Hypervalent iodine reagents for heterocycle synthesis and functionalization

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Abstract: Hypervalent iodine reagents have been vastly applied in many significant oxidative reactions. This surging interest in iodine reagents is mainly due to the very useful oxidizing properties, combined with their benign environmental character and commercial availability. In this review, we focus on the representative transformations that used the common hypervalent iodine reagents as oxidants in heterocycle synthesis and functionalizations, based on the type of the hypervalent iodine reagents.

Keywords: hypervalent iodine reagent, heterocycle synthesis, heterocycle functionalization, oxidative reaction

Introduction

The 1990s witnessed rapid development of hypervalent iodine chemistry. The intense interest is mainly due to the remarkable oxidizing properties of hypervalent iodine reagents and their attractive features such as easy to handle, low toxicity, availability of supply, and environmental benignity.¹⁻²⁰ Two of their most important synthetic applications are in the constructions of heterocyclic skeletons and functionalization of heterocycles, such as three- to seven-membered rings and spiro compounds, under metal-free reaction conditions. Some representative transformations have been shown in Figure 1. In this review, we summarize, with representative examples, the reactions involving various hypervalent iodine (III) and (IV) reagents used as oxidants for the syntheses and functionalization of heterocyclic compounds. The organization of the presentation is based on the type of the hypervalent iodine reagents.

Hypervalent iodine (III) reagents

The common classification of hypervalent iodine (III) reagents is according to the type of ligands attached to the iodine atom, as shown in Figure 2.¹⁰,¹⁶ These broadly applied hypervalent iodine (III) reagents, namely, iodosylarenes ¹, (dichloroiodo)arenes ²a, (difluoroiodo)arenes ²b, [bis(aclyoxy)iodo]arenes ³, [hydroxy(toslyoxy)iodo]benzene ⁴(Koser’s reagent), iodonium salts ⁵, iodonium ylides and iodonium imides, and the benziodoxole-based hypervalent iodine reagents ⁶ and ⁷ (Togni’s reagents), have been found to be powerful and effective oxidants for the synthesis of heterocycles and for facilitating functionalization of heterocyclic compounds via atom transfer reactions.
Iodosylarenes

An important synthetic application of iodosobenzene (PhIO) is promoting oxidative annulation during the construction of heterocyclic framework. For example, Ueno et al.\textsuperscript{21} reported a direct preparation of heteroaromatic compounds of imidazoles 9a, thiazoles 9b, and imidazo[1,2-\textit{a}]pyridines 10 through reactions of alcohol substrates 8 with PhIO catalyzed by \textit{p}-toluenesulfonic acid monohydrate and followed by further reactions with thioamide, benzamidine, and 2-aminopyridine, respectively, under basic conditions (Figure 3).

In 2010, Fan et al.\textsuperscript{22} described a PhIO-mediated synthesis of the three-membered \textit{N}-benzoyl aziridines 12 and the five-membered oxazolines 13 through an intramolecular oxidative cyclization of substrates 11 in the presence of catalytic amount of tetra-butylammonium iodide (Figure 4A-a). Similar conditions were applied to the synthesis of the four-membered oxetanes 15 and azetidines 17 from substrates 14 and 16, respectively (Figure 4A-b and -c).\textsuperscript{23,24} The proposed mechanism has been shown in Figure 4B.

In addition, PhIO can also be used as an efficient oxidant for the functionalization of heterocycles. For example, five- or six-membered lactams 19 could be obtained in moderate yields through the oxidation of cyclic amines 18 with PhIO using \textit{H}_2\textit{O} as solvent (Figure 5).\textsuperscript{25} Moriarty et al.\textsuperscript{26} reported the oxidation of trimethylsilyl ketene acetics of lactones 20 in methanol, mediated by PhIO, to afford the corresponding \textalpha-\textit{methoxylated carbonyl compounds 21 in good yields (Figure 6). They also found that reaction of dihydropyran 22 with PhIO in \textit{H}_2\textit{O} could afford tetrahydro-2-furaldehyde 23 via carbocationic ring contraction (Figure 7). Under the same conditions, cyclohexene and styrene were converted into the corresponding aldehyde products through rearrangement oxidations.\textsuperscript{27}
In the presence of PhIO and I₂, N- or O-centered radicals could be generated, respectively, from amides or alcohols.²⁸–³⁰ In 2000, Francisco et al reported the synthesis of homochiral 7-oxa-2-azabicyclo[2.2.1]heptane ring system 28 from specifically protected phosphoramidate derivatives of carbohydrates 24 under the conditions mentioned earlier. Mechanistic studies demonstrated a reaction path involving a hemolytic fragmentation of a hypothetical iodoamide intermediate 26 (Figure 8).³⁰ It is worth noting that the applications of PhIO can be significantly restricted in nonpolar solvents due to low

