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Hypervalent iodine(III): selective and efficient single-electron-transfer (SET) oxidizing agent

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ABSTRACT

In 1994, we first determined the single-electron-transfer (SET) oxidation ability of phenyliodine(III) bis(trifluoroacetate) (PIFA) toward phenyl ethers, affording the corresponding aromatic cation radicals. Since then, hypervalent iodine(III) has been utilized as a selective and efficient SET oxidizing agent that enables a variety of direct C–H functionalizations of aromatic rings in electron-rich arenes under mild conditions. We have now extended the original method to work in a series of heteroaromatic compounds such as thiophenes, pyrroles, and indoles. The investigations and results obtained since the start of this century are summarized in this article.

1. Introduction

With the recent increasing impetus for developing greener synthetic processes, hypervalent iodine reagents are gaining much attention in modern organic synthesis.[1] A number of trivalent and pentavalent iodine reagents, e.g., phenyliodine(III) diacetate (PIDA), phenyliodine(III) bis(trifluoroacetate) (PIFA), [hydroxy(tosyloxy)iodo]benzene (HTIB, Koser's reagent), iodosobenzene, Dess–Martin periodinane (DMP), and 2-iodoxybenzoic acid (IBX), are now commercially available, and they serve as a useful synthetic tool due to their low toxicity, high stability, ready availability, easy handling, and unique reactivities similar to that of a series of heavy metals, such as lead^{IV}, mercury^{II}, cadmium^{IV}, and thallium^{III}-based agents. These beneficial features as safe and non-toxic organo-oxidants make them universal agents to perform environmentally friendly oxidations, replacing the classical methods that use highly toxic oxidizers. Extensive research studies have been found to date in the literature for investigating the basic reactivities of both iodine(III) and iodine(V) compounds. Based on their contributions for the total syntheses of biologically important natural products and their pivotal intermediates,[2] PIDA and PIFA play particularly important roles to reproduce the biomimetic phenolic oxidation processes under mild conditions.[3–6] The pentavalent DMP and its precursor, IBX, are also known as mild and highly selective reagents showing a broad scope of functional group tolerance for alcohol oxidations.[7,8]

In most cases, the reactivities of hypervalent iodine(III) reagents are typically explained by the two-electron-transfer processes involving the initial ligand exchange of substrates at the iodine centers and successive reductive elimination step to release the iodoarene co-product.[9] For example, the oxidation of phenols **1** with PIDA or PIFA could proceed via a mechanism involving the Type I intermediate, in which the phenolic oxygen initially reacts with the iodine center of the reagents (Eq. 1). Following attack of the nucleophiles (alcohols,[3a,5a–d] amides,[3b] carboxylic acids,[3a,5e–g] water,[3c,5h] oximes,[5i,j] alkenes and alkynes[4a,b,j,k] or enamides,[3d,e] electron-rich aromatic rings,[3f,g,4b–g,l,m] fluoride ion,[6] etc.) at the *para*- or *ortho*-positions of the phenol rings, various cyclohexadienones **2** would be produced, together with the iodobenzene co-product. On the other hand, the hypervalent iodine(III) reagents shown in Figure 1 are also known to act as selective and efficient single-electron-transfer (SET) oxidizing agents for electron-rich aromatic compounds if treated under specific reaction conditions.

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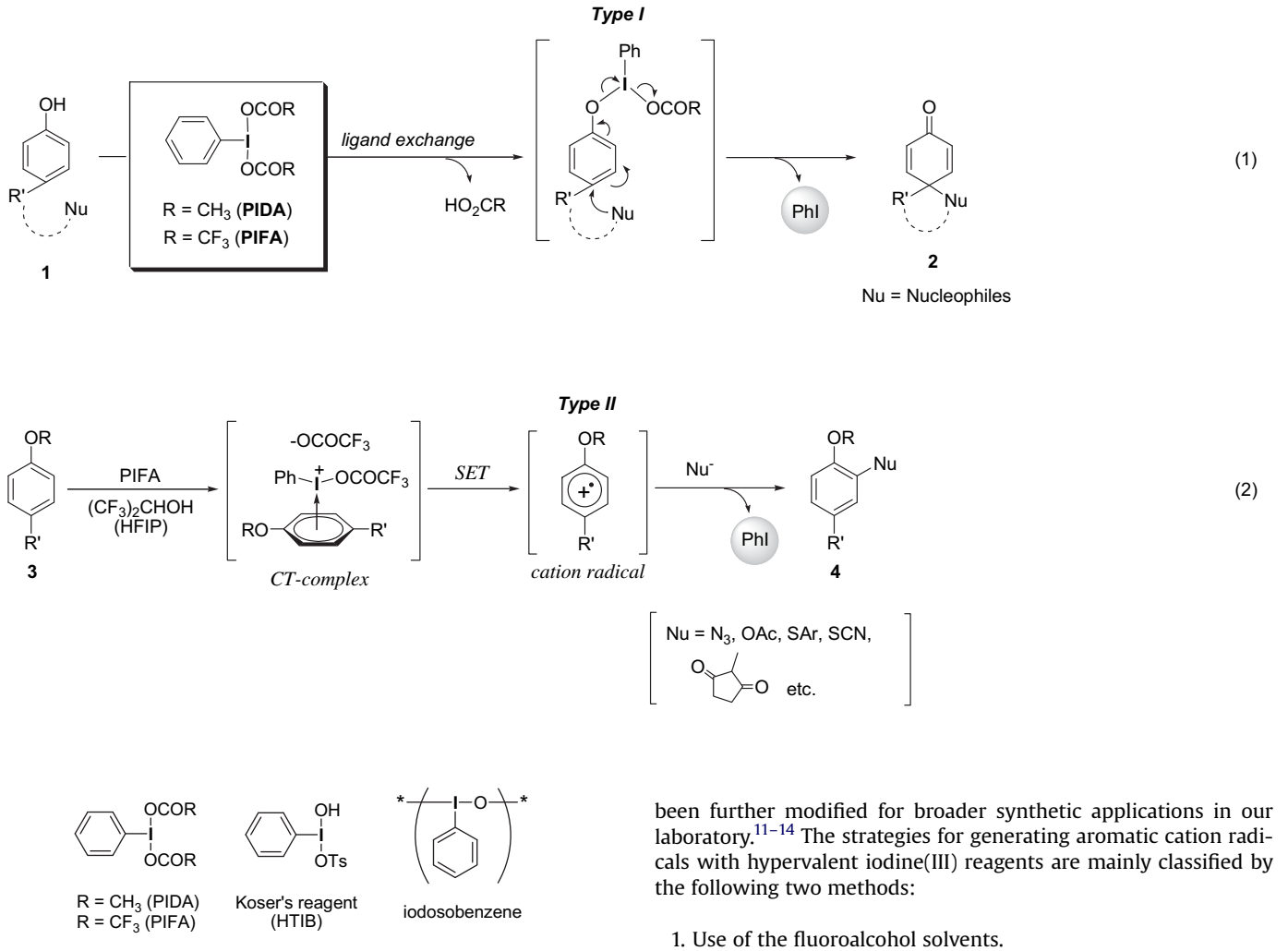


Figure 1. Hypervalent iodine(III) reagents as single-electron-transfer (SET) oxidizing agents for electron-rich aromatic rings.

Regarding this, we reported in 1990 the novel and direct nucleophilic substitution of *p*-substituted phenyl ethers **3** by azide (N_3^-) using a hypervalent iodine(III) reagent, PIFA, in the highly polar, but low nucleophilic fluoroalcohol solvents, 1,1,1,3,3,3-hexafluoro-2-propanol (HFIP) or 2,2,2-trifluoroethanol (TFE) (Eq. 2).[10a] It was quite surprising as phenyl ethers **3** (R=alkyl) are generally inert to iodine(III) reagents and would not react via the reaction mechanism with the Type I phenoxy iodine(III) intermediates. This unusual phenomenon clearly indicated that a new mechanism leading to the substitution products **4** should be involved in the reaction. Based on detailed UV and ESR spectroscopic studies, the generation of Type II aromatic cation radicals induced by the SET oxidation through the charge-transfer (CT) complex of phenyl ethers **3** and PIFA could be determined.[10b] The reactive intermediate was then effectively trapped by the azide nucleophile, resulting in the formation of **4**. Interestingly, the umpolung of the aromatic rings occurred without the use of any metal agent. That is the first case confirming the presence of a cation radical intermediate during the hypervalent iodine-mediated oxidations, and the organoiodine compounds, specifically PIFA, were determined to have an excellent SET oxidation ability toward electron-rich aromatic rings.

As such, the reactivity of hypervalent iodine species highly depends on the employed reaction conditions, and the reagents are now extensively utilized as an efficient and selective SET oxidizing agent. In this decade, the original method for phenyl ethers **3** has been further modified for broader synthetic applications in our laboratory.[11–14] The strategies for generating aromatic cation radicals with hypervalent iodine(III) reagents are mainly classified by the following two methods:

1. Use of the fluoroalcohol solvents.

HFIP and TFE are unique alcohol solvents that exhibit high ionizing powers with low nucleophilicities, which would effectively stabilize in situ generated reactive aromatic cation radical species.[15] Therefore, the formation of aromatic cation radicals by the action of the hypervalent iodine(III) reagents should be facilitated in this media.

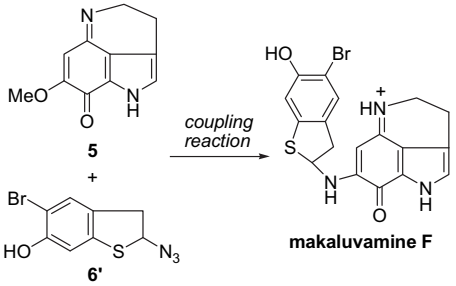
2. Addition of the appropriate Lewis acids.

By coordination to the ligand at the iodine atoms, the acid additives could enhance the SET oxidizing ability of the reagents toward aromatic compounds and thus assist in the smooth generation of aromatic cation radical species. Typical examples include the classically-used $BF_3 \cdot Et_2O$[11] and TMSOTf[12] as well as the soft solid acids, such as heteropoly acids (HPAs)[13] and other series of solid clay catalysts.[14]

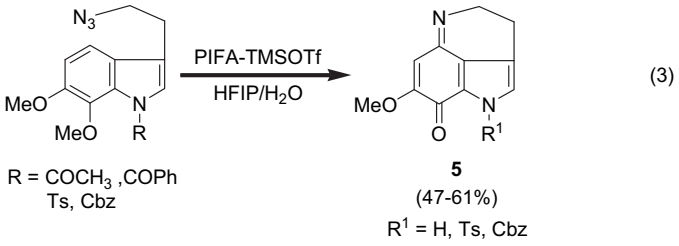
As already shown in Eq. 2, the former enables the selective attack of general nucleophiles (N_3^-, AcO^-, ArS^- [Ar=aryl], SCN^-, and β-dicarbonyl compounds, etc.) at the *ortho*-positions of the cation radical intermediates, furnishing the oxidative aromatic substitution of a variety of *p*-substituted electron-rich phenyl ethers **3** in good yields.[11] Hence, this process has appeared, even recently, in the synthetic courses of non-natural and naturally-occurring molecules having important and diverse biological actions.[16]

Meanwhile, the latter method has significant advantages in controlling the reactivity of the oxidants and the reaction course. As a result, PIFA showed a wide array of reactivities depending on the

added Lewis acids, and became a versatile SET oxidizing agent compatible for more extensive applications. First, we found that the PIFA–$BF_3 \cdot Et_2O$ and PIFA–TMSOTf combinations are particularly effective as the intramolecular variant for the substitution reactions of Eq. 2. For example, the synthesis of pyrroloiminoquinones **5** via intramolecular cyclization of the *N*-protected indoles having the azide side chain was the most successful with the PIFA–TMSOTf system (Eq. 3).[12] A similar cyclization process of sulfide to dihydrobenzothiophene **6**, on the other hand, smoothly proceeded when the reaction was conducted with PIFA–$BF_3 \cdot Et_2O$ in CH_2Cl_2 (Eq. 4).[11a] The functionalized dihydrobenzothiophene **6′** was then obtained after azidation α- to the sulfur atom of **6** and the following deprotection of the acetoxy group. Coupling of **5** and **6′** led to completion of the first total synthesis of a natural product, (±)-makaluvamine F and its analogs (Scheme 1),[17a,b] the key precursors of which were also used in our laboratory for the asymmetric total syntheses of the related sulfur-containing antitumor marine alkaloids, the discorhabdins.[17c,d]



Scheme 1. Final coupling step of **5** and **6′** in the total synthesis of (±)-makaluvamine F.



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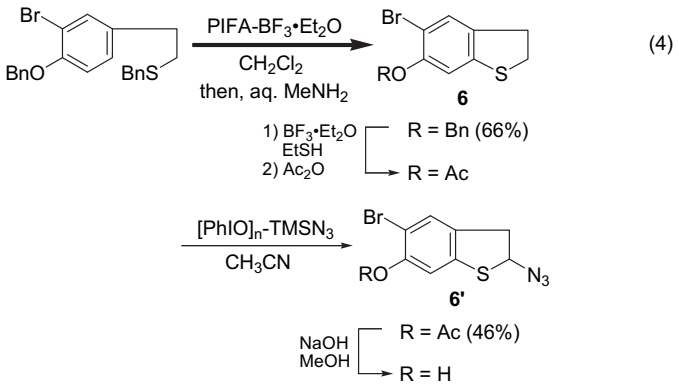
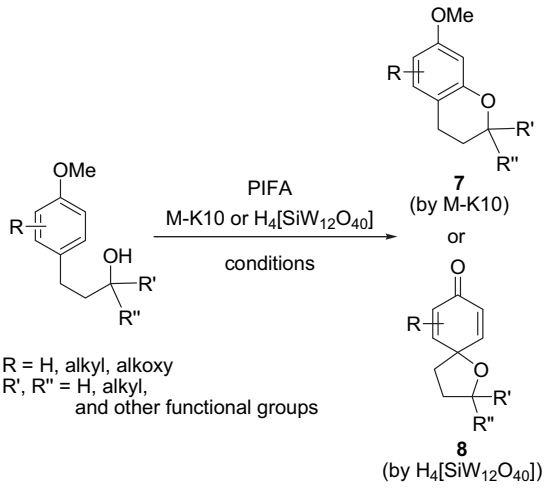


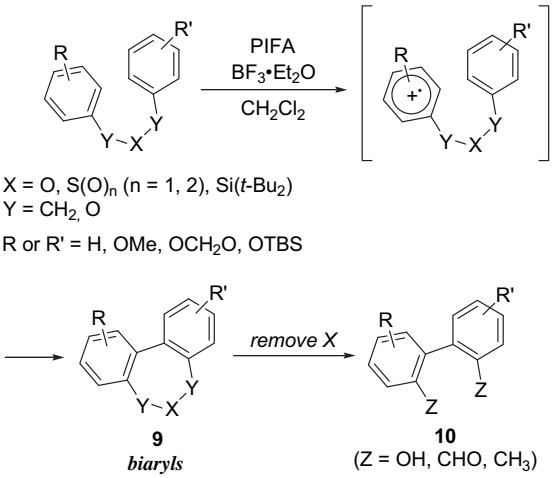
(4)

For the intramolecular attack of hydroxyl groups, the combination of PIFA-M-K10 (montmorillonite K10) clay or HPAs was employed to afford chromans **7** or spirocyclized products **8**, respectively (Eq. 5).[13e,14]



(5)

Although the phenolic-type couplings using hypervalent iodine reagents through the Type I intermediates are known,[3f,g,4e–j] the biaryl coupling of phenyl ether compounds has never been reported. The biaryl substructure is a central building block in not only a large number of bioactive natural products, such as polyketides, terpenes, lignanes, coumarins, flavonoids, tannins, and many alkaloids, but also the ligand of metal catalysts in asymmetric synthesis.[18] Thus, we then extended the above methods to the intramolecular oxidative biaryl coupling process. In particular, our newly developed biaryl synthetic method utilizing the oxygen-, sulfur-, and silicon-tethered templates could provide a practical route for multi-substituted biaryls **9** (Eq. 6).[11b,c] With the activated PIFA, each substrate afforded products **9** in excellent yields by the SET process. The dibenzoheterocyclic structures of **9** were finally cleaved by known general procedures to give the symmetrical or unsymmetrical biaryls **10**.



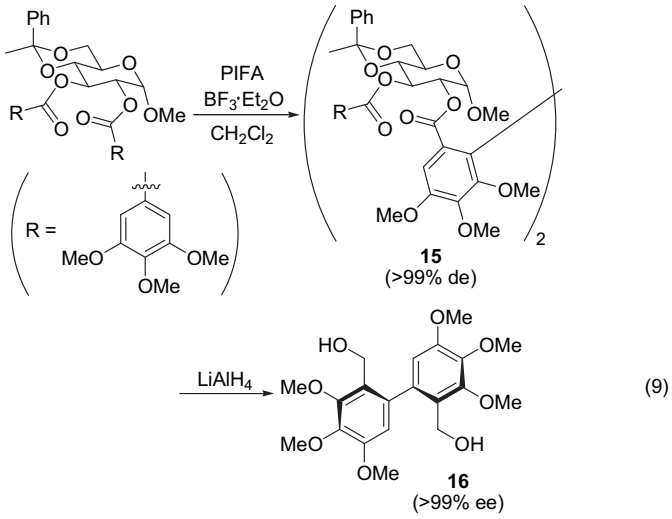
(6)

Interestingly, the use of HPAs as an activator of PIFA showed a remarkable difference to $BF_3 \cdot Et_2O$ in the reactions of the methoxy-substituted bisaryl substrates **11** (Eq. 7). The treatment of **11a** with a combination of PIFA and $BF_3 \cdot Et_2O$ should typically deliver the biaryl compound **13a**.[11b,c] While the spirodienone **12a** was only obtained from the same substrate **11a** when using HPAs instead of $BF_3 \cdot Et_2O$, the coupling site of the reaction was controlled at the *p*-position by the methoxy group.[13a,b] The application of this novel method was most distinct for the non-phenolic coupling of the

benzyltetrahydroisoquinolines for the construction of the morphinandienone-type alkaloid skeletons,[13c,d] which are the important precursors of many pharmaceutical compounds,[19] for example, *O*-methyl flavinantine **12b**. Generally, the chemical oxidation of laudanosine **11b** (and its derivatives) results in the formation of glaucine **13b**, not the morphinandienones.[20] In contrast to the other chemical oxidants, the exclusive formation of the morphinandienone-type product **12b** should occur by using the new reagent combination (PIFA–HPAs) from **11b**.

