivatives, we further prepared VDCP **7i**, in which the VDCP moiety is connected with a tosylated sulfur atom (Scheme 5). However, no reaction occurred and the starting materials were fully recovered upon conducting the reaction under the standard protocol, probably because the nucleophilicity of the sulfur atom was weakened by the tosyl group and its steric effect hampered the cyclization. Afterwards, we utilized VDCP substrates **7** having a free thiol group to conduct the reaction and found that the cyclization smoothly took place, affording the desired thiophenes **8** in good yields. As shown in Scheme 5, R^2 substituents as a broad range of alkyl or cycloalkyl groups were all suitable for this reaction, affording the corresponding thiophenes **8a–8h** in 80–93% yields.

To further unveil the reaction mechanism, we carried out a series of control experiments (Scheme 6) and density functional theory (DFT) calculations (Scheme 7). When VDCP **1aj** was utilized as the substrate for the reaction under the standard conditions, instead of the desired pyrrole product, a cyclopropane ring-opened product **3aja** was obtained in 40% yield, suggesting that during the reaction of **1aj** with NIS, I^+ tended to add to the middle carbon atom of the allene moiety to generate an allyl cationic intermediate **A** (Scheme 6a). Afterwards, the cyclopropane in **1aj**



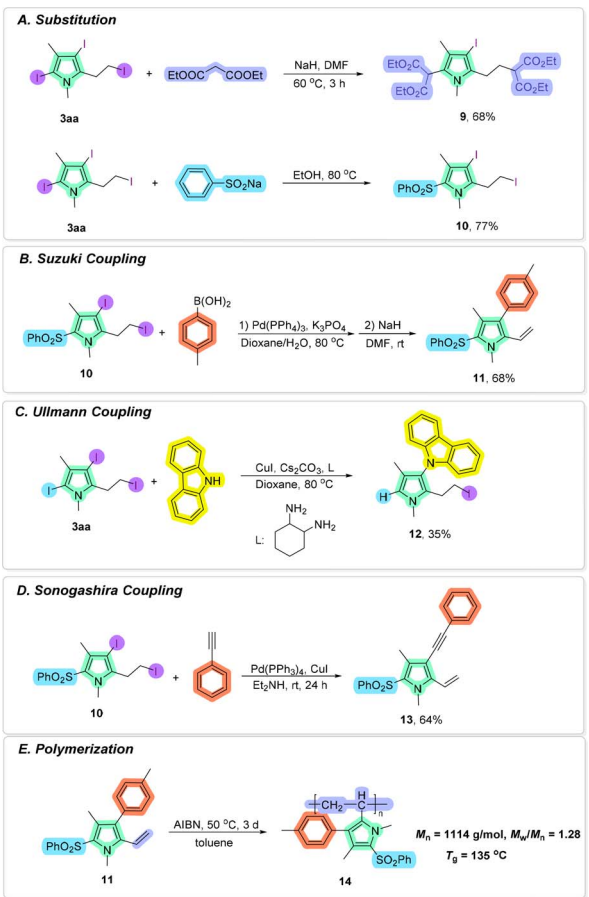
Scheme 7 (a) DFT calculation of **3aa**. (b) Proposed reaction mechanism of **3aa**. (c) DFT calculation of **8a**. (d) Proposed reaction mechanism of **8a**.

was attacked by iodine anion to afford the cyclopropane ring-opened product **3aja**. Subsequently, we attempted to trap the reaction intermediates in the system at −78 °C with VDCP **1r** as the substrate to verify the possible reaction pathway (Scheme 6b). Unfortunately, we did not trap any useful intermediate presumably due to the very fast reaction rate of this transformation. In addition, it was found that using **1r** as the substrate, no reaction occurred in the absence of NIS (Scheme 6c). Moreover, when the employed amount of NIS was reduced to 2.0 equiv., a large amount of diiodinated product **3ra′** was afforded under the standard conditions, indicating that the triiodosubstituted product was forged by the iodination of the diiodosubstituted product (Scheme 6d). In addition, when **1ak** was used as a substrate, we isolated a by-product **3aka′** in 46% yield. However, **3aka′** was unable to convert to the desired product under standard conditions (Scheme 6e). Therefore, **3aka′** was not an active intermediate for this reaction, thus we exclude the possible halocyclization and deprotection pathway (see page S17 in the ESI†).