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**Figure 4 (A)** (a) PhIO-mediated synthesis of three-membered ring 12 and five-membered ring 13. (b) PhIO-mediated synthesis of oxetane 15. (c) PhIO-mediated synthesis of azetidine 17 (B) Proposed mechanism of (a) and (c).

**Abbreviations:** PhIO, iodosobenzene; eq., equivalent; TBAI, tetra-butylammonium iodide; THF, tetrahydrofuran; rt, room temperature; h, hours.
solubility. Therefore, the majority of the known reactions occurs in polar solvents and are catalyzed by a Lewis acid or a transition metal catalyst, with only a few cases reported to be in a nonpolar solvent or without the involvement of a catalyst. One of the rare examples is the formation of lactams 30 in CHCl₃ from the cyclic amino acids 29 via initial imine formation followed by oxidative decarboxylation (Figure 9).³¹

(Difluoriodio)arenes
As fluorinating reagents, (difluoriodio)arenes (ArIF₂) have found many synthetic applications for the syntheses of biologically and pharmaceutically interesting F-containing heterocyclic compounds.³²,³³ In 1991, Caddick et al.³² reported the reaction of 1-(arylthio)glycosides 31 with TolIF₂, which afforded various 1-fluoroglycosides 32 in moderate-to-good yields (Figure 10).

Upon treating the iodoaldyl substituted four-, five-, and six-membered cyclic ethers 33–35 with TolIF₂, the five-, six-, and seven-membered cyclic ethers 36–38 were stereoselectively synthesized in moderate-to-good yields (Figure 11).³⁴

Dichlorioiodoarene
(Dichlorioiodo)arenes (ArICl₂) have been used as chlorinating reagents to carry out modification of various heterocyclic compounds. For example, reaction of N-protected pyrrolidine 39 with 4-nitrobenzeniododichloride afforded α-hydroxy-β,β-dichloropyrrolidine 40 as the main product via a complicated ionic mechanism involving a C(sp³)–H bond activation process (Figure 12). This oxidation gave an α,β,β-oxidation pattern relative to the nitrogen of the heterocycle.³⁵

An effective system consisting of a combination of PhICl₂ and Pb(SCN)₂ was developed by Prakash et al.³⁶ for convenient thiocyanation of various enol silyl ethers 41 (Figure 13).

Recently, Hepples et al.³⁷ reported a Lewis base-catalyzed chlorination method for the diazocarbonyl compound 43a and isatin-3-hydrazone 43b by using PhICl₂, both of which led to the same product 44 (Figure 14).

The common feature of these reactions is the transfer of the two chlorine ligands from PhICl₂ in a germinal fashion rather than vicinal.³⁷,³⁸

In 2014, He et al.³⁹ reported a method for the direct synthesis of oxazolidin-2-ones 46 and imidazolidin-2-ones 48 from 1,3-diols 45 and 3-amino alcohols 47 using combined PhICl₂ and NaN₃ (Figure 15).

[Bis(acyloxy)iodo]arenes
[Bis(acyloxy)iodo]arenes (ArI(OCOR)₂), notably the easily prepared and commercially available phenyliodine diacetate (PIDA) and phenyliodine bis(trifluoroacetate) (PIFA), have been widely used as oxidizing reagents in various syntheses of heterocycles. In this review, the applications of PIDA and PIFA are presented based on the type of heterocycles obtained.

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**Figure 5** PhIO-mediated functionalization of cyclic amines.
Abbreviations: PhIO, iodosobenzene; rt, room temperature; h, hours.