This type of biaryl coupling reaction was also successful in an intermolecular fashion. Under the optimized conditions with the activated PIFA, the oxidative biaryl coupling of electron-rich aromatic compounds, that is, phenyl ethers and alkylarenes, directly gave the self-coupling products, the biphenyl and binaphthyl dimers **14**, in high yields (Eq. 8).[11e,f] Here, replacement of PIFA with recyclable alternatives is also possible and could improve the reactions for more practical ones.

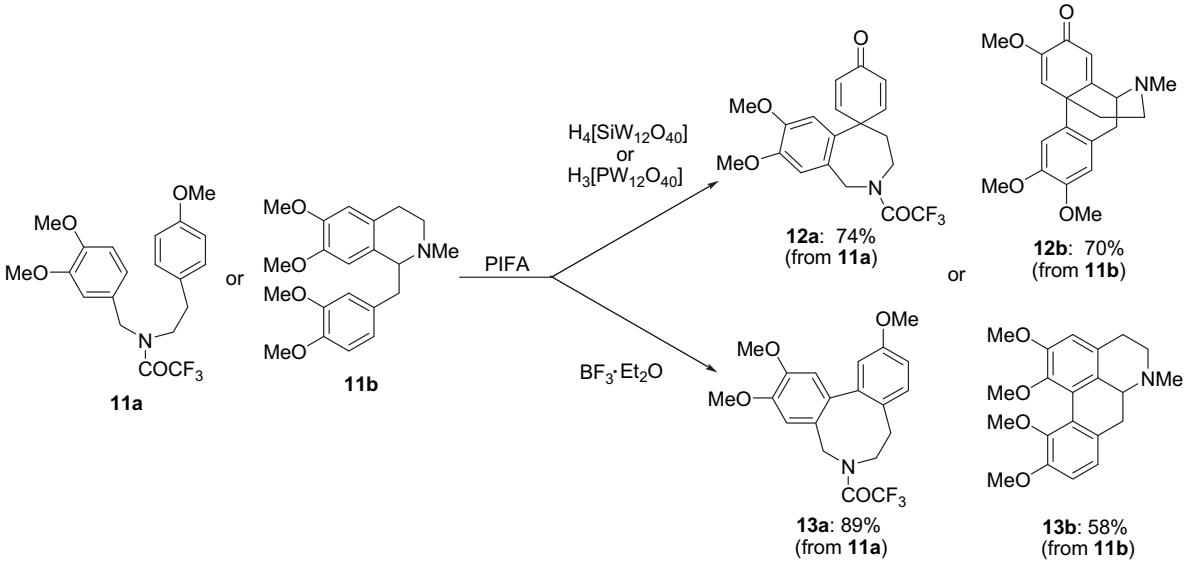
The PIFA-induced intermolecular oxidative coupling was further used for the synthesis of the optically pure chiral biaryls. Utilizing α-D-glucose frameworks as inexpensive chiral templates, the biaryls **15** were generally obtained with high diastereomeric excesses.[11d] Especially, the synthesis of **16**, a potent precursor leading to ellagitannin, was achieved with an extremely high ee value through **15**, which was obtained by the stereo-selective intermolecular oxidative coupling (Eq. 9). Removal of the sugar template by $LiAlH_4$ in the product **15** yielded the optically pure biphenyl **16** (>99% ee).



(9)

As exemplified by these transformations,[10–14] hypervalent iodine(III) reagents, obviously PIFA, as well as their related in situ activated species are promising for reproducing SET oxidation processes that were classically promoted by highly toxic heavy-metal oxidants. Although the initial prospective of the user-friendly organo-oxidants seems to be a simple replacement of these heavy metals, this changes rapidly as the unique reactivities and selectivities are revealed. In our study, we have recently extended our original methods using phenyl ethers **3** and related compounds to work even in a series of heteroaromatic compounds such as thiophenes, pyrroles, and indoles, by choosing a suitable Lewis acid additive and reaction conditions (Eq. 10).[21–24] The use of hypervalent iodine(III) reagents was indispensable for success of each reaction, and notably, other typical organic and inorganic oxidants were unsatisfactory in terms of the reaction yields and product selectivities in these cases.

We now summarize our accomplishment on this theme and report the results obtained since the start of this century. Through this research, hypervalent iodine(III) reagents have become a unique and efficient SET oxidizing agent not only for the conversions of electron-rich benzene rings, but also of heteroaromatics.



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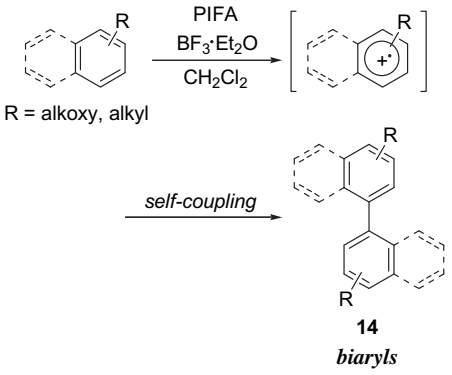

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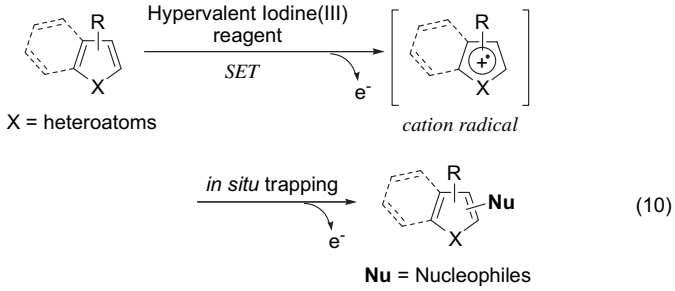
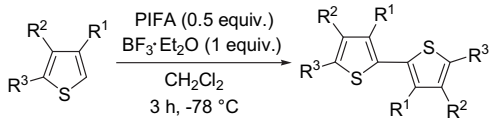


(10)

2. Result and discussion

2.1. Oxidative biaryl coupling reactions of thiophenes using PIFA–$BF_3\cdot Et_2O$ or PIFA–TMSOTf[21]

The treatment of 2,4-dimethylthiophene with 0.5 equiv of PIFA in the presence of $BF_3\cdot Et_2O$ in CH_2Cl_2 at −78 °C gave a corresponding dimer **17a** in moderate yield (Scheme 2). In fluoroalcohol solvents, TFE and HFIP, the dimer **17a** was not obtained, while the formation of diaryliodonium(III) salts **35** usually occurred instead (see below, Section 2.4).[24] The reaction of other di- or tri-alkyl derivatives also proceeded in similar ways. This method could provide the α,α′-linked dimer as the sole coupling product and α,β′-linked regioisomers of **17a** and **17b** were not detected in each case.

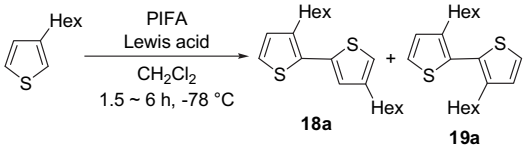


$R^1 = R^3 = Me$, $R^2 = H$ (**17a**): 44% (65%)
R^1 = hexyl , $R^2 = H$, $R^3 = Me$ (**17b**): 45% (68%)
$R^1 = R^2 = R^3 = Me$ (**17c**): 36% (65%)

Scheme 2. Oxidative coupling reaction of alkylthiophenes with PIFA–$BF_3\cdot Et_2O$ to give symmetrical 2,2′-bithiophenes **17**. Yield based on consumed substrates are shown in parenthesis.

The direct oxidative coupling of 3-alkylthiophenes seems to be more difficult, as the forming dimers, **18** or **19**, might be further oxidized and react at the free α-positions due to their lower oxidation potentials than the initial monomers.[25]

Therefore, no direct oxidative coupling method of the 3-alkylthiophenes, to our knowledge, has yet appeared in the literature, though the strategy is a very straightforward and convenient route. In fact, the electro-chemical conditions and metal oxidants, such as Fe^{III}, Tl^{III}, Ru^{III}, and Mo^{V}, have not been utilized for dimerization of these 3-alkylthiophenes, but for oligomerization and polymerization processes.[26] However, surprisingly, the corresponding α-free bithiophenes **18a** [head to tail (H–T) dimer] and **19a** [head to head (H–H) dimer] were directly obtained from 3-hexylthiophene when the reaction was conducted using our



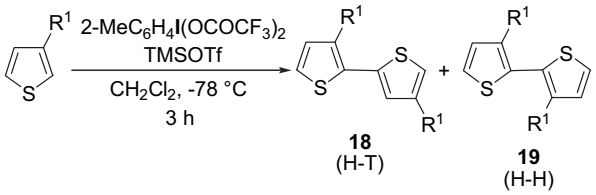
Lewis acid: $BF_3\cdot Et_2O$ 68% (**18a**/**19a** = 46/54)
Bu_2BOTf 71% (64/36)
TMSOTf 41% (94/6)
TMSOTf 72% (81/19)[a)]

Scheme 3. Effect of Lewis acid additive on regioselectivity; (a) 2-Me(C_6H_4) $I(OCOCF_3)_2$ was used instead of PIFA.

coupling conditions (Scheme 3). Although the observed product distribution of the dimers **18** and **19** was nearly equal in the PIFA–$BF_3\cdot Et_2O$ combination, further screening of the Lewis acid improved the regioselectivity. Thus, by using the weak TMSOTf, the H–T dimer **18a** was preferentially formed (**18a**/**19a**=94:6). The yield was also increased by changing the reagent to 2-MeC_6H_4-$I(OCOCF_3)_2$, and the bithiophene mixture of **18a** and **19a** was obtained in better yield with an acceptable selectivity.

A similar product distribution was observed in the series of 3-alkylthiophenes (Table 1). Thiophenes having longer alkyl chains produced dimers with a higher H–T dimer selectivity under these conditions, albeit in lower product yields (Entries 2 and 3). On the other hand, the smaller the alkyl chains, the lower the observed regioselectivity (Entries 4 and 5). The sterically demanding secondary substituents seem to more preferentially force the formation of the H–T dimers **18** compared to the primary alkyl groups (Entries 6 and 7). However, 3-*tert*-butyl thiophene did not give either **18** or **19**, but a tail-to-tail (T–T) dimer was formed (the result is not shown). The bromo-containing thiophene gave the dimers **18h** and **19h**, which could be further modified utilizing the remaining bromo functionality (Entry 8). With respect to the products, the polymerization of **18** can yield the corresponding α-linked H–T-type regioregular polymers having an excellent degree of co-planarity compared to that prepared from the thiophene monomer.[27] Therefore, the H–T dimers **18** have been the focus of much attention as useful precursors of high-quality electroconductive organic materials.[28]

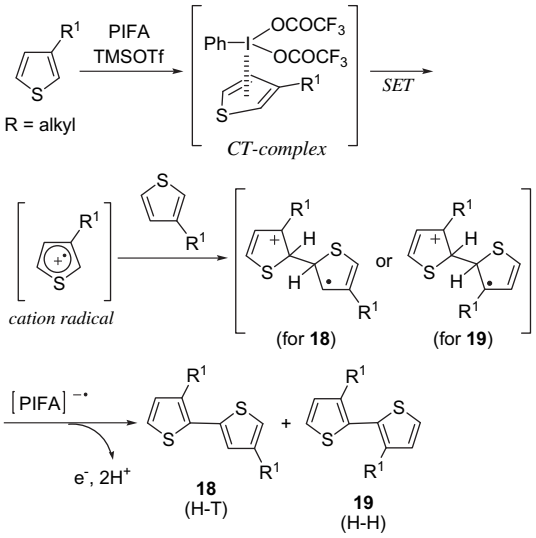
Table 1
Preferential H–T dimer formation of 3-alkylthiophenes[a]



Entry	R^1	Product	Yield[b]
1	Hexyl	**18a**+**19a** (81:19)	72 (90)[d]
2	Heptyl	**18b**+**19b** (92:8)	52
3[c]	Octyl	**18c**+**19c** (95:5)	30
4	Methyl	**18d**+**19d** (80:20)	72
5	Butyl	**18e**+**19e** (77:23)	88
6	*i*-Butyl	**18f**+**19f** (87:13)	98
7[c]	*c*-Hexyl	**18g**+**19g** (90:10)	67
8	$(CH_2)_6Br$	**18h**+**19h** (82:18)	62

[a] The molar ratio of thiophene, iodine(III), and TMSOTf is 3:1:2. The excess amounts of thiophene (1 equiv relative to iodine(III)) were recovered by silica gel column chromatography after the reactions.
[b] Isolated yield calculated from the amount of iodine(III) used.
[c] PIFA was used as oxidant.
[d] Yield based on consumed starting material.

The reaction mechanism for the direct α,α′-bithiophene synthesis is represented by the oxidative coupling of the 3-alkylthiophenes (Scheme 4). Analogous to those of our originally developed PIFA-induced SET oxidation processes for phenyl ethers **3** and alkylarenes,[10–14] the thiophene cation radicals should be formed by the action of PIFA–Lewis acids through the CT-complex. The formed radicals then react with the neutral thiophene molecules. We have confirmed that this process to furnish the biaryl C–C bond of bithiophenes could selectively occur at the 2-position of the cation radicals rather than at the 5-position (see also Section 2.3).[29] Thus, the selective coupling between the 2-position of the cation radicals and the 5-position of the neutral thiophenes accounts for the formation of the H–T linked α,α′-bithiophenes **18**, otherwise the H–H dimers **19** were obtained. Finally, the reactions were completed by

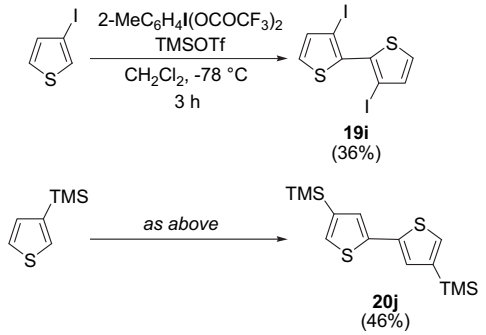


Scheme 4. Reaction mechanism.

the further one-electron oxidation and successive deprotonation to afford the H–T dimers **18** and H–H dimers **19**. Over-oxidations of the dimers would not occur when using the hypervalent iodine reagents, probably because the reactivity of the reagent combinations is high enough to complete the initial SET oxidation process before yielding the dimers.

The addition of the Lewis acids was essential for inducing the effective SET oxidation process. Both $BF_3 \cdot Et_2O$ and TMSOTf could enhance the electrophilicity of the iodine center of PIFA by coordinating to the trifluoroacetoxy ligand.[30] The added Lewis acids thus seem to facilitate the initial interaction of PIFA with thiophenes to form the CT-complex before inducing SET. On the other hand, the precise role of the added Lewis acids on the product selectivity is still unclear, but the persistent radicals are thought to be confined in the coordination sphere of the iodine(III)–Lewis acid complex, by which the product distribution might be controlled.[31]

In contrast to the above cases, the reaction of 3-iodo or 3-trimethylsilyl thiophenes selectively offered the H–H dimer **19i** and T–T dimer **20j** under the same reaction conditions (Scheme 5). The formation of **19i** is probably due to the electronic character of the halogen atom, while the latter is apparently due to steric reasons. Based on the existence of the numerous transformations for the C–halogen and C–Si bonds, these products should be the potential useful precursors for other various H–H or T–T type bithiophene derivatives.

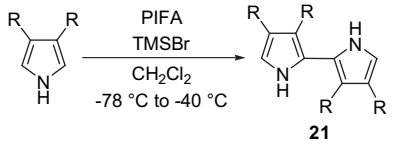


Scheme 5. Selective formation of functionalized H–H dimer **19i** or T–T dimer **20j**.

2.2. Oxidative biaryl coupling reactions of pyrroles and indoles using PIFA–TMSBr[22]

Bipyrrole structures are ubiquitous in natural products, pigments, porphyrin mimics, and components for molecular recognition and self-assembly systems.[32] As the valuable precursor of electroactive organic materials, some electron-rich bipyrroles have recently found new applications due to their high conductivities in the oligomer and polymer forms.[33] However, the synthetic methods for the preparation of these electron-rich bipyrroles are quite limited,[34] and the majorities are the indirect approaches that require multistep transformations involving decarboxylation steps.[35] The direct oxidative coupling of pyrrole themselves is a more attractive way to prepare these bipyrroles,[36] but little attention has currently been paid to this method because of the difficulty in suppressing the formation of byproducts and the need to use stoichiometric amounts of expensive transition metals.

Considering the situation, we then planned to apply the SET strategy using hypervalent iodine reagents as a new straightforward synthetic method for the formation of bipyrroles from 1*H*-pyrroles. Accordingly, the reactions of 1*H*-pyrroles were first examined under the above mentioned conditions with PIFA–$BF_3 \cdot Et_2O$ or PIFA–TMSOTf (Scheme 6). However, these combinations were less effective for the present pyrrole coupling since the pyrroles caused acid-catalyzed oligomerizations by treatment with $BF_3 \cdot Et_2O$ and TMSOTf even in the absence of PIFA. Due to the serious background side reactions, the selection of other suitable activators of PIFA was essential to realize the planned reaction. Fortunately, further screening of the Lewis acid led to finding a more appropriate activator, TMSBr; it functions as an efficient promoter not only to activate PIFA for inducing the desired SET oxidation process, but also to suppress the oligomerization of the pyrroles during the coupling reactions. Using 2 equiv of TMSBr relative to PIFA, the desired coupling of the pyrroles proceeded within 1 h to afford the α,α′-bipyrroles **21a**–**d** in good yields. The pyrrole itself produced only the α,α′-bipyrrole **21a** among the possible three regioisomers, the 2,2′-, 2,3′-, and 3,3′-bipyrroles. It should be noted that protection of the nitrogen atom of the pyrroles was not necessary and the 1*H*-pyrroles were usable in the reactions. As mentioned from a mechanistic point of view (see Scheme 4 for thiophenes), half the amount of the reagent relative to the pyrroles was rationally required for full conversion of the substrates in the oxidative coupling strategy, and thus ca. 1 equiv of the starting materials could be recovered after the reactions by the usual chromatographic workup.