We subsequently embarked on DFT calculations to gain insight into the reaction mechanism. All calculations have been performed at the SMD(DCM)/B3LYP/6-311+G(d,p)//B3LYP/6-31G(d) level with the Gaussian 16 program.[11] The solvation Gibbs free energy profile in dichloromethane for the suggested reaction pathway is shown in Scheme 7a (see Table S7 in the ESI† for more information). We investigated the reaction pathway starting from the complex **1a+NIS** shown in Scheme 7a. Firstly, **1a+NIS** undergoes cyclization *via* **TS1** with an energy barrier of 18.0 kcal mol^{-1} to form a cationic intermediate **INT1**. The Ts moiety in **INT1** promotes subsequent dehydrogenation to generate **INT2** and release TsH through an activation barrier of 23.7 kcal mol^{-1}, which is a highly exothermic process and indicates that the process shown in Scheme 7a is thermodynamically favorable and has a possibility to take place. In addition, the intermediate **INT3** is obtained by adding iodine anion to the system. Then, the intermediate **INT3** undergoes a cyclopropane ring-opening step to give the pyrrole intermediate **INT4** *via* **TS3** with an energy barrier of 9.4 kcal mol^{-1}, which is also an exothermic process.

Based on the aforementioned experimental results and the detailed DFT calculations, we propose a plausible reaction mechanistic paradigm (Scheme 7b). Initially, in the presence of NIS, the intramolecular nucleophilic attack of the nitrogen atom to the allylic cation moiety *via* transition state **1A** affords cyclized cationic intermediate **1B**. Then, the Ts moiety in **1B** promotes subsequent dehydrogenation to give another cyclized cationic intermediate **1C** and release TsH. Subsequently, the iodine anion attacks cyclopropane and undergoes a ring-opening reaction of cyclopropane to yield the zwitterionic intermediate **1D** (see Fig. S5 in the ESI† for more information), which undergoes a subsequent aromatization to furnish the desired pyrrole intermediate **1E**. Finally, the halogenation reaction of **1E** in the presence of base and NIS gives the desired triiodosubstituted product **3aa**. Furan derivatives **6** were generated by a similar mechanism. However, the low reactivity of furans made it difficult to perform further halogenation reactions under the standard conditions, only furnishing diiodosubstituted products.

Next, we investigated the mechanistic details for the generation of thiophene derivatives through computational studies (Scheme 7c). The intermediate **INT1′** undergoes cyclization and intramolecular hydrogen transfer *via* **TS1′** with an energy barrier of 12.6 kcal mol^{-1} to generate a stable spirocyclic intermediate **INT2′**. The transition state **TS1′** is probably stabilized by *N*-iodosuccinimide in the system. Subsequently, the intermediate **INT3′** is generated through a cyclopropane ring opening reaction in the presence of NIS, passing through **TS2′** with an energy barrier of 24.1 kcal mol^{-1}. The following deprotonation takes place to afford the product complex **INT3′** *via* **TS3′** with an energy barrier of 10.3 kcal mol^{-1}. On the basis of DFT calculations shown in Scheme 7c, the plausible reaction mechanism for the production of **8a** is depicted in Scheme 7d. Initially, **7a** is cyclized by intramolecular nucleophilic attack to yield intermediate **2B** *via* the transition state **2A**. Subsequently, **8a** is produced through cyclopropane ring opening and deprotonation induced by *N*-iodosuccinimide.



Scheme 8 Synthetic transformations. (A) **3aa** (0.5 mmol), NaH (2.5 equiv.), DMF (5.0 mL), 60 °C; **3aa** (0.5 mmol), $PhSO_2Na$ (2.0 equiv.), EtOH; (B) **10** (0.2 mmol), 4-$MeC_6H_4B(OH)_2$ (2.5 equiv.), $Pd(PPh_3)_4$ (10 mol%), K_3PO_4 (3.0 equiv.); (C) **3aa** (0.2 mmol), carbazole (1.5 equiv.), CuI (20 mol%), Cs_2CO_3 (2.0 equiv.); (D) **10** (0.2 mmol), phenylacetylene (2.0 equiv.), $Pd(PPh_3)_4$ (5 mol%), CuI (10 mol%), (E) **11**, AIBN, toluene.