**Figure 6** PhIO-mediated oxidation affording α-methoxylated carbonyl compounds.
Abbreviation: PhIO, iodosobenzene.

**Figure 7** PhIO-mediated oxidation of dihydropyran.
Abbreviation: PhIO, iodosobenzene.

**Figure 8** Synthesis of the homochiral 7-oxa-2-azabicyclo[2.2.1]heptane ring system.
Abbreviations: PhIO, iodosobenzene; IHA, intramolecular hydrogen abstraction reaction.

**Figure 9** PhIO-mediated conversion of proline into 2-pyrrolidone in nonpolar solvent.
Abbreviations: PhIO, iodosobenzene, rt, room temperature; d, days.
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Figure 10 Synthesis of various 1-fluoroglycosides with TolIF$_2$.
Abbreviations: rt, room temperature; DCM, dichloromethane.

Figure 11 Ring-expansion reactions induced by TolIF$_2$.
Abbreviations: eq., equivalent; rt, room temperature; h, hour; DCM, dichloromethane.

Figure 12 Synthesis of $\alpha$-hydroxy-$\beta$,$\beta$-dichloropyrrolidine with 4-NO$_2$PhICl$_2$.
Abbreviation: eq., equivalent.

Figure 13 PhICl$_2$/Pb(SCN)$_2$-mediated thiocyanation of enol silyl ethers leading to lactone 42.
Abbreviations: rt, room temperature; DCM, dichloromethane.

Figure 14 Lewis base-catalyzed chlorination facilitated by PhICl$_2$.
Abbreviations: eq., equivalent; rt, room temperature; min, minutes; DCM, dichloromethane.

Figure 15 (A) Direct synthesis of oxazolidin-2-ones and imidazolidin-2-ones using PhICl$_2$ and NaN$_3$ (B) Proposed mechanism.
Abbreviations: eq., equivalent; h, hours.
Three-membered heterocyclic products

In 2009, our group reported the synthesis of the smallest unsaturated $N$-containing heterocycle, namely, 2H-azirine 50, via PIDA-mediated intramolecular oxidative azirination of the substituted enamine derivatives 49 under mild conditions (Figure 16). A similar strategy was later applied to the one-pot synthesis of isoxazoles from enamines 49.40

Five-membered heterocyclic compounds

Pyrrole

Mediated by PIFA, the synthesis of polysubstituted pyroles 52 was achieved via a tandem dimerization/cyclocondensation of enamines 51 (Figure 17). Asymmetrical polysubstituted pyroles were obtained from enamine esters or ketones mediated by PIFA in the presence of BF$_3$·Et$_2$O.42

Indole

In 2006, the syntheses of $N$-arylated and $N$-alkylated indoles 54 from enamine derivatives 53 were realized through a PIFA-mediated intramolecular oxidative C($sp^2$)–N bond formation (Figure 18A). The same strategy was also applied to the synthesis of carbazolones via PIFA-mediated intramolecular cyclization of 2-aryl enamines.45 In 2009, a variety of functionalized indoles 56 were synthesized from $N$-aryl enamines 55 via PIDA-mediated oxidative C($sp^2$)–C($sp^2$) involving no transition metals (Figure 18B).46

Azole

In 2007, Das et al.47 reported the condensation of $\alpha$-hydroxy ketones 57 with aldehydes and ammonium acetate by using PIDA as the sole oxidant. The reaction furnished the cyclized imidazole product 58 through an oxidative C($sp^2$)–N bond formation (Figure 19). Various 2-arylbenzimidazoles and benzimidazoles were later synthesized adopting the same methodology.48

In 1996, Kotali49 realized the synthesis of aminoindazole derivatives 60 from the o-aminoaryl ketone acylhydrazones 59 via PIDA-mediated N–N bond formation (Figure 20).

In 2012, intramolecular oxidative C–O coupling of N-(4-alkoxy-phenyl) and N-(4-acetamido-phenyl) benzamides was found to afford the benzoxazole products in high yields under metal-free conditions by using PIFA as an oxidant and TMSOTf as a catalyst (Figure 21).50
Upon treating β-monosubstituted enamines 63 with PIFA, an intermolecular cross-coupling occurred and was succeeded by condensation to provide the 4,5-disubstituted 2-(trifluoromethyl)oxazoles 64 (Figure 22). In this approach, the trifluoromethyl moiety in one of the PIFA ligands was incorporated into the final products at the C2 position.