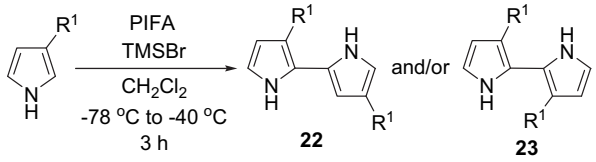
R = H (**21a**): 78%
R = Et (**21b**): 75% (69%)[a)]
R = *i*-Bu (**21c**): 60%
R,R = -$(CH_2)_4$- (**21d**): 61%

Scheme 6. Direct oxidative coupling of pyrroles and 3,4-disubstituted pyrroles. (a) Yield based on the consumed pyrrole.

The C–C bond formation in the coupling reaction of the 3-substituted pyrroles also occurred at each α-position (Table 2). The observed regioselectivity of the coupling products **22** and **23** was similar in extent to the 3-alkylthiophenes (see Table 1). Thus, the crude bipyrrole products typically contained two regioisomers, the unsymmetrical H–T dimers **22** and symmetrical H–H dimers **23**. In the present bipyrrole synthesis, this would not be a problem for obtaining each type of pure bipyrrole **22** and **23**, as these products were separable by purification using typical chromatographic techniques (see the Experimental section). No H–T and H–H dimer was formed from 3-*tert*-butyl thiophene because of the steric repulsion between the two bulky groups (Eq. 11).[37] Although the

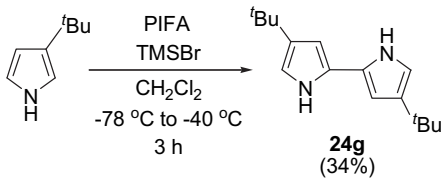
electron-deficient pyrroles, such as the *N*-tosylpyrrole, were still unreactive as expected, the presence of several functional groups (ester, arene, ether, halogen, etc.) in the side chains of the pyrroles was acceptable (Entries 3–6). Therefore, the present method has the potential to provide a practical route for constructing a new class of bipyrroles.

Table 2
Synthesis of α-linked bipyrroles using PIFA[a]



Entry	R^1	Yield[b]	
1	Methyl	58% (**22a**)	12% (**23a**)
2	Heptyl	60% (**22b**)	9% (**23b**)
3	$(CH_2)_3CO_2Me$	82% (**22c**)	13% (**23c**)
4	Phenyl	70% (**22d**)	13% (**23d**)
5	4-$MeOC_6H_4$	52% (**22e**)	<1% (**23e**)
6	4-BrC_6H_4	68% (**22f**)	8% (**23f**)

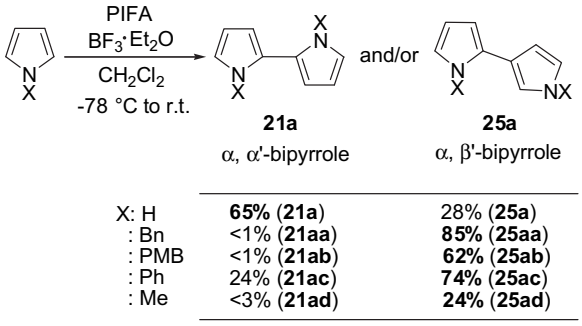
[a] The molar ratio of pyrroles, PIFA, and TMSBr is 3:1:2. The excess amount of remaining substrates (0.5–1 equiv relative to PIFA) were recovered after the reactions by column chromatography on neutral alumina.
[b] Isolated yield calculated from the amount of PIFA.



(11)

When the reaction was applied to 3-methylindole, dihydroindole **27** was formed together with the bisindole **26** (Scheme 7). As the isolated **27** did not produce the bisindole **26** under the reaction conditions, a stepwise mechanism involving the addition product **27** was excluded for the formation of **26**. Rather, the production of **27** should be regarded as the result of an acid-induced background side reaction of the indole via the iminium ion.[38] Our persistent attempts to detect intermediates in the pyrrole coupling also suggested the absence of an alternative stepwise reaction pathway through addition-type intermediates like the dihydroindole **27**. Based on these experiments as well as our continuous studies, we considered the involvement of the pyrrole cation radicals,[39] which were generated by SET from the pyrroles toward PIFA–TMSBr.

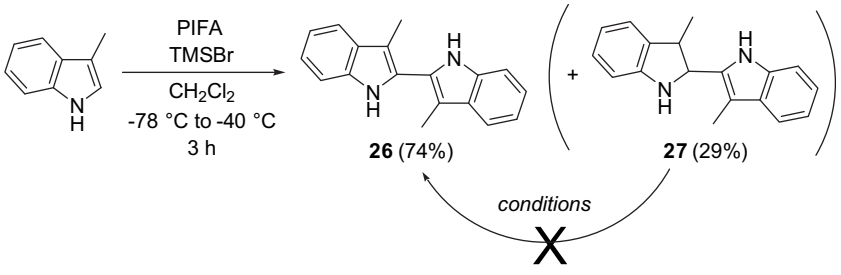
Modification of the steric environment around the nitrogen atom of the pyrrole allows control of the product selectivity (Scheme 8). In all instances, any substituent at the nitrogen atom of the pyrrole would contribute to the production of the α,β′-bipyrroles **25**, and **25aa–ad** were produced by the coupling of the *N*-substituted pyrrole derivatives, while the 1*H*-pyrrole mainly gave the α,α′-bipyrrole **21a**. The benzyl groups showed the highest α,β′-bipyrrole selectivities among those examined, which could be removed after the coupling reactions according to standard deprotection procedures. Since the *N*-substituted pyrroles are exceptionally stable even in the presence of the strong Lewis acid, $BF_3{\cdot}Et_2O$, its use is plausible here for obtaining the α,β′-bipyrrole products **25aa–ad** in good yields, otherwise TMSBr tends to produce certain amounts of α,α′-bipyrroles **21aa–ad** similar to the results observed for the 1*H*-pyrroles. The *N*-substituent of the pyrroles was thus an important factor for the reactions regarding both the product selectivity and stability of the starting substrates. Unfortunately, the method is quite case-sensitive and was not applicable to other ring-substituted pyrrole derivatives, such as the 3-alkyl and aryl pyrroles. However, considering the absence of an alternative facile approach to obtain these unique molecules,[40] the α,β′-bipyrroles **25** prepared from the present method appear to be usable as the common component for other modified compounds having the α,β′-bipyrrole frameworks.



Scheme 8. Influence of *N*-substituent for α,β′-bipyrrole synthesis. PMB=*p*-methoxybenzyl.

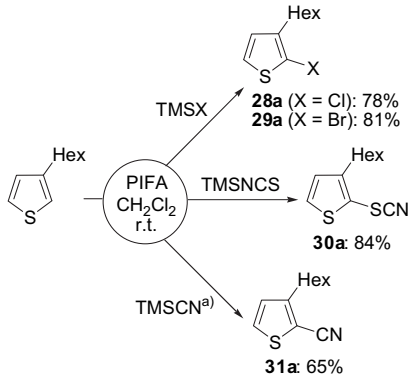
2.3. Introduction of nucleophiles for heteroaromatic compounds using PIFA by oxidative substitution

During the reaction of heteroaromatic compounds with hypervalent iodine(III) reagents, the formation of diaryliodonium (III) salts **35** is accelerated in HFIP and TFE (see Section 2.4).[24] Due to this remarkable solvent effect for producing reactions for the condensation products **35**, the aromatic substitution shown in Eq. 2 fairly occurred in heteroaromatic compounds in the fluoroalcohol solvents[10] and typically resulted in failure. Despite the limitation, several nucleophiles could be introduced in standard solvents by utilizing the second strategy with the Lewis acid-activated PIFA. In 3-hexylthiophene, halogens were introduced by treatment with PIFA and TMSX (X=Cl or Br) in CH_2Cl_2 (Scheme 9). We have examined the other silicon-based nucleophiles, TMSNCS and TMSCN, for thiocyanation and cyanation in the same



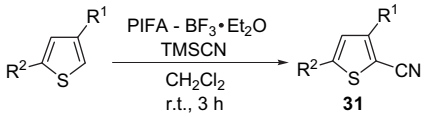
Scheme 7. Oxidative coupling reaction of 3-methylindole.

substrate. With PIFA–$BF_3 \cdot Et_2O$, both trials could provide the substitution products **30a** or **31a** in good yields. In particular, the last case became a unique and efficient method to selectively introduce the cyano functionality into a wide range of electron-rich heteroaromatic compounds, without the need for any pre-functionalization.[23]



Scheme 9. Oxidative introduction of several nucleophiles toward thiophene using PIFA–Lewis acids in dichloromethane. (a) In the presence of $BF_3 \cdot Et_2O$.

The reported methods for direct introduction of the cyano group into heteroaromatic compounds mostly rely on the use of highly reactive and unstable cyano cation equivalents (^{+}CN),[41] by which the difficulty of the reaction control and preparation of unstable reagents were sometimes encountered. From this view point, a direct cyanating method under oxidative conditions using the stable cyanide anion (^{-}CN) is very attractive.[42] This results in a series of thiophenes that support the versatility of this new method with PIFA–$BF_3 \cdot Et_2O$ and TMSCN (Scheme 10). All reactions occurred at the α-position of the thiophenes. In the 3-substituted thiophenes, the 2-cyanated products **31a–e** were selectively obtained. Likewise, the reaction is quite sensitive relative to the electronic character of the thiophenes. The presence of some donating groups, e.g., OMe, on the thiophene ring was acceptable, but no cation radicals were formed at all in the thiophenes possessing electron-withdrawing groups such as an ester or cyano functionality. This fact suggests that over-oxidation of the cyanated products **31** would not occur during the reactions, which is responsible for the observed high product selectivity. Therefore, no detectable side products derived from the over-oxidations of **31** were obtained even when using an excess amount of PIFA (2 equiv).

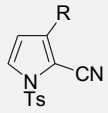
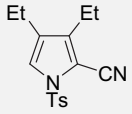
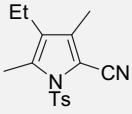
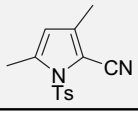


R^1 = Hex, R^2 = H (**31a**): 65%
R^1 = Me, R^2 = H (**31b**): 79%
R^1 = *c*-Hex, R^2 = H (**31c**): 59%
R^1 = OMe, R^2 = H (**31d**): 42%
R^1 = Ph, R^2 = H (**31e**): 68%
R^1 = H, R^2 = Me (**31f**): 62%[a)]

Scheme 10. PIFA-induced direct α-cyanation of thiophenes using TMSCN as cyanide source. (a) GC yield.

Considering the results in Scheme 10, we extended the new cyanating method to other heteroaromatic compounds having oxidation potentials similar to those of the thiophenes. Since the 1*H*-pyrroles caused the acid-promoted oligomerization as a background reaction by the persistent $BF_3 \cdot Et_2O$ (Section 2.2), an appropriate protecting group of the pyrrole nitrogen atom that can modulate the stability and nucleophilicity of the pyrrole ring was evaluated. Among the series of *N*-protected pyrroles, the oxidation potential of *N*-tosylpyrrole [E_p^{ox} (V vs SCE)=1.96],[43] which lies between the values of the 3-alkylthiophenes[44] and alkylbenzenes,[45] seems to be the most suitable for this transformation. Indeed, *N*-tosylpyrrole was fully converted to 2-cyano-*N*-tosylpyrrole **32a** in 83% yield (Table 3, Entry 1). The corresponding 2-cyanated products were obtained in poorer yields with other *N*-substituents (Bn, PMB, Ph, Me, Boc, etc.). The tosyl groups in the product **32a** was removable by the standard deprotection protocols.[46]

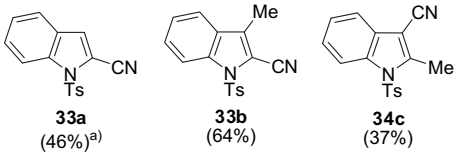
Table 3
Direct α-cyanation of *N*-tosylpyrroles induced by PIFA–$BF_3 \cdot Et_2O$[a]

Entry	α-Cyano pyrrole	Product	Yield[b]
			
1	R=H	**32a**	83
2	R=Methyl	**32b**	70
3	R=Heptyl	**32c**	71
4	R=$(CH_2)_3CO_2Me$	**32d**	86
5	R=*t*-Butyl	**32e**	94
6	R=2-BrC_6H_4	**32f**	97
7	R=4-BrC_6H_4	**32g**	90
8	R=4-$OMeC_6H_4$	**32h**	45
9		**32i**	73
10		**32j**	58
11		**32k**	43

[a] All reactions were carried out by using 3 equiv of TMSCN, 2 equiv of PIFA, and 4 equiv of $BF_3 \cdot Et_2O$ for 3 h at room temperature.
[b] Isolated yield.

The cyanating reaction was applicable for a wide range of substituted pyrroles as summarized in Table 3. The reaction of pyrroles having aliphatic or aromatic substituents at their 3-position afforded the corresponding 2-cyanated products **32b–h** (Entries 2–8). The steric difference in the substituent did not affect the regioselectivity and yield (Entry 5). ^1H NMR measurement of the crude cyanated products revealed that the selectivity of the reaction position is high enough to produce less than 3% of other regioisomeric products. The observed yield of **32h** was lower because of the competitive oxidations by PIFA attributed to the electron-rich phenyl ether ring (Entry 8).

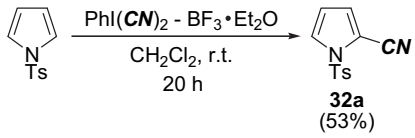
This cyanation protocol was also available for the *N*-tosyl indoles, despite the slightly problematic yield and regioselectivity



Scheme 11. Reaction of indole derivatives. (a) The product included small amount of β-cyano isomer.

(Scheme 11). For the *N*-tosylindole, the α-cyanated **33a** was produced, but a small amount of the regioisomeric isomer derived from the reaction at the β-position was also detected. 2-Methyl-*N*-tosylindole gave the α-cyanated product **33b**, and 3-methyl-*N*-tosylindole reacted at the 3-position in turn, as anticipated by the *N*-tosylindole result.

The reaction mechanism to introduce the cyanide should be considered to be similar to that of the previous oxidative substitution of phenyl ethers **3** and alkylarenes by oxygen, nitrogen, sulfur, and carbon nucleophiles, including the cation radical intermediates.[10,11] However, premixing of all reagents was essential in the order of PIFA, TMSCN, and $BF_3 \cdot Et_2O$ to produce the best performance in this system. They were mixed for 30 min before adding the substrates, otherwise the yield of the cyanated products was slightly lower. This appears to imply that the real oxidant for the reaction was not just PIFA. As an alternative species for initiating the cyanation, we focused on the hypervalent iodine reagents having a cyano ligand. These types of compounds were previously synthesized from $[PhIO]_n$ or PIFA and TMSCN through ligand exchange.[47] With this perspective, we prepared (dicyanoiodo)-benzene ($PhI(CN)_2$) according to the literature method,[47a] and used it with $BF_3 \cdot Et_2O$ for the reaction (Scheme 12). Although $PhI(CN)_2$ was inherently not reactive to *N*-tosylpyrrole, it gradually started the reaction after activation by $BF_3 \cdot Et_2O$, and the cyanated product **32a** was produced, *without the addition of the external cyanide source*, *TMSCN*. Therefore, the rapid transfer of the cyano ligand from the iodine(III) atom to the cation radicals, not directly from TMSCN, seem to be one of the important driving forces of the present reaction.

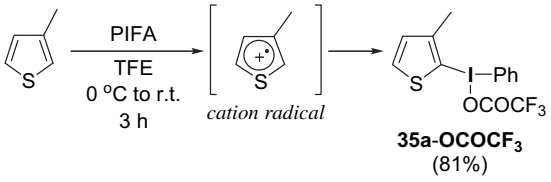


Scheme 12. Direct cyanating reaction using (dicyanoiodo)benzene $PhI(CN)_2$ with $BF_3 \cdot Et_2O$.

To summarize, a plausible mechanism of the cyanating reaction is depicted in Scheme 13. Initially, PIFA reacted with TMSCN to produce $PhI(CN)_2$ or its analog (Y=$OCOCF_3$) by facile ligand exchange between the cyanide and trifluoroacetoxy group at the iodine(III) center. The formed iodine(III)–CN species was then activated by the Lewis acid to induce the SET oxidation of the heteroaromatic compounds, generating the cation radical intermediates. The reactive cation radical intermediates could be directly measured by electron spin resonance (ESR) spectroscopy in this system.[23b] The regioselective cyano-transfer toward the intermediates[48] followed by a further one-electron oxidation and deprotonation gave the products **31** or **32** along with an iodobenzene co-product.

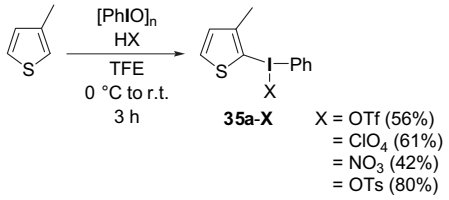
2.4. Direct dehydrative approach for heteroaromatic iodonium(III) salts in fluoroalcohol solvents[24]

The use of fluoroalcohol media is promising for aromatic cation radical generation in the iodine(III)-induced SET oxidation.[10] This principle should be available for heteroaromatic compounds, and indeed, the thiophenes produced the corresponding cation radical in HFIP or TFE like the previous transformations described in Section 2.3, the presence of which was also detectable by ESR and UV spectroscopy.[49] If a good leaving group effectively accommodating the anion charge was present in a ligand, the reaction with heteroaromatic compounds typically resulted in the formation of diaryliodonium(III) salts having it as a counterion, as exemplified in Eq. 12. The present dehydrative condensation is very facile and clean, only producing water as the co-product.[50]



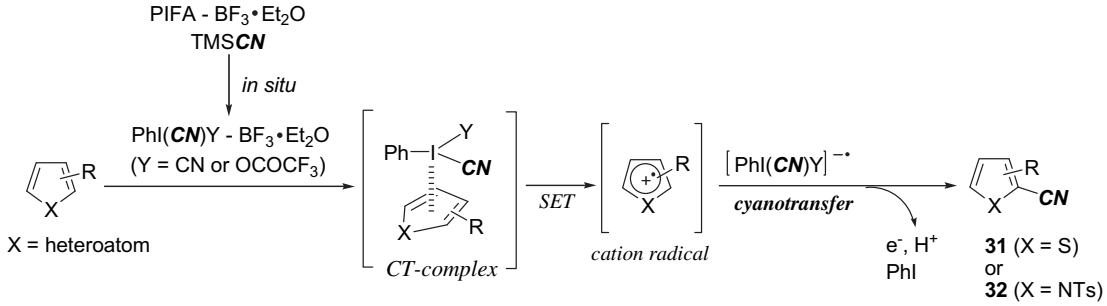
(12)

The chemical and physical properties of the diaryliodonium(III) salts highly depend on the nature of the anionic counterpart. Modification of the counterions was easily attainable using another reagent, that is, $[PhIO]_n$ (Scheme 14). A variety of Brønsted acids were conveniently introduced to the products **35a** as the counterions, X, by this strategy.