The synthetic utility of the current protocol was demonstrated by diverse derivatizations of the obtained pyrrole product **3aa**. As illustrated in Scheme 8A, substitution of **3aa** with diethyl malonate under basic conditions in DMF successfully provided functionalized pyrrole **9** in 68% yield. In addition, in the presence of sodium benzenesulfinate, **3aa** could be substituted to give pyrrole **10** in 77% yield.[12] Moreover, pyrrole **10** could be effectively transformed into the corresponding product through a Pd-catalyzed Suzuki–Miyaura cross-coupling reaction with 4-methylphenylboronic acid[13] and a combined elimination reaction under basic conditions in DMF[14] (for pyrrole **11**) (Scheme 8B). A carbazole substituted pyrrole **12** could be obtained in 35% yield through a Cu-catalyzed Ullmann reaction with carbazole (Scheme 8C). Furthermore, the Sonogashira coupling[15] reaction of pyrrole **10** with phenylacetylene afforded pyrrole **13** in 64% yield (Scheme 8D). In addition, polypyrroles have been widely used in electrochemistry, and biomedical and sensor applications due to their excellent conductive properties.[16] Polymerization of pyrrole **11** with AIBN as the radical initiator furnished the polymeric product **14** with a molecular weight of 1114 g mol^{-1} (M_w/M_n = 1.28) and the glass transition temperature (T_g) as 135 °C[17] (Scheme 8E).

Conclusions

In summary, we have established a novel and practical strategy for the rapid construction of functionalized pyrroles, furans and thiophenes under metal-free and mild conditions. This synthetic protocol is quite efficient, affording these five-membered heterocycles in moderate to excellent yields within a short reaction time (<30 min.) through NXS mediated desulfonylative/dehydrogenative cyclization of vinylidenecyclopropanes (VDCPs). Compared with traditional reaction modes that frequently employ different synthetic methods to prepare the related substrate depending on the required heteroatom (N, O, S), this reaction can easily provide these heterocycles through a single way. Furthermore, the reaction mechanism was investigated by a series of control experiments and DFT calculations. DFT calculations revealed that a desulfonylative reaction is initiated by the intramolecular nucleophilic attack of the nitrogen atom on the allylic cation moiety and the desulfonylative reaction is the rate-determining step. In addition, the dehydrogenative cyclization may involve a synergistic effect of *N*-iodosuccinimide and iodine anion. Moreover, synthetic transformations demonstrated that this strategy could realize concise synthesis of multi-substituted five-membered heterocyclic compounds and polymers. Further studies on discovering the detailed mechanism and novel reaction types to synthesize other useful compounds are underway.

Data availability

Experimental and computational data have been made available as the ESI.†

Author contributions

Z. Meng, J. Yan and C. Ning contributed to the investigation. Z. Meng and Y. Wei contributed to the calculations. Z. Meng, Y. Wei and M. Shi contributed to the conceptualization and writing-original draft.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

We are grateful for the financial support from the National Key R & D Program of China (2022YFC2303100), the National Natural Science Foundation of China (21372250, 21121062, 21302203, 21772037, 21772226, 21861132014, 91956115 and 22171078) and the Fundamental Research Funds for the Central Universities 222201717003.

References

1 (*a*) V. Bhardwaj, D. Gumber, V. Abbot, S. Dhiman and P. Sharma, *RSC Adv.*, 2015, **5**, 15233–15266; (*b*) S. K. Kulkarni and V. P. Singh, *Curr. Top. Med. Chem.*, 2007, **7**, 251–263; (*c*) M. Ochi, K. Yamada, H. Kawakami, A. Tatsukawa, H. Kotsuki and K. Shibata, *Tetrahedron Lett.*, 1992, **33**, 7531–7534; (*d*) R. A. Craig and B. M. Stoltz, *Chem. Rev.*, 2017, **117**, 7878–7909; (*e*) E. M. Sorenson, P. Culver and V. A. Chiappinelli, *Neuroscience*, 1987, **20**, 875–884; (*f*) A. Mishra, C. Q. Ma and P. Bäuerle, *Chem. Rev.*, 2009, **109**, 1141.