In 2010, Saito et al reported the oxidative cycloisomerization of propargylamide derivatives 65, mediated by PIDA in AcOH or AcOH-HFIP and affording the corresponding 2,5-disubstituted oxazoles 66 (Figure 23).

Treating anthranilamides 67a or salicylamides 67b with PIDA in the presence of potassium hydroxide, the 2-benzimidazolones 68a and 2-benzoxazolones 68b were, respectively, obtained in good yields (Figure 24). The postulated mechanistic pathway suggested an initial Hofmann-type rearrangement followed by a sequential intramolecular cyclization of the intermediate isocyanate.

In 2008, PIFA-mediated intramolecular cyclization of the thiobenzamides 69 resulting in the benzothiazoles 70 via reactive intermediates of aryl radical cations was described (Figure 25A). Later on, Kumar et al applied the polymer-supported PIDA to construct the benzothiazoles 73 from the corresponding o-amino benzenethiol components 71 and aldehydes 72 (Figure 25B).

**Lactone**

In 2007, Dohi et al developed a direct construction of the biologically important aryl lactone 76 from carboxylic acid 74 using combined PIDA and KBr (Figure 26). The aryl group in the substrate was understood to be indispensable due to the benzyl radical intermediate 75 as suggested by the mechanism. The aryl lactone product 76 was achieved via hydrogen abstraction and then cyclization.

**Spiro heterocycles and bisindolines**

In 2012, Wang et al reported a PIFA-mediated synthesis of spirooxindoles 78 from anilide derivatives 77 bearing an appropriate α-arylamino carboxyl group (Figure 27). These processes feature a metal-free oxidative C(sp2)–C(sp3) bond formation, followed by oxidative spirocyclization.
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Figure 23 PIDA-mediated synthesis of 2,5-disubstituted oxazoles in AcOH or AcOH-HFIP.
Abbreviations: PIDA, phenyliodine diacetate; rt, room temperature.

Figure 24 PIDA/KOH-mediated synthesis of 2-benzimidazolones and 2-benzoxazolones.
Abbreviation: PIDA, phenyliodine diacetate.

Figure 25 (A) PIFA-mediated intramolecular synthesis of benzothiazoles. (B) PIFA-mediated intermolecular synthesis of benzothiazoles.
Abbreviations: PIFA, phenyliodine bis(trifluoroacetate); PS, polymer-supported.

Figure 26 PIDA/KBr-mediated synthesis of aryl lactones.
Abbreviation: PIDA, phenyliodine diacetate.

Recently, Zhang et al. reported a PIFA-mediated cascade annulation of internal alkyne, affording the spiro heterocycle (Figure 28). This process encompasses not only two sequential C–N/C–O bond formations but also the insertion of a carbonyl oxygen, all in one pot.

In 2014, Kim et al. realized a cascade intramolecular oxidative dianimation of olefins by using PIFA as an oxidant and a halide as an additive, leading to the synthesis of a variety of bisindolines (Figure 29).

Six- and seven-membered heterocycles
A PIFA-mediated oxidative C(sp²)–C(sp²) bond formation between two aryl rings was reported by Kita et al. Later, this oxidative coupling strategy was widely applied to the conversion of various biaryl substrates tethered by a relatively labile linker attached to the heterocycles, such as a silaketale, sulfide, sulfoxide, sulfone, or dibenzylether. For example, Moreno et al. described an efficient synthesis of benzo[c]phenanthridine and phenanthridinone from properly substituted benzylnaphthylamine and naphthylbenzamide, respectively, through a PIFA-mediated intramolecular oxidative C–C bond formation between the two electron-rich phenyl rings (Figure 30).

Liu et al. reported the syntheses of a variety of 3-aryquinolinol-2-one compounds from the N-methyl-N-phenylcinnamamide. The reactions involved an exclusive 1,2-aryl migration along with a metal-free oxidative C–C bond formation, mediated by PIFA in the presence of a Lewis acid (Figure 31).

In 2001, Arisawa et al. reported a PIFA-mediated direct intramolecular cyclization of α-(aryl)alkyl-β-dicarbonyl compounds leading to the spirobenzannulated products. Both meta- and para-substituted phenol ether derivatives containing cyclic or acyclic 1,3-dicarbonyl moieties on the side chain underwent the annulation in a facile manner (Figure 32).