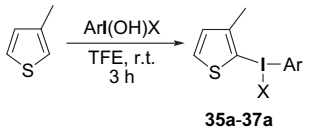


Scheme 14. Thienyl iodonium(III) salts having differential X.

A significant number of Koser's-type reagents are now readily available,[51] and variation of the reagents in the reaction could expand the structural diversity of the obtained products. The selected examples are shown in Scheme 15. Iodonium salts **35**–**37** having differential aryl rings and counterions X were obtained from a single thiophene substrate, after precipitation of the products **35**–**37** by replacement of the reaction solvent, TFE, to the non-polar Et_2O. A significant advantage of using fluoroalcohol solvents is what various types of reagents can be usable in these ways.



Scheme 13. A plausible reaction mechanism for direct cyanating reaction of heteroaromatic compounds.



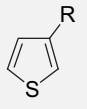
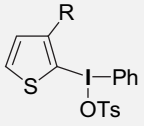
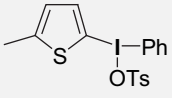
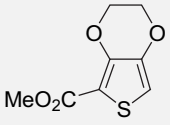
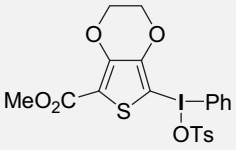
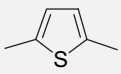
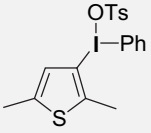
35a-37a

Ar	X	
Ph	OTs	**35a-OTs** (98%)
mesityl	OTs	**36a-OTs** (78%)
C_6F_5	OTs	**37a-OTs** (70%)
Ph	OMs	**35a-OMs** (89%)
Ph	OCs	**35a-OCs** (92%)

Scheme 15. Formation of iodonium(III) sulfonates. Ms=methanesulfonyl, Cs=(±)-10-camphorsulfonyl.

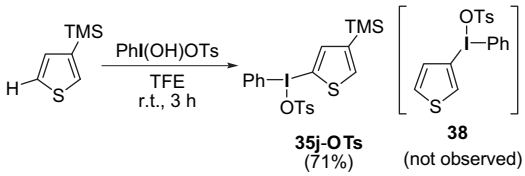
Table 4 represents the versatility of the thiophene substrates when using PhI(OH)OTs. Based on our expectation, the scope and selectivity of the reactions were similar to those of the transformations having already appeared in Tables 1–3 and Scheme 5. The condensation preferentially occurred at the α-position of thiophene atom, among which the 2-position was more reactive in the 3-substituted thiophenes (Entries 1–6). In all cases, no other iodine(III) impurities and regioisomeric products were contaminated in the products **35**. On the other hand, the α-disubstituted thiophenes could afford the β-thienyl iodonium salt **35i-OTs** (Entry 9). A remarkable solvent effect was clearly observed in each case, and the reactions finished within a shorter reaction time (3 h) when compared to other solvents, such as CH_2Cl_2.[50b] These thienyliodonium(III) salts **35-OTs** show a wide range of applicability as photoacid generator (PAG) for cationic polymerization processes,[52a] active bactericides,[52b,c] and as arylating agents in organic synthesis.[53]

Table 4
Scope of thiophene substrates[a]

Entry	Thiophene	Product (**35-OTs**)	Yield[b]
			
1	R=Methyl	**35a-OTs**	98
2	R=*i*-Butyl	**35b-OTs**	93
3	R=*c*-Hexyl	**35c-OTs**	74
4	R=OMe	**35d-OTs**	89
5	R=Br	**35e-OTs**	95
6	R=4-$MeO_2CC_6H_4$	**35f-OTs**	98
7		 **35g-OTs**	93
8		 **35h-OTs**	88
9		 **35i-OTs**	62

[a] Reactions were performed using equimolar amount of thiophenes and PhI(OH)OTs in TFE (0.20 M) for 3 h at room temperature.
[b] Isolated yield of pure product after precipitation.

A unique selectivity was observed in the organosilicon compound. In the competitive reaction of the C–H and C–Si bonds in 3-trimethylsilylthiophene, an *ipso*-substitution product **38** as a result of electrophilic substitution via the Wheland type of σ-complex[50] was not obtained, but instead produced a dehydrative condensation product **35j-OTs** (Scheme 16).[54] Therefore, the present direct and waste-free approach based on the cation radical strategy[55] has a broad range of versatility for the synthesis of various diaryliodonium(III) salts[56] as well as a unique selectivity not available by other methods.



35j-OTs (71%) **38** (not observed)

Scheme 16. Competitive reaction between C–H and C–Si bonds.

3. Conclusion

In this article, we describe our continuous effort regarding the use of hypervalent iodines as a selective and efficient SET oxidizing agent, especially emphasizing the extension of the original method in phenyl ethers **3** to the heteroaromatic compounds. As a result, several new facile and useful oxidative transformations of thiophenes, pyrroles, and indoles, have been developed by choosing the appropriate Lewis acids or fluoroalcohol solvents. The use of hypervalent iodines as an oxidant was essential for each reaction progress, hence the success of which apparently relies on the excellent SET oxidation ability of the reagents as well as their mild nature of reactivity to only permit the desired oxidations.

After discovering that PIFA works as an excellent SET oxidizing agent for affording aromatic cation radicals,[10] it has been playing a main role in exploiting the new field of chemistry. Due to their activity, a variety of other iodine reagents such as $[PhIO]_n$ and HTIB are now being used. In particular, utilization of the adamantane-type reagents (Fig. 2),[57] which were originally developed by us as useful recyclable alternatives to PIFA and HTIB, is the next promising step for making these reactions greener and more practical.[58]

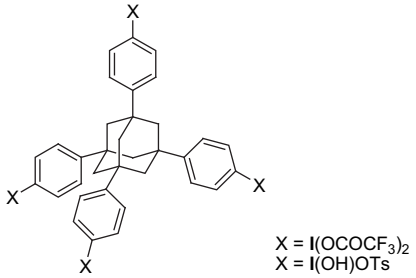


Figure 2. Adamantane-type recyclable alternatives to PIFA and HTIB.

In closing, the innovative research front of this area that has appeared in the past few years should be noted. One is that the biaryl coupling methods illustrated in Eq. 8 have been successfully extended to the unprecedented selective and high-yield intermolecular cross-coupling processes.[59] More recently, a novel and metal-free cross-coupling method of heteroaromtatic compounds has been developed utilizing the diaryliodonium(III) salts in Section 2.4, which can partially replace conventional biaryl syntheses that require multi-steps and use of transition metals.[60] Surprisingly, the competitive formation of homodimers would not

occur in these cases by using hypervalent iodines(III), while other oxidants (V^{V}, Mn^{III}, Mo^{V}, Fe^{III}, Tl^{III}, and Pb^{IV}-based heavy metals in strong acids, nitric acid-based oxidants, anodic oxidations, combination of palladium catalysts and oxidants, etc.) were invalid, based on our studies, for obtaining the cross-coupling products due to the difficulty in suppressing the self-dimerization process of aromatic substrates to produce undesired homobiaryls. Thus, these methods involving the hypervalent iodine-induced SET oxidation processes as the key step have become unique and valuable new metal-free direct C–H functionalization processes of electron-rich aromatic compounds.

By these contributions, hypervalent iodines will continue to make an impact as unique and efficient SET oxidizing agents in the 21st century. We hope that the summarized principles and the results provided herein should provide seminal guidance for understanding the versatility of these reagents in the SET oxidations and for promising their future development in a variety of new SET oxidizing chemical processes.

4. Experimental

4.1. General

Melting points (mp) are uncorrected. The ^{1}H NMR (and ^{13}C NMR) spectra were recorded by a JEOL JMN-300 spectrometer operating at 300 MHz (75.3 MHz for ^{13}C NMR) in $CDCl_3$ at 25 °C with tetramethylsilane as the internal standard. The data are reported as follows: chemical shift in parts per million (δ), integration, multiplicity (s=singlet, d=doublet, t=triplet, q=quartet, brs=broad singlet, m=multiplet), and coupling constant (Hz). The infrared spectra (IR) were obtained using a Hitachi 270-50 spectrometer. The mass spectra were obtained using a Shimadzu GCMS-QP 5000 instrument with ionization voltages of 70 eV. The high resolution mass spectra and elemental analysis were performed by the Elemental Analysis Section of Osaka University. The column chromatography and TLC were carried out on Merck Silica gel 60 (230–400 mesh) and Merck Silica gel F_{254} plates (0.25 mm), respectively. The spots and bands were detected by UV irradiation (254, 365 nm). $PhI(OCOCF_3)_2$ (PIFA) is prepared according to the literature procedure.[61] PhI(OH)OTs (HTIB, Koser's reagent), $[PhIO]_n$, $BF_3\cdot Et_2O$, TMSOTf, and TMSBr are commercially available compounds and were used as received. *N*-Tosylated pyrroles and indoles were prepared from corresponding 1*H*-pyrroles and *p*-toluenesulfonyl chloride as the usual N-tosylation procedures.[46b] Solvents and all other starting materials were obtained from commercial suppliers and were used without further purification.

4.2. General procedure for oxidative biaryl coupling of thiophenes using PIFA–$BF_3\cdot Et_2O$

$BF_3\cdot Et_2O$ (0.26 mL, 2.0 mmol) and PIFA (430 mg, 1.0 mmol) were added sequentially to a stirred solution of 2,4-dimethylthiophene (224 mg, 2.0 mmol) in CH_2Cl_2 (3 mL) at −78 °C under a nitrogen atmosphere. The mixture was stirred for 3 h under the same reaction condition. Aqueous workup with saturated $NaHCO_3$ at 0 °C followed by column chromatography (SiO_2/*n*-hexane) gave the corresponding bithiophene **17a** (98 mg, 0.44 mmol) in 44% yield.

*4.2.1. 3,3′,5,5′-Tetramethyl-2,2′-bithiophene (**17a**).* Colorless crystals, mp 61–62 °C (EtOH). (lit.[62] mp 61 °C (EtOH)). IR (KBr) cm^{-1}: 2916, 2856, 1440, 1211, 1132, 914, 825. ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.09 (s, 6H), 2.43 (s, 6H), 6.56 (s, 2H) ppm. ^{13}C NMR (75.3 MHz, $CDCl_3$) δ 14.6, 15.2, 127.2, 128.3, 136.0, 138.9 ppm. MS *m*/*z* 222 $[M]^{+}$.

*4.2.2. 3,3′-Dihexyl-5,5′-dimethyl-2,2′-bithiophene (**17b**).* A colorless oil. IR (KBr) cm^{-1}: 2923, 2854, 1454, 912, 742. ^{1}H NMR (270 MHz, $CDCl_3$) δ 0.81–0.91 (m, 6H), 1.18–1.34 (m, 12H), 1.43–1.56 (m, 4H), 2.41 (t, 4H, *J*=8.1 Hz), 2.44 (s, 6H), 6.59 (s, 2H) ppm. ^{13}C NMR (67.8 MHz, $CDCl_3$) δ 14.0, 15.3, 22.5, 28.8, 29.1, 30.6, 31.6, 126.5, 126.8, 139.1, 142.0 ppm. Anal. Calcd for $C_{22}H_{34}S_2$: C, 72.86; H, 9.45; S, 17.68. Found: C, 73.07; H, 9.38; S, 17.41.

*4.2.3. 3,3′,4,4′,5,5′-Hexamethyl-2,2′-bithiophene (**17c**).* A colorless solid, mp 165–167 °C (EtOH) (lit.[63] mp 163–165 °C (EtOH)). IR (KBr) cm^{-1}: 2914, 2852, 1444, 912, 742. ^{1}H NMR (270 MHz, $CDCl_3$) δ 2.00 (s, 6H), 2.05 (s, 6H), 2.34 (s, 6H) ppm. ^{13}C NMR (67.8 MHz, $CDCl_3$) δ 12.7, 13.3, 14.0, 132.3, 133.3, 136.2 ppm. MS *m*/*z* 250 $[M]^{+}$.

4.3. General procedure for regioselective oxidative coupling of 3-alkylthiophenes with PIFA–TMSOTf

TMSOTf (0.36 mL, 2.0 mmol) and PIFA (430 mg, 1.0 mmol) were sequentially added to a stirred solution of 3-hexylthiophene (0.50 g, 3.0 mmol) in CH_2Cl_2 (2.5 mL) at −78 °C under a nitrogen atmosphere. The mixture was stirred for 3 h under the same reaction condition. An aqueous workup with saturated $NaHCO_3$ at 0 °C followed by column chromatography (SiO_2/*n*-hexane) gave the corresponding 2,2′-bithiophenes **18a** and **19a** in 41% yield as a mixture. The formation of two regioisomers, H–T and H–H, was confirmed by using a previously reported procedure.[64]

*4.3.1. 3,4′-Dihexyl-2,2′-bithiophene (**18a**)[20] and 3,3′-dihexyl-2,2′-bithiophene (**19a**)[21].* A yellow oil. IR (KBr) cm^{-1}: 2950, 2850, 1457, 1377. ^{1}H NMR (300 MHz, $CDCl_3$) δ 0.84–0.92 (m, 6H, for **18a** and **19a**), 1.15–1.37 (m, 12H, for **18a** and **19a**), 1.46–1.70 (m, 4H, for **18a** and **19a**), 2.49 (4H, t, *J*=7.5 Hz, for **19a**), 2.63 (t, 2H, *J*=8.4 Hz, for **18a**), 2.74 (t, 2H, *J*=8.4 Hz, for **18a**), 6.90–6.94 (m, for **18a** and **19a**), 7.03 (s, 1H, for **18a**), 7.12 (d, 1H, *J*=5.5 Hz, for **18a**), 7.27 (d, 2H, *J*=5.1 Hz, for **19a**) ppm. ^{13}C NMR (75.3 MHz, $CDCl_3$) δ 14.1, 22.5, 22.6, 28.7, 29.0, 29.1, 29.2, 29.7, 30.4, 30.5, 30.6, 30.7, 31.6, 31.7, 119.9, 123.4, 125.2, 127.3, 128.5, 128.7, 129.9, 130.9, 135.8, 139.3, 142.3, 143.5 ppm. HRMS (FAB) Calcd for $C_{20}H_{30}S_2$ $[M]^{+}$ 334.1789, found 334.1784.

*4.3.2. 3,4′-Diheptyl-2,2′-bithiophene (**18b**) and 3,3′-diheptyl-2,2′-bithiophene (**19b**).* A colorless oil. ^{1}H NMR (300 MHz, $CDCl_3$) δ 0.86 (m, 6H, for **18b** and **19b**), 1.23–1.45 (m, 16H, for **18b** and **19b**), 1.48–1.68 (m, 4H, for **18b** and **19b**), 2.49 (t, 4H, *J*=7.8 Hz, for **19b**), 2.60 (t, 2H, *J*=7.8 Hz, for **18b**), 2.74 (t, 2H, *J*=7.8 Hz, for **18b**), 6.86–6.98 (m, for **18b** and **19b**), 7.14 (d, 1H, *J*=5.4 Hz, for **18b**), 7.27 (d, 2H, *J*=5.1 Hz, for **19b**) ppm. HRMS (FAB) Calcd for $C_{22}H_{34}S_2$ $[M]^{+}$ 362.2102, found 362.2087.

*4.3.3. 3,4′-Dioctyl-2,2′-bithiophene (**18c**) and 3,3′-dioctyl-2,2′-bithiophene (**19c**).* A colorless oil. IR (KBr) cm^{-1}: 2923, 2853, 1464, 1377, 1200, 1086, 831, 721, 652. ^{1}H NMR (300 MHz, $CDCl_3$) δ 0.83–0.96 (m, 6H, for **18c** and **19c**), 1.16–1.42 (m, 20H, for **18c** and **19c**), 1.47–1.70 (m, 4H, for **18c** and **19c**), 2.48 (t, 4H, *J*=7.8 Hz, for **19c**), 2.59 (t, 2H, *J*=7.8 Hz, for **18c**), 2.73 (t, 2H, *J*=7.8 Hz, for **18c**), 6.87–6.95 (m, for **18c** and **19c**), 7.12 (d, 1H, *J*=5.1 Hz, for **18c**), 7.26 (d, 2H, *J*=5.1 Hz, for **19c**) ppm. ^{13}C NMR (75.3 MHz, $CDCl_3$) δ 14.1, 15.2, 22.6, 28.7, 29.1, 29.2, 29.3, 29.4, 29.5, 30.4, 30.5, 30.7, 31.8, 119.8, 123.3, 125.2, 127.3, 128.5, 128.7, 129.8, 130.9, 135.8, 139.3, 142.3, 143.5 ppm. Anal. Calcd for $C_{24}H_{38}S_2$: C, 73.78; H, 9.80; S, 16.42. Found: C, 73.83; H, 9.82; S, 16.13.

*4.3.4. 3,4′-Dimethyl-2,2′-bithiophene (**18d**)[65] and 3,3′-dimethyl-2,2′-bithiophene (**19d**).* A yellow oil. IR (KBr) cm^{-1}: 2950, 2850, 1457, 1377. ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.17 (s, 6H, for **19d**), 2.28 (s, 3H, for **18d**), 2.38 (s, 3H, for **18d**), 6.86–6.93 (m, for **18d** and **19d**), 7.11 (d, 1H, *J*=5.1 Hz, for **18d**), 7.24 (d, 2H, *J*=5.1 Hz, for **19d**) ppm. ^{13}C NMR

(75.3 MHz, $CDCl_3$) δ 14.6, 15.3, 15.7, 120.4, 123.0, 124.9, 127.8, 129.3, 130.0, 131.3, 133.7, 136.3, 136.4, 138.0, 141.32 ppm.