2 G. D. Yin, Z. H. Wang, A. H. Chen, M. Gao, A. X. Wu and Y. J. Pan, *J. Org. Chem.*, 2008, **73**, 3377–3383.

3 (*a*) V. Amarnath, D. C. Anthony, K. Amarnath, W. M. Valentine, L. A. Wetterau and D. G. Graham, *J. Org. Chem.*, 1991, **56**, 6924–6931; (*b*) C. Paal, *Ber. Dtsch. Chem. Ges.*, 1884, **17**, 2756–2767; (*c*) L. Knorr, *Ber. Dtsch. Chem. Ges.*, 1884, **17**, 2863–2870.

4 A. Hantzsch, *Ber. Dtsch. Chem. Ges.*, 1890, **23**, 1474.

5 (*a*) M. A. Calter, R. M. Phillips and C. Flaschenriem, *J. Am. Chem. Soc.*, 2005, **127**, 14566–14567; (*b*) F. Feist, *Ber. Dtsch. Chem. Ges.*, 1902, **35**, 1537–1544; (*c*) E. Benary, *Ber. Dtsch. Chem. Ges.*, 1911, **44**, 489–493.

6 O. Hinsberg, *Ber. Dtsch. Chem. Ges.*, 1910, **43**, 901–906.

7 (*a*) I. Nakamura and Y. Yamamoto, *Chem. Rev.*, 2004, **104**, 2127–2198; (*b*) M. Gao, C. He, H. Chen, R. Bai, B. Cheng and A. Lei, *Angew. Chem., Int. Ed.*, 2013, **52**, 6958–6961; (*c*) Z. W. Gilbert, R. J. Hue and I. A. Tonks, *Nat. Chem.*, 2016, **8**, 63–68; (*d*) M. Zhang, X. Fang, H. Neumann and M. Beller, *J. Am. Chem. Soc.*, 2013, **135**, 11384–11388; (*e*) K. Y. Dong, A. Humeidi, W. Griffith, H. Arman, X. F. Xu and M. P. Doyle, *Angew. Chem., Int. Ed.*, 2021, **60**, 13394–13400; (*f*) X. M. Wang, A. Lerchen, C. G. Daniliuc and F. Glorius, *Angew. Chem., Int. Ed.*, 2018, **57**, 1712–1716; (*g*) V. Y. Chen and O. Kwon, *Angew. Chem., Int. Ed.*, 2021, **60**, 8874–8881; (*h*) H. M. Jin and A. Fürstner, *Angew. Chem.,*

Int. Ed., 2020, **59**, 13618–13622; (*i*) D. Kurandina and V. Gevorgyan, *Org. Lett.*, 2016, **18**, 1804–1807; (*j*) L. Pan, B. H. Zheng, X. H. Yang, L. P. Deng, Y. F. Li and Q. Liu, *Adv. Synth. Catal.*, 2021, **363**, 234–243.

8 (*a*) W. G. Hu, Q. Q. Zhan, H. W. Zhou, S. S. Cao and Z. Y. Jiang, *Chem. Sci.*, 2021, **12**, 6543–6550; (*b*) Y. J. Liu, W. P. Luo, T. T. Xia, Y. W. Fang, C. Du, X. P. Jin, Y. Li, L. Zhang, W. Lei and H. Wua, *Org. Chem. Front.*, 2021, **8**, 1732–1738; (*c*) X. X. Gong, M. J. Wang, S. Q. Ye and J. Wu, *Org. Lett.*, 2019, **21**, 1156–1160.

9 (*a*) M. Shindo, Y. Yoshimura, M. Hayashi, H. Soejima, T. Yoshikawa, K. Matsumoto and K. Shishido, *Org. Lett.*, 2007, **9**, 1963–1966; (*b*) A. Aponick, C. Y. Li, J. Malinge and E. F. Marques, *Org. Lett.*, 2009, **11**, 4624–4627; (*c*) F. Yang, T. N. Jin, M. Bao and Y. Yamamoto, *Tetrahedron*, 2011, **67**, 10147–10155; (*d*) W. W. Tan and N. Yoshikai, *J. Org. Chem.*, 2016, **81**, 5566–5573.