In 1990, Kikugawa and Kawase reported an intramolecular oxidative C(sp²)–N bond formation in substrates via a nitrenium ion intermediate. This oxidative amidation protocol was later applied in many explorations of novel means to construct heterocyclic framework.

Starting from N-methoxybenzamide and alkyne, Misu and Togo developed a straightforward synthesis of isoquinolones using PIDA generated in situ through an intermolecular organocatalytic annulation (Figure 34).

The indenocarboxamides could be converted to the fused indeno-1,4-diazepinones through intramolecular oxidative C–N bond formations mediated by PIFA (Figure 35). Moreover, various PIFA-promoted intramolecular amidation reactions have been developed for the formation of five-, six-, and seven-membered heterocycles.

In 2014, Zhao and Du described a PIFA-mediated oxidative coupling of the two aryl groups in either 2-acylamino-N-phenylbenzamides or 2-hydroxy-N-phenylbenzamides...
100 to afford the dibenzodihydro-1,3-diazepin-2-ones 99 and dibenzo[d,f][1,3]oxazepin-6(7H)-ones 101, respectively (Figure 36). The reaction sequence involves an oxidative C(sp^2)–C(sp^2) aryl–aryl bond formation, C(sp^2)–C/O bond cleavage, and an intramolecular lactamization/lactonization. The unique feature of this conversion is the concomitant insertion of the ortho-substituted N or O atom into the tether, realized for the first time.76

A variety of systems involving PIDA/PIFA have been developed to realize functionalization of heterocyclic compounds. Some representative examples are discussed later.

**Iodination**

By using a combination of PIFA and I\(_2\), Benhida et al\(^7^7\) developed an iodination method suitable for electron-deficient heterocyclic compounds including substituted indoles 102 (Figure 37) and coumarins. Moreover, the methodologies offered reaction conditions mild enough to ensure the survival of sensitive protecting group such as acetyl and tert-butyldimethylsilyl. The methods were also applied to the iodination of substituted pyrazoles in providing the corresponding 4-iodopyrazole derivatives.78

Likewise, PIFA-mediated direct cyanations of various heterocyclic compounds including pyrroles, thiophenes, and indoles were realized using trimethylsilyl cyanide as a source of CN.79 For example, cyanation of N-tosylpyroles 104 at the C2 position was achieved by using trimethylsilyl cyanide along with PIFA with moderate-to-excellent selectivity (Figure 38).

Bifunctionalization of glycals 106, including homogeneous azidization and selenylation, has been realized by...
Figure 28  (A) PIFA-mediated conversion of internal alkynes to spiro heterocycles via cascade annulation. (B) Proposed mechanism.
Abbreviations: PIFA, phenyliodine bis(trifluoroacetate); rt, room temperature; h, hours; DCM, dichloromethane.
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Figure 29 (A) PIDA-mediated synthesis of bisindolines via cascade intramolecular oxidative deamination. (B) Proposed mechanism. Abbreviations: PIDA, phenyliodine diacetate; rt, room temperature; h, hours; DMF, N,N-dimethylformamide.

Figure 30 PIFA-mediated synthesis of benzo[c]phenanthridine and phenanthridinone. Abbreviation: PIFA, phenyliodine bis(trifluoroacetate); DCM, dichloromethane.

Figure 31 PIFA-mediated synthesis of 3-arylquinolin-2-ones from N-methyl-N-phenylcinnamamides through oxidative C–C bond formation/1,2-aryl migration. Abbreviations: PIFA, phenyliodine bis(trifluoroacetate); rt, room temperature; TFA, trifluoroacetic acid; DCE, 1,2-dichloroethane.

Figure 32 PIFA-mediated direct intramolecular cyclization of α-(arylalkyl)-β-dicarbonyl compounds. Abbreviations: PIFA, phenyliodine bis(trifluoroacetate); TFE, 2,2,2-Trifluoroethanol.

Figure 33 PIFA-mediated synthesis of N-aryl-N-methoxyamides via an intramolecular oxidative C–N bond formation. Abbreviation: PIFA, phenyliodine bis(trifluoroacetate).