*4.3.5. 3,4′-Dibutyl-2,2′-bithiophene (**18e**) and 3,3′-dibutyl-2,2′-bithiophene (**19e**).* A yellow oil. IR (KBr) cm^{-1}: 3051, 2930, 2858, 1732, 1456, 1377, 1263, 1088, 831, 748, 652. ^1H NMR (300 MHz, $CDCl_3$) δ 0.85–0.97 (m, 6H, for **18e** and **19e**), 1.20–1.45 (m, 4H, for **18e** and **19e**), 1.46–1.68 (m, 4H, for **18e** and **19e**), 2.50 (t, 4H, J=7.8 Hz, for **19e**), 2.60 (t, 2H, J=7.8 Hz, for **18e**), 2.75 (t, 2H, J=7.8 Hz, for **18e**), 6.87–6.96 (m, for **18e** and **19e**), 7.13 (d, 1H, J=5.4 Hz, for **18e**), 7.26 (d, 2H, J=5.1 Hz, for **19e**) ppm. ^{13}C NMR (75.3 MHz, $CDCl_3$) δ 13.8, 13.9, 22.3, 22.4, 22.6, 28.4, 28.8, 30.1, 30.2, 32.5, 32.8, 119.8, 123.3, 125.1, 127.3, 128.5, 128.7, 129.8, 130.9, 134.1, 139.3, 142.2, 143.9 ppm. Anal. Calcd for $C_{16}H_{22}S_2$: C, 69.01; H, 7.96; S, 23.03. Found: C, 69.01; H, 7.93; S, 22.74.

*4.3.6. 3,4′-Diisobutyl-2,2′-bithiophene (**18f**) and 3,3′-diisobutyl-2,2′-bithiophene (**19f**).* A yellow oil. ^1H NMR (300 MHz, $CDCl_3$) δ 0.79–0.92 (m, 12H, for **18f** and **19f**), 1.79–1.91 (m, 2H, for **18f** and **19f**), 2.34 (d, 4H, J=8.1 Hz, for **19f**), 2.43 (d, 2H, J=7.8 Hz, for **18f**), 2.58 (d, 2H, J=7.8 Hz, for **18f**), 6.81–6.92 (m, for **18f** and **19f**), 7.09 (1H, d, J=5.4 Hz, for **18f**), 7.24 (d, 2H, J=5.1 Hz, for **19f**) ppm. HRMS (FAB) Calcd for $C_{16}H_{22}S_2$ $[M]^+$ 278.1163, found 278.1152.

*4.3.7. 3,4′-Dicyclohexyl-2,2′-bithiophene (**18g**) and 3,3′-dicyclohexyl-2,2′-bithiophene (**19g**).* A yellow oil. IR (KBr) cm^{-1}: 2923, 2851, 1728, 1448, 1263, 1124, 943, 833, 731, 708, 650. ^1H NMR (300 MHz, $CDCl_3$) δ 1.15–1.56 (m, for **18g** and **19g**), 1.65–1.87 (m, for **18g** and **19g**), 1.99–2.02 (m, 2H, for **18g**), 2.57–2.65 (m, for **18g** and **19g**), 2.96–3.01 (m, 1H, for **18g**), 6.91 (s, 1H, for **18g**), 6.97–7.05 (m, for **18g** and **19g**), 7.15 (d, 1H, J=5.4 Hz, for **18g**), 7.31 (d, 2H, J=5.1 Hz, for **19g**) ppm. ^{13}C NMR (75.3 MHz, $CDCl_3$) δ 26.1, 26.6, 26.7, 34.1, 34.4, 34.5, 38.1, 38.2, 39.6, 118.5, 123.8, 125.4, 126.1, 126.4, 127.3, 127.5, 130.1, 135.5, 144.8, 147.5, 149.26 ppm. Anal. Calcd for $C_{20}H_{26}S_2$: C, 72.67; H, 7.93; S, 19.40. Found: C, 72.66; H, 7.86; S,19.09.

*4.3.8. 3,4′-Bis(6-bromohexyl)-2,2′-bithiophene (**18h**) and 3,3′-bis(6-bromohexyl)-2,2′-bithiophene (**19h**).* A yellow oil. IR (KBr) cm^{-1}: 2931, 1726, 1556, 1529, 1456, 1257, 1219, 1085, 1037, 831, 725, 644. ^1H NMR (300 MHz, $CDCl_3$) δ 1.14–1.88 (m, 8H, for **18h** and **19h**), 2.45 (t, 4H, J=7.8 Hz, for **19h**), 2.56 (t, 2H, J=7.8 Hz, for **18h**), 2.70 (t, 2H, J=7.8 Hz, for **18h**), 3.29–3.39 (m, 4H, for **18h** and **19h**), 6.81–6.92 (m, for **18h** and **19h**), 7.09 (d, 1H, J=5.4 Hz, for **18h**), 7.24 (d, 2H, J=5.1 Hz, for **19h**) ppm. HRMS (FAB) Calcd for $C_{20}H_{28}Br_2S_2$ $[M]^+$ 489.9999, found 489.9988.

*4.3.9. 3,3′-Diiodo-2,2′-bithiophene (**19i**).* A yellow solid, mp 49–50 °C (hexane/AcOEt). IR (KBr) cm^{-1}: 3097, 2924, 1759, 1595, 1473, 1437, 1390, 1332, 1261, 1139, 1082, 900, 850, 796, 713. ^1H NMR (300 MHz, $CDCl_3$) δ 7.18 (d, 2H, J=5.4 Hz), 7.41 (d, 2H, J=5.4 Hz) ppm. ^{13}C NMR (75.3 MHz, $CDCl_3$) δ 85.1, 129.3, 134.9, 135.6 ppm. HRMS (FAB) Calcd for $C_8H_4S_2I_2$ $[M]^+$ 417.7844, found 417.7850.

*4.3.10. 4,4′-Bis(trimethylsilyl)-2,2′-bithiophene (**20j**)[66].* A gray solid, mp 75–78 °C (MeOH). IR (KBr) cm^{-1}: 2953, 2895, 1654, 1485, 1377, 1249, 1182, 1105, 935, 833, 748, 692. ^1H NMR (300 MHz, $CDCl_3$) δ 0.26 (s, 18H), 7.17 (d, 2H, J=1.2 Hz), 7.26 (d, 2H, J=1.2 Hz) ppm. ^{13}C NMR (75.3 MHz, $CDCl_3$) δ −0.70, 128.4, 130.4, 138.0, 142.9 ppm.

4.4. General procedure for direct oxidative coupling of pyrroles using a combination of PIFA and TMSBr

To a stirred solution of 1*H*-pyrrole (111 mg, 0.9 mmol) in CH_2Cl_2 (15 mL), PIFA (0.3 mmol) and TMSBr (0.6 mmol) were quickly added at −78 °C. The reaction mixture was then stirred for 1 h, while the reaction temperature was maintained below −40 °C. After the reaction completion, saturated aqueous $NaHCO_3$ (ca. 20 mL) was added to the mixture, and then stirred for an additional 10 min at ambient temperature. The organic layer was separated and the aqueous phase was extracted with CH_2Cl_2. The combined extract was dried with Na_2SO_4 and evaporated. The residue was purified by column chromatography (SiO_2 (neutral)/*n*-hexane–AcOEt) to give the pure 2,2′-bipyrrole **21a** (56 mg, 75%) as a colorless oil. The less polar fractions gave unreacted pyrrole as a pure form (31 mg).

*4.4.1. 2,2′-Bi-1H-pyrrole (**21a**).* A colorless solid, mp 187–189 °C (hexane/AcOEt). IR (KBr) cm^{-1}: 3366, 3123, 3103, 1574, 1518, 1454, 1425, 1404, 1261, 1097, 1032, 912, 891, 775, 743, 658. ^1H NMR (300 MHz, $CDCl_3$) δ 6.05–6.19 (m, 4H), 6.70–6.72 (m, 2H), 8.23 (br s, 2H) ppm. ^{13}C NMR (75.3 MHz, $CDCl_3$) δ 103.5, 109.4, 117.6, 125.9 ppm. Anal. Calcd for $C_8H_8N_2$: C, 72.70; H, 6.10; S, 20.92. Found: C, 72.41; H, 6.22; S, 20.92.

*4.4.2. 3,3′,4,4′-Tetraethyl-2,2′-bi-1H-pyrrole (**21b**)[67].* A colorless solid, mp 90–92 °C (hexane/AcOEt). IR (KBr) cm^{-1}: 3373, 2963, 2867, 1553, 1435, 1371, 1327, 1259, 1190, 1086, 1063, 1038, 947, 912, 742, 650. ^1H NMR (300 MHz, $CDCl_3$) δ 1.05 (t, 6H, J=7.8 Hz), 1.25 (t, 6H, J=7.8 Hz), 2.42 (q, 4H, J=7.8 Hz), 2.52 (q, 4H, J=7.8 Hz), 6.53 (br s, 2H), 7.58 (br s, 2H) ppm. ^{13}C NMR (75.3 MHz, $CDCl_3$) δ 14,1, 16.0, 17.9, 18.6, 113.8, 121.1, 122.9, 125.2 ppm. MS *m*/*z* 244 $[M]^+$.

*4.4.3. 3,3′,4,4′-Tetrakis(2-methylpropyl)-2,2′-bi-1H-pyrrole (**21c**).* yellow oil. IR (KBr) cm^{-1}: 3477, 3379, 2866, 1464, 1433, 1381, 1364, 1339, 1167, 1091, 912, 743, 650. ^1H NMR (300 MHz, $CDCl_3$) δ 0.78 (d, 12H, J=6.6 Hz), 0.93 (d, 12H, J=6.6 Hz), 1.60–1.69 (m, 2H), 1.76–1.85 (m, 2H), 2.23 (d, 4H, J=7.2 Hz), 2.30 (d, 4H, J=7.2 Hz), 6.48 (s, 2H), 7.66 (br s, 2H) ppm. ^{13}C NMR (75.3 MHz, $CDCl_3$) δ 22.6, 22.7, 29.2, 29.3, 34.3, 35.1, 114.6, 120.5, 122.0, 122.7 ppm. HRMS (FAB) Calcd for $C_{24}H_{40}N_2$ $[M]^+$ 356.3191, found 356.3189.

*4.4.4. 4,4′,5,5′,6,6′,7,7′-Octahydro-1,1′-bi-1H-isoindole (**21d**).* A yellow oil. IR (KBr) cm^{-1}: 3442, 3371, 2930, 2847, 1560, 1435, 1387, 1317, 1256, 1184, 1132, 1076, 1032, 955, 916, 822, 733, 650. ^1H NMR (300 MHz, CD_2Cl_2) δ 1.72–1.78 (m, 8H), 2.58–2.63 (m, 8H), 6.46 (br s, 2H), 7.92 (br s, 2H) ppm. ^{13}C NMR (75.3 MHz, $CDCl_3$) δ 21.8, 22.6, 23.5, 23.9, 112.0, 114.7, 120.1, 120.2 ppm. HRMS (FAB) Calcd for $C_{16}H_{20}N_2$ $[M]^+$ 240.1626, found 240.1641.

In the reaction of 3-substituted 1*H*-pyrroles, two regioisomers [head to tail dimers (**22**, major products)] and [head to head dimers (**23**, minor products)] were formed. These regioisomers were separable by usual column chromatography techniques (SiO_2 (neutral)/*n*-hexane–AcOEt), the regiochemistry of which was determined according to the literature.[33a]

*4.4.5. 3,4′-Dimethyl-2,2′-bi-1H-pyrrole (**22a**)[33a].* A yellow oil. IR (KBr) cm^{-1}: 3377, 3096, 2924, 2866, 1562, 1504, 1435, 1381, 1261, 1207, 1173, 1097, 1063, 1030, 972, 912, 889, 793, 741, 689. ^1H NMR (300 MHz, $CDCl_3$) δ 2.14 (s, 3H), 2.20 (s, 3H), 6.00–6.04 (m, 1H), 6.07 (t, 1H, J=2.4 Hz), 6.49–6.53 (m, 1H), 6.59 (t, 1H, J=2.4 Hz), 7.93 (br s, 2H) ppm. ^{13}C NMR (75.3 MHz, $CDCl_3$) δ 11.8, 12.0, 106.7, 111.3, 114.5, 115.4, 116.5, 119.6, 122.1, 125.6 ppm. MS, *m*/*z*: 160 $[M]^+$.

*4.4.6. 3,3′-Dimethyl-2,2′-bi-1H-pyrrole (**23a**)[33a].* A yellow oil. ^1H NMR (300 MHz, CD_2Cl_2) δ 2.16 (s, 6H), 6.14 (t, 2H, J=2.4 Hz), 6.72 (t, 2H, J=2.4 Hz), 7.95 (br s, 2H). MS, *m*/*z*: 160 $[M]^+$.

*4.4.7. 3,4′-Diheptyl-2,2′-bi-1H-pyrrole (**22b**).* A yellow oil. IR (KBr) cm^{-1}: 3371, 2924, 2853, 1684, 1437, 1377, 1107, 976, 891. ^1H NMR (300 MHz, $CDCl_3$) δ 0.80–0.95 (m, 6H), 1.22–1.38 (m, 16H), 1.53–1.64 (m, 4H), 2.48 (t, 2H, J=7.5 Hz), 2.56 (t, 2H, J=7.5 Hz), 5.97–6.12 (m,

1H), 6.12 (t, 1H, *J*=2.7 Hz), 6.47–6.65 (m, 1H), 6.68 (t, 1H, *J*=2.7 Hz), 7.91 (br s, 1H), 7.95 (br s, 1H) ppm. ^{13}C NMR (75.3 MHz, $CDCl_3$) δ 14.1(×2), 22.7, 26.5, 27.0, 29.2(×2), 29.5, 29.6, 31.1, 31.2, 31.8, 31.9, 106.0, 109.8, 114.6, 116.6, 120.4, 121.7, 125.4, 125.6 ppm. HRMS (FAB) Calcd for $C_{22}H_{36}N_2$ $[M]^+$ 328.2878, found 328.2862.

*4.4.8. 3,3′-Diheptyl-2,2′-bi-1H-pyrrole (**23b**).* A yellow oil. ^{1}H NMR (300 MHz, CD_2Cl_2) δ 0.80–0.92 (m, 6H), 1.22–1.30 (m, 16H), 1.57–1.55 (m, 4H), 2.39 (t, 4H, *J*=7.8 Hz), 6.12 (t, 2H, *J*=2.7 Hz), 6.74 (t, 2H, *J*=2.7 Hz), 7.97 (br s, 2H) ppm. MS, *m*/*z*: 328 $[M]^+$.

*4.4.9. [2,2′-Bi-1H-pyrrole]-3,4′-dibutanoic acid dimethyl ester (**22c**).* A yellow oil. IR (KBr) cm^{-1}: 3377, 2949, 2853, 1713, 1556, 1537, 1504, 1454, 1433, 1140, 1101, 1003, 912, 797, 743. ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.82–2.03 (m, 4H), 2.33–2.46 (m, 4H), 2.54 (t, 2H, *J*=7.8 Hz), 2.61 (t, 2H, *J*=7.8 Hz), 3.67 (s, 3H), 3.70 (s, 3H), 6.02–6.04 (m, 1H), 6.07 (t, 1H, *J*=2.7 Hz), 6.62–6.64 (m, 1H), 6.67 (t, 1H, *J*=2.7 Hz), 8.09 (br s, 1H), 9.03 (br s, 1H) ppm. ^{13}C NMR (75.3 MHz, $CDCl_3$) δ 25.7, 26.2, 26.3, 26.4, 32.9, 33.6, 51.5, 51.7, 104.9, 109.9, 115.4, 116.6, 118.3, 122.3, 123.6, 125.4, 174.4, 175.2 ppm. HRMS (FAB) Calcd for $C_{18}H_{24}N_2O_4Na$ $[M+Na]^+$ 355.1634, found 355.1628.

*4.4.10. [2,2′-Bi-1H-pyrrole]-3,3′-dibutanoic acid dimethyl ester (**23c**).* A yellow oil. ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.82–1.99 (m, 4H), 2.35 (t, 4H, *J*=7.3 Hz), 2.52 (t, 4H, *J*=7.3 Hz), 3.64 (s, 6H), 6.12 (t, 2H, *J*=2.7 Hz), 6.78 (t, 2H, *J*=2.7 Hz), 8.61 (br s, 2H). MS, *m*/*z*: 332 $[M]^+$.

*4.4.11. 3,4′-Diphenyl-2,2′-bi-1H-pyrrole (**22d**).* A colorless solid, mp 60–62 °C (hexane/CH_2Cl_2). IR (KBr) cm^{-1}: 3379, 2855, 1790, 1682, 1177, 912, 743, 650. ^{1}H NMR (300 MHz, $CDCl_3$) δ 6.35 (t, 1H, *J*=2.7 Hz), 6.50–6.52 (m, 1H), 6.74 (t, 1H, *J*=2.7 Hz), 6.85–6.87 (m, 1H), 7.09–7.51 (m, 10H), 7.98 (br s, 1H), 8.14 (br s, 1H) ppm. ^{13}C NMR (75.3 MHz, $CDCl_3$) δ 103.5, 109.8, 110.2, 114.6, 117.9, 120.8, 121.0, 124.90, 125.20, 125.60, 125.80, 126.1, 128.1, 128.6, 135.3, 136.2 ppm. HRMS (FAB) Calcd for $C_{14}H_{16}N_2$ $[M]^+$ 284.1313, found 284.1299.

*4.4.12. 3,3′-Diphenyl-2,2′-bi-1H-pyrrole (**23d**).* A yellow oil. ^{1}H NMR (300 MHz, $CDCl_3$) δ 6.46 (t, 2H, *J*=2.7 Hz), 6.74 (t, 2H, *J*=2.7 Hz), 7.14–7.22 (m, 2H), 7.23–7.36 (m, 4H), 7.38–7.45 (m, 4H), 8.00 (br s, 2H) ppm. MS, *m*/*z*: 284 $[M]^+$.