10 (*a*) M. Shi, L. X. Shao, J. M. Lu, Y. Wei, K. Mizuno and H. Maeda, *Chem. Rev.*, 2010, **110**, 5883–5913; (*b*) S. Yang and M. Shi, *Acc. Chem. Res.*, 2018, **51**, 1667–1680; (*c*) D. H. Zhang, X. Y. Tang and M. Shi, *Acc. Chem. Res.*, 2014, **47**, 913–924; (*d*) K. H. Rui and M. Shi, *Org. Chem. Front.*, 2019, **6**, 1816–1820; (*e*) Z. Meng, X. Y. Zhang and M. Shi, *Org. Chem. Front.*, 2021, **8**, 3796–3801; (*f*) C. Xu, C. Ning, S. Yang, Y. Wei and M. Shi, *Adv. Synth. Catal.*, 2021, **363**, 1727–1732; (*g*) C. Ning, K. H. Rui, Y. Wei and M. Shi, *Chem. Sci.*, 2022, **13**, 7310–7317.

11 M. J. Frisch, G. W. Trucks, H. B. Schlegel, G. E. Scuseria, M. A. Robb, J. R. Cheeseman, G. Scalmani, V. Barone, G. A. Petersson, H. Nakatsuji, X. Li, M. Caricato, A. V. Marenich,J. Bloino, B. G. Janesko, R. Gomperts, B. Mennucci, H. P. Hratchian, J. V. Ortiz, A. F. Izmaylov, J. L. Sonnenberg, D. Williams-Young, F. Ding, F. Lipparini, F. Egidi, J. Goings, B. Peng, A. Petrone,T. Henderson, D. Ranasinghe, V. G. Zakrzewski, J. Gao, N. Rega,G. Zheng, W. Liang, M. Hada, M. Ehara, K. Toyota, R. Fukuda, J. Hasegawa, M. Ishida, T. Nakajima, Y. Honda, O. Kitao, H. Nakai,T. Vreven, K. Throssell, J. A. Montgomery Jr., J. E. Peralta, F. Ogliaro, M. J. Bearpark, J. J. Heyd, E. N. Brothers, K. N. Kudin,V. N. Staroverov, T. A. Keith, R. Kobayashi, J. Normand,K. Raghavachari, A. P. Rendell, J. C. Burant, S. S. Iyengar, J. Tomasi, M. Cossi, J. M. Millam, M. Klene, C. Adamo, R. Cammi, J. W. Ochterski, R. L. Martin, K. Morokuma, O. Farkas,J. B. Foresman and D. J. Fox, Gaussian, Inc., Wallingford CT, 2016.

12 M. Z. Miao, X. Xu, L. J. Xu and H. J. Ren, *Eur. J. Org. Chem.*, 2014, **27**, 5896–5900.

13 K. Cui, M. Gao, H. Y. Zhao, D. F. Zhang, H. Yan and H. H. Huang, *Molecules*, 2019, **24**, 1594.

14 E. C. Taylor and W. B. Young, *J. Org. Chem.*, 1995, **24**, 7947–7952.

15 E. R. Wearing, D. E. Blackmun, M. R. Becker and C. S. Schindler, *J. Am. Chem. Soc.*, 2021, **39**, 16235–16242.

16 (*a*) E. N. Zarea, T. Agarwal, A. Zarepour, F. Pinelli, A. Zarrabi, F. Rossi, M. Ashrafizadehc, A. Malekif, M. A. Shahbazi, T. K. Maiti, R. S. Varma, F. R. Tayi, M. R. Hamblinj, V. Mattoli and P. Makvandi, *Appl. Mater. Today*, 2021, **24**, 101117; (*b*) P. Pinyou, V. Blay, J. Monkrathok, P. Janphuang, K. Chansaenpak and J. P. S. Lisnund, *Microchim. Acta*, 2022, **189**, 410; (*c*) L. Hao, C. Y. Dong, L. F. Zhang, K. M. Zhu and D. M. Yu, *Polymers*, 2022, **14**, 5139; (*d*) X. T. Ding, T. Xu, J. Gao, Y. M. Qi, H. M. Zhang and L. T. Qu, *J. Mater. Chem. B*, 2017, **5**, 5733–5737; (*e*) M. Wysocka and K. Winkler, *Electrochim. Acta*, 2017, **258**, 1421–1434.

17 L. L. Liao, Z. H. Wang, K. G. Cao, G. Q. Sun, W. Zhang, C. K. Ran, Y. W. Li, L. Chen, G. M. Cao and D. G. Yu, *J. Am. Chem. Soc.*, 2022, **144**, 2062–2068.