*4.4.13. 3,4′-Bis(4-methoxyphenyl)-2,2′-bi-1H-pyrrole (**22e**).* A yellow oil. IR (KBr) cm^{-1}: 3369, 3002, 2937, 2909, 2835, 1611, 1556, 1526, 1510, 1493, 1464, 1441, 1425, 1391, 1288, 1244, 1178, 1109, 1096, 1076, 1030, 912, 833, 793, 743, 698, 650. ^{1}H NMR (300 MHz, $CDCl_3$) δ 3.82 (s, 3H), 3.83 (s, 3H), 6.32 (t, 1H, *J*=2.7 Hz), 6.48–6.49 (m, 1H), 6.81 (t, 1H, *J*=2.7 Hz), 6.83–6.85 (m, 1H), 6.86–6.94 (m, 4H), 7.35 (d, 2H, *J*=8.4 Hz), 7.44 (d, 2H, *J*=8.4 Hz), 8.04 (br s, 1H), 8.27 (br s, 1H) ppm. ^{13}C NMR (75.3 MHz, $CDCl_3$) δ 55.2, 55.3, 102.9, 110.4, 113.7, 114.0, 114.1, 117.6, 120.4, 120.8, 125.1, 126.0, 126.1, 128.2, 128.7, 129.4, 157.8, 158.1 ppm. HRMS (FAB) Calcd for $C_{22}H_{20}N_2O_2$ $[M]^+$ 344.1525, found 344.1519.

*4.4.14. 3,4′-Bis(4-bromophenyl)-2,2′-bi-1H-pyrrole (**22f**).* A yellow oil. IR (KBr) cm^{-1}: 3450, 3369, 1591, 1514, 1494, 1479, 1441, 1410, 1385, 1261, 1175, 1105, 1070, 1009, 912, 829, 800, 743, 650. ^{1}H NMR (300 MHz, $CDCl_3$) δ 6.36 (t, 1H, *J*=2.7 Hz), 6.52–6.54 (m, 1H), 6.83 (t, 1H, *J*=2.7 Hz), 6.95–6.97 (m, 1H), 7.25–7.52 (m, 8H), 8.02 (br s, 1H), 8.26 (br s, 1H) ppm. ^{13}C NMR (75.3 MHz, $CDCl_3$) δ 103.8, 110.2, 115.0, 118.2, 119.2, 119.9, 120.0, 120.9, 124.5, 125.7, 126.5, 129.6, 131.7, 131.8, 134.1, 135.0 ppm. HRMS (FAB) Calcd for $C_{20}H_{14}N_2Br_2$ $[M]^+$ 439.9524, found 439.9529.

*4.4.15. 3,3′-Bis(4-bromophenyl)-2,2′-bi-1H-pyrrole (**23f**).* A oil. ^{1}H NMR (300 MHz, $CDCl_3$) δ 6.45 (t, 2H, *J*=2.7 Hz), 6.79 (t, 2H, *J*=2.7 Hz), 7.21 (d, 4H, *J*=8.4 Hz), 7.39 (d, 4H, *J*=8.4 Hz), 8.00 (br s, 2H) ppm. MS, *m*/*z*: 439 $[M]^+$.

*4.4.16. 4,4′-Bis(1,1-dimethylethyl)-2,2′-bi-1H-pyrrole (**24g**)[37a].* A colorless solid, mp 162–164 °C (hexane/AcOEt). IR (KBr) cm^{-1}: 3473, 3360, 2966, 1783, 1555, 1444, 1359, 1292, 1107, 912, 742. ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.26 (s, 18H), 6.08 (s, 2H), 6.45 (s, 2H), 7.64 (br s, 2H). ^{13}C NMR (75.3 MHz, $CDCl_3$) δ 30.5, 31.7, 102.3, 112.2, 125.9, 136.4. MS, *m*/*z*: 244 $[M]^+$.

*4.4.17. 2,3′-Bi-1H-pyrrole (**25a**)[23].* A colorless solid, mp 102–103 °C (hexane/AcOEt). IR (KBr) cm^{-1}: 3402, 3124, 2252, 1793, 1608, 1525, 1427, 1111, 912, 792. ^{1}H NMR (300 MHz, $CDCl_3$) δ 6.22–6.24 (m, 2H), 6.31–6.32 (m, 1H), 6.68–6.78 (m, 2H), 6.80–6.81 (m, 1H), 8.07 (br s, 2H) ppm. ^{13}C NMR (75.3 MHz, $CDCl_3$) δ 103.6, 105.8, 109.1, 113.2, 116.6, 117.5, 118.6, 128.3 ppm.

*4.4.18. 1,1′-Dibenzyl-2,3′-bipyrrole (**25aa**).* A colorless oil. IR (KBr) cm^{-1}: 3063, 3028, 2922, 1497, 1452, 1339, 1282, 1078, 1028, 918, 708, 623. ^{1}H NMR (300 MHz, $CDCl_3$) δ 4.98 (s, 2H), 5.18 (s, 2H), 6.14 (dd, 1H, *J*=3.0, 2.1 Hz), 6.18–6.21 (m, 2H), 6.55 (t, 1H, *J*=2.1 Hz), 6.60 (t, 1H, *J*=3.0 Hz), 6.67 (dd, 1H, *J*=3.0, 2.1 Hz), 6.98–7.07 (m, 4H), 7.21–7.31 (m, 6H) ppm. ^{13}C NMR (75.3 MHz, $CDCl_3$) δ 50.6, 53.4, 106.9, 107.9, 109.0, 116.2, 119.4, 121.2, 121.4, 126.2, 126.9, 127.6, 128.5, 128.6, 129.7, 137.7, 139.2 ppm. HRMS(FAB) Calcd for $C_{22}H_{20}N_2Na$ $[M+Na]^+$ 335.1532, found 335.1528.

*4.4.19. 1,1′-Bis(4-methoxybenzyl)-2,3′-bipyrrole (**25ab**).* A colorless oil. IR (KBr) cm^{-1}: 2926, 1612, 1514, 1462, 1247, 1174, 1033, 916, 819, 773, 709. ^{1}H NMR (300 MHz, $CDCl_3$) δ 3.77 (s, 3H), 3.79 (s, 3H), 4.92 (s, 2H), 5.10 (s, 2H), 6.14–6.19 (m, 3H), 6.55 (t, 1H, *J*=1.5 Hz), 6.60 (t, 1H, *J*=1.5 Hz), 6.64 (t, 1H, *J*=1.5 Hz), 6.80 (d, 2H, *J*=6.6 Hz), 6.83 (d, 2H, *J*=6.6 Hz), 6.93 (d, 2H, *J*=6.6 Hz), 7.03 (d, 2H, *J*=6.6 Hz) ppm. ^{13}C NMR (67.8 MHz, $CDCl_3$) δ 50.1, 52.9, 55.2, 55.3, 106.9, 107.8, 109.0, 113.9, 114.0, 116.2, 119.3, 121.0, 121.2, 127.6, 128.6, 129.7, 129.8, 131.3, 158.6, 159.2 ppm. HRMS (FAB) Calcd for $C_{24}H_{24}N_2O_2$ $[M]^+$ 372.1838, found $C_{24}H_{24}N_2O_2$ 372.1834.

*4.4.20. 1,1′-Diphenyl-2,2′-bipyrrole (**21ac**).* A colorless solid, mp: 102–105 °C (hexane/CH_2Cl_2). IR (KBr) cm^{-1}: 3064, 2924, 1599, 1500, 1454, 1410, 1344, 1211, 1166, 1070, 1035, 122, 761. ^{1}H NMR (300 MHz, $CDCl_3$) δ 6.31 (dt, 2H, *J*=2.1, 0.6 Hz), 6.43–6.44 (m, 2H), 6.56–6.58 (m, 4H), 6.75–6.77 (m, 2H), 6.99–7.04 (m, 6H) ppm. ^{13}C NMR (75.3 MHz, $CDCl_3$) δ 109.0, 112.4, 122.2, 123.7, 125.0, 125.4, 128.4, 140.1 ppm. MS, *m*/*z*: 284 $[M]^+$.

*4.4.21. 1,1′-Diphenyl-2,3′-bipyrrole (**25ac**).* A yellow oil. IR (KBr) cm^{-1}: 3058, 1599, 1504, 1462, 1352, 1319, 1184, 1074, 1036, 912, 743, 694, 650. ^{1}H NMR (300 MHz, $CDCl_3$) δ 6.07 (dd, 1H, *J*=3.3, 1.7 Hz), 6.31–6.40 (m, 2H), 6.63–6.66 (m, 1H), 6.83–6.86 (m, 1H), 6.90–6.94 (m, 1H), 7.16–7.28 (m, 4H), 7.31–7.40 (m, 6H) ppm. ^{13}C NMR (75.3 MHz, $CDCl_3$) δ 107.85, 108.73, 110.50, 116.16, 118.35, 118.82, 119.83, 122.75, 125.30, 126.45, 126.94, 128.70, 128.99, 129.39, 140.21, 140.74 ppm. HRMS (FAB) Calcd for $C_{20}H_{17}N_2$ $[M+H]^+$ 285.1392, found 285.1394.

*4.4.22. 1,1′-Dimethyl-2,3′-bipyrrole (**25ad**).* A colorless oil. IR (KBr) cm^{-1}: 3099, 2943, 1595, 1510, 1417, 1356, 1284, 1186, 1087, 995, 742. ^{1}H NMR (300 MHz, $CDCl_3$) δ 3.64 (s, 6H), 6.10–6.12 (m, 2H), 6.21 (t, 1H, *J*=2.1 Hz), 6.57–6.60 (m, 2H), 6.63 (t, 1H, *J*=1.8 Hz). ^{13}C NMR (75.3 MHz, $CDCl_3$) δ 34.8, 36.1, 106.4, 107.1, 108.5, 116.4, 119.6, 121.7, 121.8, 129.7. HRMS (EI) Calcd for $C_{10}H_{12}N_2$ $[M]^+$ 160.1001, found 160.1000.

*4.4.23. 3,3′-Dimethyl-2,2′-biindole (**26**)[68].* A yellow solid, mp 158–161 °C (hexane/CH_2Cl_2). IR (KBr) cm^{-1}: 3406, 3057, 2918, 2860,

1551, 1454, 1420, 1333, 1240, 1176, 1152, 1115, 1099, 1011, 912, 745, 650. ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.37 (s, 6H), 7.17 (t, 2H, J=7.2 Hz), 7.25 (t, 2H, J=7.2 Hz), 7.35 (d, 2H, J=7.2 Hz), 7.61 (d, 2H, J=7.2 Hz), 7.92 (br s, 2H) ppm. ^{13}C NMR (75.3 MHz, $CDCl_3$) δ 9.7, 110.7, 118.9, 119.6, 120.1, 122.5, 126.6, 129.1, 136.1 ppm. MS, m/z: 260 $[M]^+$.

*4.4.24. 3-Methyl-2-(3-methylindol-2-yl)indoline (**27**)*[69]. A colorless solid, mp 126–129 °C (hexane/CH_2Cl_2=1:1). IR (KBr) cm^{-1}: 3353, 3030, 2862, 1614, 1485, 1469, 1452, 1290, 1203, 1153, 1084, 1003, 912, 743, 650. ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.35 (d, 3H, J=6.6 Hz), 2.31 (s, 3H), 3.16–3.26 (m, 1H), 4.68 (d, 1H, J=10.5 Hz), 6.65 (d, 1H, J=7.8 Hz), 6.81 (t, 1H, J=7.5 Hz), 7.02–7.18 (m, 3H), 7.22 (d, 1H, J=7.8 Hz), 7.52 (d, 1H, J=7.5 Hz), 8.30 (br s, 1H) ppm. ^{13}C NMR (75.3 MHz, $CDCl_3$) δ 8.7, 16.4, 45.2, 64.2, 108.3, 109.5, 110.7, 118.4, 119.4, 119.6, 121.8, 123.2, 127.7, 129.2, 132.9, 134.4, 135.2, 149.7 ppm. MS, m/z: 262 $[M]^+$.

4.5. General procedure for oxidative introduction of nucleophiles using PIFA

To a stirred solution of 3-hexylthiophene (168 mg, 1.0 mmol) in CH_2Cl_2 (10 mL), PIFA (430 mg, 1.0 mmol) and TMSCl (0.25 mL, 2.0 mmol) were quickly added at 0 °C. The reaction mixture was then stirred for 3 h. After the reaction completion, saturated aqueous $NaHCO_3$ was added to the mixture, and then stirred for an additional 10 min at ambient temperature. The organic layer was separated and the aqueous phase was extracted with CH_2Cl_2. The combined extract was dried with Na_2SO_4 and evaporated. The residue was purified by column chromatography (SiO_2/n-hexane) to give the pure chlorothiophene **28a** (158 mg, 78%) as a colorless oil.

*4.5.1. 2-Chloro-3-hexylthiophene (**28a**).* A colorless oil. IR (KBr) cm^{-1}: 2930, 2858, 2253, 1028, 912, 650. ^{1}H NMR (300 MHz, $CDCl_3$) δ 0.89 (t, 3H, J=6.9 Hz), 1.15–1.43 (m, 6H), 1.52–1.59 (m, 2H), 2.56 (t, 2H, J=7.5 Hz), 6.79 (d, 1H, J=5.4 Hz), 7.02 (d, 1H, J=5.4 Hz) ppm. ^{13}C NMR (75.3 MHz, $CDCl_3$) δ 14.1, 22.6, 27.9, 28.9, 29.6, 31.6, 121.0, 124.4, 127.9, 139.2 ppm. HRMS (EI) Calcd for $C_{10}H_{15}SCl$ $[M]^+$ 202.0583, found 202.0611.

*4.5.2. 2-Bromo-3-hexylthiophene (**29a**).* A colorless oil. IR (KBr) cm^{-1}: 2928, 2856, 2251, 1466, 1408, 1377, 912, 743. ^{1}H NMR (300 MHz, $CDCl_3$) δ 0.89 (t, 3H, J=6.9 Hz), 1.30–1.37 (m, 6H), 1.52–1.59 (m, 2H), 2.56 (t, 2H, J=7.5 Hz), 6.79 (d, 1H, J=5.4 Hz), 7.18 (d, 1H, J=5.4 Hz) ppm. ^{13}C NMR (75.3 MHz, $CDCl_3$) δ 14.1, 22.6, 28.9, 29.4, 29.7, 31.6, 108.8, 125.1, 128.2, 141.7 ppm. HRMS (EI) Calcd for $C_{10}H_{15}SBr$ $[M]^+$ 246.0077, found 246.0092.

*4.5.3. 2-Thiocyanato-3-hexylthiophene (**30a**).* A colorless oil. IR (KBr) cm^{-1}: 2928, 2858, 2253, 2158, 1466, 1393, 912, 743, 650. ^{1}H NMR (300 MHz, $CDCl_3$) δ 0.92 (t, 3H, J=6.9 Hz), 1.29–1.41 (m, 6H), 1.55–1.69 (m, 2H), 2.79 (t, 2H, J=7.5 Hz), 7.00 (d, 1H, J=5.4 Hz), 7.50 (d, 1H, J=5.4 Hz) ppm. ^{13}C NMR (75.3 MHz, $CDCl_3$) δ 14.0, 22.5, 29.0, 29.2, 30.1, 31.5, 110.5, 112.3, 129.4, 131.9, 152.1 ppm. HRMS (EI) Calcd for $C_{11}H_{15}NS_2$ $[M]^+$ 248.0542, found 248.0543.

4.6. General procedure for direct cyanation of heteroaromatic compounds

To a stirred solution of PIFA (860 mg, 2.0 mmol) and $BF_3\cdot Et_2O$ (0.49 mL, 4.0 mmol) in CH_2Cl_2 (1 mL) added trimethylsilyl cyanide (0.38 mL, 3.0 mmol) at room temperature. After stirring 30 min, *N*-tosylpyrrole (221 mg, 1 mmol) was added in one portion and stirred for additional 3 h. After the reaction completed, saturated aqueous sodium thiosulfate (ca. 5 mL) was added to the mixture. The organic layer was separated and aqueous phase was extracted with CH_2Cl_2. The combined extract was dried with Na_2SO_4 and evaporated. The residue was purified by column chromatography (SiO_2/n-hexane–Et_2O) to give pure **32a** (205 mg, 83%).

*4.6.1. 3-Hexylthiophene-2-carbonitrile (**31a**).* A slightly yellow oil. IR (KBr) cm^{-1}: 2214. ^{1}H NMR (300 MHz, $CDCl_3$) δ 0.89 (t, 3H, J=6.9 Hz), 1.20–1.48 (m, 6H), 1.51–1.73 (m, 2H), 2.79 (t, 2H, J=7.5 Hz), 6.97 (d, 1H, J=5.1 Hz), 7.26 (d, 1H, J=5.1 Hz) ppm. ^{13}C NMR (75.3 MHz, $CDCl_3$) δ 14.0, 22.5, 28.8, 29.8, 30.1, 31.5, 105.4, 114.3, 128.5, 131.6, 154.8 ppm. Anal. Calcd for $C_{11}H_{15}NS$: C, 68.35; H, 7.82; N, 7.25. Found: C, 68.56; H, 7.87; N, 6.98.

*4.6.2. 3-Methylthiophene-2-carbonitrile (**31b**)*[70]. A slightly yellow oil. IR (KBr) cm^{-1}: 2214. ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.45 (3H, s), 6.94 (1H, d, J=5.1 Hz), 7.46 (1H, d, J=5.1 Hz) ppm. ^{13}C NMR (75.3 MHz, $CDCl_3$): δ 15.2, 105.8, 114.2, 129.5, 131.5, 149.5 ppm.

*4.6.3. 3-Cyclohexylthiophene-2-carbonitrile (**31c**).* A slightly yellow oil. IR (KBr) cm^{-1}: 2220. ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.05–1.98 (m, 10H), 2.84–2.86 (m, 1H), 6.93 (d, 1H, J=5.1 Hz), 7.40 (d, 1H, J=5.1 Hz) ppm. ^{13}C NMR (75.3 MHz, $CDCl_3$) δ 25.8, 26.3, 33.6, 39.8, 104.2, 114.4, 126.5, 131.8, 159.9 ppm. Anal. Calcd for $C_{11}H_{13}NS$: C, 69.07; H, 6.85; N, 7.32. Found: C, 69.05; H, 6.98; N, 7.03.

*4.6.4. 3-Methoxythiophene-2-carbonitrile (**31d**)*[71]. A colorless oil. IR (KBr) cm^{-1}: 2214. ^{1}H NMR (300 MHz, $CDCl_3$) δ 4.02 (s, 3H), 6.72 (d, 1H, J=5.1 Hz), 7.36 (d, 1H, J=5.1 Hz) ppm. ^{13}C NMR (75.3 MHz, $CDCl_3$) δ 59.1, 86.7, 113.5, 116.1, 131.6, 165.6 ppm.

*4.6.5. 3-Phenylthiophene-2-carbonitrile (**31e**).* A slight yellow oil. IR (KBr) cm^{-1}: 2214. ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.23 (d, 1H, J=5.1 Hz), 7.23–7.50 (m, 3H), 7.54 (d, 1H, J=5.1 Hz), 7.65 (dd, 2H, J=8.4, 1.8 Hz) ppm. ^{13}C NMR (75.3 MHz, $CDCl_3$) δ 104.3, 114.7, 127.7, 128.2, 129.0, 129.1, 131.8, 133.0, 151.4 ppm. Anal. Calcd for $C_{11}H_7NS$: C, 71.32; H, 3.81; N, 7.56. Found: C, 71.05; H, 4.06; N, 7.44.

*4.6.6. 5-Methylthiophene-2-carbonitrile (**31f**)*[72]. A colorless oil. IR (KBr) cm^{-1}: 2220. ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.55 (s, 3H), 6.79 (d, 1H, J=4.8 Hz), 7.44 (d, 1H, J=4.8 Hz) ppm. ^{13}C NMR (75.3 MHz, $CDCl_3$): δ 15.4, 107.0, 114.5, 126.0, 137.8, 148.2 ppm.

*4.6.7. 2-Cyano-1-tosylpyrrole (**32a**)*[73]. Colorless crystals, mp 114–115 °C. IR (KBr) cm^{-1}: 2225. ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.44 (s, 3H), 6.32 (t, 1H, J=3.4 Hz), 6.95 (dd, 1H, J=3.4, 1.6 Hz), 7.37 (d, 2H, J=8.7 Hz), 7.47 (dd, 1H, J=3.4, 1.6 Hz), 7.93 (d, 2H, J=8.7 Hz) ppm. ^{13}C NMR (75.3 MHz, $CDCl_3$) δ 21.7, 103.7, 111.6, 112.3, 126.5, 126.6, 127.9, 130.4, 134.1, 146.5 ppm.

*4.6.8. 2-Cyano-3-methyl-1-tosylpyrrole (**32b**).* Colorless crystals, mp 114–117 °C. IR (KBr) cm^{-1}: 2222. ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.11 (s, 3H), 2.37 (s, 3H), 6.11 (d, 1H, J=3.0 Hz), 7.28–7.30 (m, 3H), 7.83 (d, 2H, J=8.1 Hz) ppm. ^{13}C NMR (75.3 MHz, $CDCl_3$) δ 12.1, 21.7, 102.1, 111.7, 114.2, 126.2, 127.8, 130.3, 134.3, 139.1, 146.2 ppm. HRMS (FAB) Calcd for $C_{13}H_{12}N_2O_2S$ $[M+H]^+$, 261.0683, found 261.0690.

*4.6.9. 2-Cyano-3-heptyl-1-tosylpyrrole (**32c**).* A colorless oil. IR (KBr) cm^{-1}: 2220. ^{1}H NMR (300 MHz, $CDCl_3$) δ 0.86 (t, 3H, J=7.5 Hz), 1.02–1.30 (m, 8H), 1.54–1.61 (m, 2H), 2.44 (s, 3H) 2.51 (t, 2H, J=7.8 Hz), 6.20 (d, 1H, J=3.3 Hz), 7.34–7.37 (m, 3H), 7.91 (d, 2H, J=8.1 Hz) ppm. ^{13}C NMR (75.3 MHz, $CDCl_3$) δ 14.0, 21.7, 22.5, 26.6, 28.8, 28.9, 29.5, 31.6, 101.5, 111.7, 113.1, 126.3, 127.7, 130.3, 134.4, 144.1, 146.2 ppm. Anal. Calcd for $C_{19}H_{24}N_2O_2S$: C, 66.25; H, 7.02; N, 8.13. Found: C, 66.17; H, 7.01; N, 8.32.

*4.6.10. 2-Cyano-1-tosylpyrrole-3-butanoic acid methyl ester (**32d**).* Colorless crystals, mp 113–115 °C (hexane/EtOAc). IR (KBr) cm^{-1}: 2220.

^{1}H NMR (300 MHz, $CDCl_3$) δ 1.89 (q, 2H, J=7.5 Hz), 2.28 (t, 2H, J=7.2 Hz), 2.44 (s, 3H), 2.58 (t, 2H, J=7.5 Hz) 3.65 (s, 3H), 6.22 (d, 1H, J=3.3 Hz), 7.38–7.40 (m, 3H), 7.92 (d, 2H, J=8.1 Hz) ppm. ^{13}C NMR (75.3 MHz, $CDCl_3$) δ 21.7, 24.7, 25.8, 33.0, 51.6, 101.7, 111.5, 112.9, 126.5, 127.8, 130.3, 134.1, 142.5, 146.3, 173.3 ppm. HRMS (FAB) Calcd for $C_{17}H_{18}N_2O_4S$ $[M+H]^+$; 347.1065, found 347.1066.

*4.6.11. 3-tert-Butyl-1-tosylpyrrole-2-carbonitrile (**32e**).* Colorless crystals, mp 65–67 °C. IR (KBr) cm^{-1}: 2220. ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.31 (s, 9H), 2.45 (s, 3H), 6.26 (d, 1H, J=3.0 Hz), 7.36–7.40 (m, 3H), 7.92 (d, 2H, J=8.4 Hz) ppm. ^{13}C NMR (75.3 MHz, $CDCl_3$) δ 21.7, 30.3, 31.9, 99.3, 111.1, 112.9, 125.6, 127.8, 130.3, 134.2, 146.2, 152.5 ppm. Anal. Calcd for $C_{16}H_{18}N_2O_2S$: C, 63.55; H, 6.00; N, 9.26. Found: C, 63.42; H, 6.08; N, 9.26.

*4.6.12. 3-(2-Bromophenyl)-1-tosylpyrrole-2-carbonitrile (**32f**).* Colorless crystals, mp 132–134 °C (hexane/EtOAc). IR (KBr) cm^{-1}: 2220. ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.44 (s, 3H), 6.56 (d, 1H, J=3.4 Hz), 7.17–7.23 (m, 1H), 7.27–7.45 (m, 4H), 7.50 (d, 1H, J=3.4 Hz), 7.62 (d, 1H, J=8.7 Hz), 7.96 (d, 2H, J=8.4 Hz) ppm. ^{13}C NMR (75.3 MHz, $CDCl_3$) δ 21.8, 102.1, 111.5, 114.5, 122.8, 125.6, 127.7, 128.0, 130.4, 131.3, 131.9, 133.5, 134.1, 140.7, 146.6 ppm. Anal. Calcd for $C_{18}H_{13}BrN_2O_2S$: C, 53.88; H, 3.27; N, 6.98. Found: C, 53.65; H, 3.27; N, 6.81.

*4.6.13. 3-(4-Bromophenyl)-1-tosylpyrrole-2-carbonitrile (**32g**).* Colorless crystals, mp 161–163 °C (hexane/EtOAc). IR (KBr) cm^{-1}: 2220. ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.37 (s, 3H), 6.46 (d, 1H, J=3.1 Hz), 7.31 (d, 2H, J=8.7 Hz), 7.37–7.55 (m, 5H), 7.89 (d, 2H, J=8.7 Hz) ppm. ^{13}C NMR (75.3 MHz, $CDCl_3$) δ 21.8, 99.5, 111.6, 112.4, 123.3, 126.9, 128.1, 128.7, 129.8, 130.5, 132.2, 134.0, 139.9, 146.7 ppm. Anal. Calcd for $C_{18}H_{13}BrN_2O_2S$: C, 53.88; H, 3.27; N, 6.98. Found: C, 53.71; H, 3.30; N, 6.98.

*4.6.14. 3-(4-Methoxyphenyl)-1-tosylpyrrole-2-carbonitrile (**32h**).* Colorless crystals, mp 85–88 °C (hexane/EtOAc). IR (KBr) cm^{-1}: 2216. ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.37 (s, 3H), 3.75 (s, 3H), 6.45 (d, 1H, J=3.3 Hz), 6.86 (d, 2H, J=8.4 Hz), 7.30 (d, 2H, J=8.1 Hz), 7.43 (d, 1H, J=3.0 Hz), 7.50 (d, 2H, J=8.7 Hz), 7.89 (d, 2H, J=8.1 Hz) ppm. ^{13}C NMR (75.3 MHz, $CDCl_3$) δ 21.8, 55.3, 98.6, 111.7, 113.0, 114.4, 123.2, 126.8, 128.0, 128.5, 130.4, 134.2, 141.1, 146.4, 160.2 ppm. Anal. Calcd for $C_{19}H_{16}N_2O_3S$: C, 64.76; H, 4.58; N, 7.95. Found: C, 64.49; H, 4.78; N, 7.72.

*4.6.15. 3,4-Diethyl-1-tosylpyrrole-2-carbonitrile (**32i**).* Colorless crystals, mp 120–122 °C (hexane/EtOAc). IR (KBr) cm^{-1}: 2220. ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.11–1.25 (m, 6H), 2.33–2.61 (m, 7H), 7.16 (s, 1H), 7.35 (d, 2H, J=8.1 Hz), 7.90 (d, 2H, J=8.1 Hz) ppm. ^{13}C NMR (75.3 MHz, $CDCl_3$) δ 13.5, 14.2, 18.1, 18.7, 21.8, 101.2, 111.9, 122.9, 127.6, 129.2, 130.1, 134.5, 144.1, 145.8 ppm. Anal. Calcd for $C_{16}H_{18}N_2O_2S$: C, 63.55; H, 6.00; N, 9.26. Found: C, 63.55; H, 5.99; N, 9.26.

*4.6.16. 4-Ethyl-3,5-dimethyl-1-tosylpyrrole-2-carbonitrile (**32j**)[74].* Colorless crystals, mp 153–156 °C (hexane/EtOAc). IR (KBr) cm^{-1}: 2214. ^{1}H NMR (300 MHz, $CDCl_3$) δ 0.98 (t, 3H, J=7.5 Hz), 2.13 (s, 3H), 2.29 (q, 2H, J=7.5 Hz), 2.39 (s, 3H), 2.43 (s, 3H), 7.34 (d, 2H, J=8.1 Hz), 7.85 (d, 2H, J=8.1 Hz) ppm. ^{13}C NMR (75.3 MHz, $CDCl_3$) δ 10.4, 12.1, 14.4, 17.4, 21.7, 102.1, 112.9, 127.2, 127.7, 130.2, 133.2, 135.5, 137.5, 145.6 ppm.

*4.6.17. 3,5-Dimethyl-1-tosylpyrrole-2-carbonitrile (**32k**).* Colorless crystals, mp 148–151 °C (hexane/EtOAc=3:1). IR (KBr) cm^{-1}: 2214. ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.08 (s, 3H), 2.37 (s, 3H), 2.38 (s, 3H), 5.80 (s, 1H), 7.28 (d, 2H, J=8.4 Hz), 7.80 (d, 2H, J=8.4 Hz) ppm. ^{13}C NMR (75.3 MHz, $CDCl_3$) δ 11.9, 15.0, 21.7, 112.6, 115.0, 127.0, 130.0, 130.8, 135.0, 137.2, 137.5, 145.6 ppm. HRMS (FAB) Calcd for $C_{14}H_{15}O_2N_2S$ $[M+H]^+$; 275.0884, found 275.0871.

*4.6.18. 1-Tosylindole-2-carbonitrile (**33a**)[73].* Colorless crystals, mp 160–162 °C (hexane/EtOAc). IR (KBr) cm^{-1}: 2224. ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.37 (s, 3H), 7.27 (d, 2H, J=7.4 Hz), 7.34 (d, 1H, J=5.6 Hz), 7.36 (s, 1H), 7.54 (t, 1H, J=7.4 Hz), 7.58 (d, 1H, J=8.1 Hz), 7.90 (d, 2H, J=8.4 Hz), 8.22 (d, 1H, J=8.1 Hz) ppm. ^{13}C NMR (75.3 MHz, $CDCl_3$) δ 21.6, 109.0, 112.2, 114.6, 122.5, 123.0, 124.7, 127.1, 127.6, 128.6, 130.2, 134.4, 136.6, 146.1 ppm.

*4.6.19. 3-Methyl-1-tosylindole-2-carbonitrile (**33b**).* Colorless crystals, mp 160–168 °C (hexane/EtOAc). IR (KBr) cm^{-1}: 2224. ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.36 (s, 3H), 2.43 (s, 3H), 7.25 (d, 2H, J=8.4 Hz), 7.35 (t, 1H, J=7.5 Hz), 7.54 (d, 2H, J=8.4 Hz), 7.86 (d, 2H, J=8.4 Hz), 8.20 (d, 1H, J=8.7 Hz) ppm. ^{13}C NMR (75.3 MHz, $CDCl_3$) δ 10.0, 21.6, 107.0, 112.1, 114.7, 120.7, 124.4, 127.0, 128.6, 128.7, 130.1, 134.3, 134.4, 136.6, 145.8 ppm. HRMS (FAB) Calcd for $C_{17}H_{15}N_2O_2S$ $[M+H]^+$; 311.0854, found 311.0850.

*4.6.20. 2-Methyl-1-tosylindole-3-carbonitrile (**34c**).* Colorless crystals, mp 146–148 °C (hexane/EtOAc). IR (KBr) cm^{-1}: 2224. ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.39 (s, 3H), 2.81 (s, 3H), 7.21–7.45 (m, 4H), 7.58 (dd, 1H, J=7.1, 1.4 Hz), 7.74 (d, 2H, J=8.4 Hz), 8.20 (dd, 1H, J=7.1, 1.4 Hz) ppm. ^{13}C NMR (75.3 MHz, $CDCl_3$) δ 15.0, 21.7, 94.5, 114.6, 119.1, 124.7, 125.7, 126.6, 126.8, 127.8, 129.7, 130.2, 135.1, 135.4, 146.0 ppm. HRMS (FAB) Calcd for $C_{17}H_{15}N_2O_2S$ $[M+H]^+$; 311.0854, found 311.0853.

4.7. General procedure for direct cyanation of *N*-tosylpyrrole by (dicyanoiodo)benzene [PhI(CN)$_2$]

To a stirred solution of $PhI(CN)_2$ (512 mg, 2.0 mmol) and $BF_3{\cdot}Et_2O$ (0.49 mL, 4.0 mmol) in CH_2Cl_2 (1 mL), *N*-tosylpyrrole (221 mg, 1 mmol) was added under nitrogen atmosphere. The solution was then stirred for 20 h at room temperature. TLC analysis of the reaction indicated that the cyanated **32a** was present as major product with a small amount remaining starting substrate. The product **32a** was separated and purified according to the general experimental procedure mentioned in Section 4.6.

4.8. General procedure for dehydrative condensation of thiophenes and hypervalent iodine(III) reagents

To a stirred solution of 3-methylthiophene (98 mg, 1.0 mmol) in 2,2,2-trifluoroethanol (5 mL), iodosobenzene (220 mg, 1.0 mmol) and perchloric acid aqueous solution (60%, 334 μL) were added at 0 °C under air, and it was stirred for 2 h at room temperature. After the reaction completed, CH_2Cl_2 was added to the mixture. The organic layer was separated and aqueous phase was extracted with CH_2Cl_2. The combined extract was dried with Na_2SO_4 and evaporated. The resulting oily crude product **35a-ClO$_4$** was precipitated by adding Et_2O with stirring. The precipitate was filtered off and dried in vacuo to give **35a-ClO$_4$** (245 mg, 61%) as a slightly black powder.

*4.8.1. (3-Methyl-2-thienyl)(phenyl)iodonium trifluoroacetate (**35a-OCOCF$_3$**).* A colorless solid, mp 137–139 °C (ether). IR (KBr) cm^{-1}: 3049, 1672, 1440, 1176, 991, 725. ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.48 (s, 3H), 6.97 (d, 1H, J=5.1 Hz), 7.27–7.43 (m, 2H), 7.49–7.54 (m, 1H), 7.61 (d, 1H, J=5.1 Hz), 7.90 (dd, 2H, J=8.4, 0.9 Hz) ppm. ^{13}C NMR (75.3 MHz, $CDCl_3$) δ 17.3, 99.9, 115.5, 119.4, 130.1, 131.5, 131.8, 133.1, 135.6, 148.3, 162.0 ppm. HRMS (FAB) Calcd for $C_{11}H_{10}IS$ $[M-OCOCF_3]^+$ 300.9548, found 300.9548.

*4.8.2. (3-Methyl-2-thienyl)(phenyl)iodonium trifluoromethanesulfonate (**35a-OTf**).* A gray solid, mp 128 °C (ether). IR (KBr) cm^{-1}:

3057, 2924, 1440, 1273, 1161, 1030, 991, 738. ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.54 (s, 3H), 7.08 (d, 1H, J=5.1 Hz), 7.52 (t, 2H, J=7.8 Hz), 7.67 (t, 1H, J=7.8 Hz), 7.86 (d, 1H, J=5.1 Hz), 8.08 (d, 2H, J=7.8 Hz) ppm. ^{13}C NMR (100.53 MHz, $CDCl_3$) δ 17.5, 98.4, 118.5, 121.8 (q, J=319 Hz), 131.1, 133.2, 133.6, 135.5, 137.8, 150.1 ppm.

*4.8.3. (3-Methyl-2-thienyl)(phenyl)iodonium perchlorate (**35a-ClO$_4$**).* A slightly black solid, mp 148–149 °C (ether). IR (KBr) cm^{-1}: 3049, 2912, 1708, 1683, 1562, 1467, 1438, 1375, 1157, 1085, 991, 823, 746. ^{1}H NMR (300 MHz, DMSO) δ 2.49 (s, 3H), 7.11 (d, 1H, J=5.4 Hz), 7.53 (t, 2H, J=7.5 Hz), 7.67 (t, 1H, J=7.5 Hz), 7.97 (d, 1H, J=5.4 Hz), 8.18 (d, 2H, J=7.5 Hz) ppm. ^{13}C NMR (75.3 MHz, DMSO) δ 17.0, 99.8, 118.7, 129.9, 131.8, 132.0, 134.5, 136.6, 147.7 ppm. HRMS (FAB) Calcd for $C_{11}H_{10}IS$ [M−ClO_4]$^+$ 300.9548, found 300.9555.

*4.8.4. (3-Methyl-2-thienyl)(phenyl)iodonium nitrate (**35a-NO$_3$**).* A yellow solid, mp 151 °C (ether). IR (KBr) cm^{-1}: 3099, 1410, 1300, 1028, 993, 732. ^{1}H NMR (300 MHz, DMSO) δ 2.49 (s, 3H), 7.10 (d, 1H, J=5.4 Hz), 7.53 (t, 2H, J=7.5 Hz), 7.66 (t, 1H, J=7.5 Hz), 7.97 (d, 1H, J=5.4 Hz), 8.17 (d, 2H, J=7.5 Hz) ppm. ^{13}C NMR (75.3 MHz, DMSO) δ 17.0, 100.0, 118.9, 129.9, 131.7, 131.9, 134.5, 136.6, 147.5 ppm. HRMS (FAB) Calcd for $C_{11}H_{10}IS$ [M−NO_3]$^+$ 300.9548, found 300.9550.

4.9. General procedure for the preparation of diaryliodonium(III) tosylates 35-OTs

To a stirred solution of 3-methylthiophene (98 mg, 1.0 mmol) in 2,2,2-trifluoroethanol (5 mL), [hydroxyl(tosyloxy)iodo]benzene (392 mg, 1.0 mmol) was added in one portion at room temperature under air, and it was stirred for 2 h. MeOH was then added to the reaction mixture when the solvents were removed under vacuum. The resulting oily crude product **35a-OTs** was precipitated by adding Et_2O with stirring. The precipitate was filtered off and dried in vacuo to give **35a-OTs** (396 mg, 84%) as a gray powder.

*4.9.1. (3-Methyl-2-thienyl)(phenyl)iodonium tosylate (**35a-OTs**)[50b].* A gray solid. Mp 165 °C (ether). IR (KBr) cm^{-1}: 3051, 1575, 1469, 1440, 1377, 1191, 1132, 1045, 1014, 991, 815, 746, 680. ^{1}H NMR (300 MHz, CD_3OD) δ 2.33 (s, 3H), 2.49 (s, 3H), 7.03 (d, 1H, J=5.1 Hz,), 7.19 (d, 2H, J=7.2 Hz), 7.46–7.49 (m, 2H), 7.59–7.67(m, 3H), 7.83 (d, 1H, J=5.1 Hz,), 8.05 (d, 2H, J=7.8 Hz) ppm. ^{13}C NMR (75.3 MHz, CD_3OD) δ 17.5, 21.3, 98.4, 118.4, 126.9, 129.8, 131.0, 133.0, 133.1, 133.4, 135.4, 137.7, 141.6, 150.0 ppm.

*4.9.2. (3-Methyl-2-thienyl)(2,4,6-trimethylphenyl)iodonium tosylate (**36a-OTs**).* A colorless solid, mp 145 °C (ether). IR (KBr) cm^{-1}: 3637, 3466, 3061, 2953, 1923, 1600, 1450, 1377, 1300, 1215, 1132, 1043, 815, 758. ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.27 (s, 3H), 2.30 (s, 3H), 2.47 (s, 3H), 2.67 (s, 6H), 6.84 (d, 1H, J=5.4 Hz), 6.93 (s, 2H), 7.00 (d, 2H, J=7.8 Hz), 7.40 (d, 2H, J=7.8 Hz), 7.48 (d, 1H, J=5.4 Hz) ppm. ^{13}C NMR (75.3 MHz, $CDCl_3$) δ 17.7, 20.9, 21.2, 27.1, 96.9, 125.8, 126.4, 128.3, 129.6, 129.7, 134.3, 139.2, 141.2, 142.3, 143.1, 147.2 ppm. HRMS (FAB): Calcd for $C_{14}H_{16}IS$ [M−OTs]$^+$: 343.0017, found 343.0026.

*4.9.3. (3-Methyl-2-thienyl)(pentafluorophenyl)iodonium tosylate (**37a-OTs**).* A colorless solid, mp 140–141 °C (ether). IR (KBr) cm^{-1}: 3091, 1633, 1487, 1390, 1195, 1078, 974, 908, 815, 756, 696. ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.35 (s, 3H), 2.49 (s, 3H), 6.81 (d, 1H, J=5.4 Hz), 7.08 (d, 2H, J=7.8 Hz), 7.37 (d, 2H, J=7.8 Hz), 7.46 (d, 1H, J=5.4 Hz) ppm. ^{13}C NMR (75.3 MHz, $CDCl_3$) δ 17.5, 21.2, 93.7, 100.0, 125.7, 128.6, 129.4, 135.5, 138.0, 140.4, 140.6, 144.3, 146.8, 149.1 ppm. HRMS (FAB): Calcd for $C_{11}H_5F_5IS$ [M−OTs]$^+$: 390.9077, found 390.9095.

*4.9.4. (3-Methyl-2-thienyl)(phenyl)iodonium methanesulfonate (**35a-OMs**).* A colorless solid, mp 144 °C (ether). IR (KBr) cm^{-1}: 3047, 1562, 1525, 1469, 1440, 1377, 1327, 1222, 1053, 991, 912, 825, 785, 742. ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.51 (s, 3H), 2.52 (s, 3H), 6.97 (d, 1H, J=5.1 Hz), 7.40 (t, 2H, J=7.5 Hz), 7.51 (t, 1H, J=7.5 Hz), 7.62 (d, 1H, J=5.1 Hz), 7.94 (d, 2H, J=7.5 Hz) ppm. ^{13}C NMR (75.3 MHz, $CDCl_3$) δ 17.5, 39.0, 98.3, 1178.0, 129.8, 131.3, 131.5, 133.6, 135.7, 148.4 ppm. HRMS (FAB) Calcd for $C_{11}H_{10}IS$ [M−OMs]$^+$ 300.9548, found 300.9550.

*4.9.5. (3-Methyl-2-thienyl)(pheny)iodonium (±)-10-camphor-sulfonate (**35a-OCs**).* A colorless solid, mp 145 °C (ether). IR (KBr) cm^{-1}: 3458, 2956, 1732, 1562, 1469, 1373, 1192, 1051, 918, 732. ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.77 (s, 3H), 1.01 (s, 3H), 1.26–1.32 (m, 1H), 1.52–1.59 (m, 1H), 1.83 (d, 1H, J=18.4 Hz), 1.89–2.00 (m, 2H), 2.25–2.32 (m, 1H), 2.51 (s, 3H), 2.54–2.62 (m, 1H), 2.68 (d, 1H, J=14.8 Hz), 3.21 (d, 1H, J=14.8 Hz), 6.98 (d, 1H, J=5.2 Hz), 7.40 (t, 2H, J=8.0 Hz), 7.50 (t, 2H, J=8.0 Hz), 7.63 (d, 1H, J=5.2 Hz), 7.96 (d, 2H, J=8.0 Hz) ppm. ^{13}C NMR (100.5 MHz, $CDCl_3$) δ 17.5, 19.7, 19.9, 24.3, 27.0, 42.6, 42.8, 47.2, 47.7, 58.5, 98.3, 118.6, 130.0, 131.3, 131.6, 133.6, 135.7, 148.7, 217.0 ppm. HRMS (FAB): Calcd for $C_{11}H_{10}IS$ [M−OCs]$^+$: 300.9548, found 300.9570.

*4.9.6. (3-Isobutyl-2-thienyl)(phenyl)iodonium tosylate (**35b-OTs**).* A colorless amorphous. IR (KBr) cm^{-1}: 3045, 2951, 1464, 1438, 1384, 1190, 1132, 1045, 912, 815, 731, 696. ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.84 (d, 6H, J=4.8 Hz), 1.86 (m, 1H), 2.33 (s, 3H), 2.62 (d, 2H, J=4.8 Hz), 6.96 (d, 1H, J=5.6 Hz), 7.11 (d, 2H, J=8.4 Hz), 7.36 (t, 2H, J=8.0 Hz), 7.49 (t, 1H, J=8.0 Hz), 7.63 (d, 2H, J=8.0 Hz), 7.68 (1H, J=5.6 Hz), 7.89 (d, 2H, J=8.4 Hz) ppm. ^{13}C NMR (100.5 MHz, $CDCl_3$) δ 21.3, 22.2, 29.8, 40.6, 97.5, 118.6, 126.0, 128.7, 129.4, 131.6, 131.8, 133.2, 136.4, 140.0, 141.8, 152.8 ppm. HRMS (FAB) Calcd for $C_{14}H_{16}IS$ [M-OTs]$^+$ 343.0017, found 343.0015.

*4.9.7. (3-Cyclohexyl-2-thienyl)(phenyl)iodonium tosylate (**35c-OTs**).* A colorless solid, mp 128–130 °C (ether). IR (KBr) cm^{-1}: 3053, 2926, 2850, 1564, 1469, 1440, 1190, 1132, 1045, 991, 914, 815, 732. ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.22–1.77 (m, 10H), 2.33 (s, 3H), 2.76 (m, 1H), 6.97 (d, 1H, J=5.6 Hz), 7.09 (d, 2H, J=8.0 Hz), 7.35 (t, 2H, J=8.0 Hz), 7.48 (t, 1H, J=8.0 Hz), 7.61 (d, 2H, J=8.0 Hz), 7.68 (d, 1H, J=5.6 Hz), 7.88 (d, 2H, J=8.0 Hz) ppm. ^{13}C NMR (100.5 MHz, $CDCl_3$) δ 21.3, 25.6, 26.1, 34.1, 42.0, 96.4, 118.9, 126.0, 127.0, 128.7, 131.5, 131.8, 133.3, 136.6, 139.9, 141.9, 158.4 ppm. HRMS (FAB) Calcd for $C_{16}H_{18}IS$ [M-OTs]$^+$ 369.0174, found 369.0165.

*4.9.8. (3-Methoxy-2-thienyl)(phenyl)iodonium tosylate (**35d-OTs**).* A blue solid, mp 49 °C (ether). IR (KBr) cm^{-1}: 3014, 1554, 1471, 1379, 1217, 1132, 1070, 1043, 1014, 771, 694. ^{1}H NMR (300 MHz, CD_3OD) δ 2.35 (s, 3H), 4.02 (s, 3H), 7.08 (d, 1H, J=6.0 Hz), 7.21 (d, 2H, J=7.8 Hz), 7.46–7.51 (m, 2H), 7.61–7.69 (m, 3H), 7.97 (d, 1H, J=6.0 Hz), 8.03 (d, 2H, J=7.8 Hz) ppm. ^{13}C NMR (75.5 MHz, CD_3OD) δ 21.3, 60.4, 77.4, 116.5, 118.7, 126.9, 129.8, 133.0, 133.4, 135.5, 138.7, 141.6, 143.6, 165.1 ppm. HRMS (FAB): Calcd for $C_{11}H_{10}IOS$ [M-OTs]$^+$: 316.9497, found 316.9504.

*4.9.9. (3-Bromo-2-thienyl)(phenyl)iodonium tosylate (**35e-OTs**).* A colorless solid, mp 49 °C (ether). IR (KBr) cm^{-1}: 3045, 1562, 1469, 1438, 1373, 1330, 1191, 1130, 1043, 1014, 860, 815, 740, 692. ^{1}H NMR (300 MHz, CD_3OD) δ 2.35 (s, 3H), 7.19–7.24 (m, 3H), 7.53 (t, 2H, J=7.8 Hz), 7.67 (d, 3H, J=7.8 Hz), 7.98 (d, 1H, J=5.7 Hz), 8.16 (d, 2H, J=7.8 Hz) ppm. ^{13}C NMR (75.5 MHz, CD_3OD) δ 21.3, 119.2, 125.6, 126.9, 129.8, 132.1, 133.2, 133.9, 135.9, 139.8, 141.4, 141.7, 143.5 ppm. HRMS (FAB): Calcd for $C_{10}H_7BrIS$ [M−OTs]$^+$: 364.8497, found 364.8501.

*4.9.10. [3-(4-Methoxycarbonyl)phenyl-2-thienyl](phenyl)-iodonium tosylate (**35f-OTs**).* A yellow solid, mp 126–128 °C (ether). IR (KBr) cm^{-1}: 3051, 1722, 1608, 1438, 1280, 1188, 1116, 1045, 1016, 912, 734. ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.30 (s, 3H), 3.98 (s, 3H), 7.03 (d, 2H,

J=7.6 Hz), 7.09 (d, 1H, J=5.6 Hz), 7.18 (t, 2H, J=7.6 Hz), 7.39 (t, 1H, J=7.6 Hz), 7.49 (m, 6H), 7.72 (d, 1H, J=5.6 Hz), 8.08 (d, 2H, J=7.6 Hz) ppm. ^{13}C NMR (100.5 MHz, $CDCl_3$) δ 21.3, 52.3, 99.7, 118.9, 120.1, 126.0, 128.6, 129.2, 130.2, 130.5, 131.3, 131.4, 133.9, 136.3, 138.7, 140.1, 141.4, 150.4, 166.5 ppm. HRMS (FAB) Calcd for $C_{18}H_{14}IO_2S$ $[M-OTs]^+$ 420.9759, found 420.9778.

*4.9.11. (5-Methyl-2-thienyl)(phenyl)iodonium tosylate (**35g-OTs**).* A brown solid, mp 89–92 °C (ether). IR (KBr) cm^{-1}: 3053, 1440, 1193, 1128, 1039, 1012, 817, 792, 738, 680. ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.30 (s, 3H), 2.51 (s, 3H), 6.65 (d, 1H, J=3.6 Hz), 7.05 (d, 2H, J=8.4 Hz), 7.30 (t, 2H, J=8.0 Hz), 7.46 (t, 1H, J=8.0 Hz), 7.54 (d, 2H, J=8.4 Hz), 7.64 (d, 1H, J=3.6 Hz), 7.93 (d, 2H, J=8.0 Hz) ppm. ^{13}C NMR (100.5 MHz, $CDCl_3$) δ 15.4, 21.3, 93.5, 118.3, 126.0, 128.1, 128.7, 131.5, 131.6, 134.0, 140.3, 140.9, 141.7, 152.2 ppm. HRMS (FAB) Calcd for $C_{11}H_{10}S$ $[M-OTs]^+$ 300.9548, found 300.9548.

*4.9.12. (7-Methoxycarbonyl-2,3-dihydro-thieno[3,4-b][1,4]dioxin-5-yl)(phenyl)iodonium tosylate (**35h-OTs**).* A colorless solid, mp 169 °C (ether). IR (KBr) cm^{-1}: 3520, 3051, 2949, 1712, 1573, 1487, 1444, 1359, 1274, 1193, 1089, 912, 740. ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.31 (s, 3H), 3.83 (s, 3H), 4.28–4.32 (m, 4H), 7.02 (d, 2H, J=7.6 Hz), 7.32 (t, 2H, J=7.6 Hz), 7.45 (m, 3H), 7.96 (d, 2H, J=7.6 Hz) ppm. ^{13}C NMR (100.53 MHz, $CDCl_3$) δ 21.2, 52.2, 65.0, 65.1, 83.8, 99.9, 116.0, 118.6, 125.8, 128.4, 131.4, 134.5, 139.7, 141.9, 144.1, 146.4, 160.2 ppm. HRMS (FAB): Calcd for $C_{14}H_{12}IO_4S$ $[M-OTs]^+$: 402.9501, found 402.9508.

*4.9.13. (2,5-Dimethyl-3-thienyl)(phenyl)iodonium tosylate (**35i-OTs**).* A colorless solid, mp 111–112 °C (ether). IR (KBr) cm^{-1}: 3539, 3047, 2918, 1562, 1469, 1193, 1132, 1045, 912, 815, 740. ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.31 (s, 3H), 2.36 (s, 3H), 2.52 (s, 3H), 6.87 (s, 1H), 7.04 (d, 2H, J=8.0 Hz), 7.31 (t, 2H, J=7.6 Hz), 7.44 (t, 1H, J=7.6 Hz), 7.50 (d, 2H, J=8.0 Hz), 7.84 (d, 2H, J=7.6 Hz) ppm. ^{13}C NMR (100.5 MHz, $CDCl_3$) δ 15.2, 17.0, 21.2, 99.6, 115.9, 125.9, 128.4, 129.5, 131.0, 131.4, 133.9, 139.3, 141.2, 142.6, 145.5 ppm. HRMS (FAB): Calcd for $C_{12}H_{12}IS$ $[M-OTs]^+$: 314.9704, found 314.9703.

*4.9.14. Phenyl(4-trimethylsilyl-2-thienyl)iodonium tolsylate (**35j-OTs**).* A colorless solid, mp 121 °C (ether). IR (KBr) cm^{-1}: 3051, 2954, 1566, 1469, 1440, 1253, 1199, 1132, 1103, 1043, 1014, 991, 883, 842, 750, 680. ^{1}H NMR (300 MHz, $CDCl_3$) δ 0.32 (s, 9H), 2.40 (s, 3H), 7.26 (d, 2H, J=7.8 Hz), 7.54 (t, 2H, J=7.5 Hz), 7.67–7.74 (m, 3H), 7.99 (s, 1H), 8.11 (s, 1H), 8.19 (d, 2H, J=7.8 Hz) ppm. ^{13}C NMR (75.5 MHz, CD_3OD) δ −0.59, 21.6, 119.1, 127.2, 130.1, 133.4, 133.9, 136.1, 136.4, 141.9, 143.8, 144.4, 146.5, 147.0 ppm. HRMS (FAB): Calcd for $C_{13}H_{16}ISSi$ $[M+H]^+$: 358.9781, found 358.9792.

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