Figure 34 Synthesis of isoquinolones from N-methoxybenzamide and diphenyl acetylene mediated by PIDA generated in situ. Abbreviations: PIDA, phenyliodine diacetate; rt, room temperature.

Mironov et al.\(^80\) through the reaction of glycals with PIDA in the presence of TMSN\(_3\) and Ph\(_2\)Se\(_2\) (Figure 39).

[Hydroxy-(organosulfonyloxy)iodo]arenes

Recently, Kawai et al.\(^81\) described a new method for the synthesis of biologically significant trifluoromethyl-2-isoxazoline N-oxides \(^111\). This conversion is realized through the intramolecular oxidative N–O coupling in β-trifluoromethyl-β-hydroxy ketoximes \(^109\), generated from trifluoromethyl-β-keto alcohols \(^108\), and mediated by [hydroxy(tosyloxy)iodo]benzene (Figure 40).\(^81\)

Treatment of \(2H\)-chromene \(^112\) with [hydroxy(tosyloxy) iodo]benzene in methanol could introduce a methoxyl group at the C4 position to afford 4-methoxy-2\(\text{H}\)-chromene \(^113\) (Figure 41).\(^82\)

Benziodoxole-based hypervalent iodine reagents

During the last decade, studies on the development of the λ\(^3\) iodine benziodoxolone reagents and their applications in facilitating organic transformations have attracted the attention of many synthetic chemists. Some representative examples are presented in this section.

In 2006, Eisenberger et al.\(^83\) reported the first use of benziodoxole-derived reagents \(5a\) and \(6b\) for CF\(_3\) transfer.
Later on, many practical applications of this class of hypervalent iodine (III) were developed.\textsuperscript{84,85}

In 2014, Wang et al\textsuperscript{86} described an intramolecular carbotrifluoromethylation of alkynes \textsuperscript{114} by using Togni’s reagent in the presence of Cu(I). A variety of trifluoromethylated heterocycles, such as 2\(H\)-chromene derivatives \textsuperscript{115} and \textsuperscript{117}, 1,2-dihydroquinoline derivative \textsuperscript{116}, and the 2\(H\)-chromene five-membered cyclic product \textsuperscript{118}, were synthesized with great substituent tolerance and high selectivity (Figure 42).

Due to the multiple reactive sites in indoles, trifluoromethylation of indole derivatives presents a challenge in synthetic chemistry. Shimizu et al\textsuperscript{87} developed a direct C2-selective trifluoromethylation of indole derivatives \textsuperscript{119} with 2-trifluoromethyl indole \textsuperscript{120} as the product by using Togni’s reagent (Figure 43). Later on, a method for the
The trifluoromethylation of indole compounds to afford the fused tricyclic indoles was established.\(^8\)

In 2014, Zhang and Studer\(^9\) reported a method for the synthesis of the biologically important 1-trifluoromethylated isoquinolines\(^12\). This transformation starts from the \(\beta\)-aryl-\(\alpha\)-isocyno-acylates\(^12\) and uses Togni’s reagent as the CF\(_3\) radical precursor to afford the products in moderate-to-excellent yield, in the absence of any transition metal (Figure 44).

Recently, by using Togni’s reagent and a simple catalyst Cul, Wang et al\(^9\) reported an elegant method for the arytrifluoromethylation of \(N\)-phenylcinnamamides\(^12\), where a series of CF\(_3\)-containing 3,4-dihydroquinolin-2(1\(H\))-ones\(^12\) were obtained regioselectively and diastereoselectively (Figure 45). The same conversion from \(\alpha\)-aryl-\(\alpha\)-isocyno-acylates to CF\(_3\)-containing dihydroquinolin-2(1\(H\))-ones was also realized under visible light conditions.\(^91\)

Another widely applied benziodoxole reagent is the \([\text{triisopropylsilyl}]\text{ethynyl}\) benziodoxolone (TIPS-EBX) for its role in introducing alkynyl groups. Although TIPS-EBX had been prepared in 1996,\(^92\) the first significant application was not reported until 2009 by Brand et al.\(^93\) Direct alkynylation of indole derivatives bearing a C2 alkynyl linker, which can be connected to a series of synthetically useful functional groups such as \(-\text{F}, -\text{Cl}, -\text{Br}, -\text{CO}_2\text{Me}, \) or \(-\text{CN}.

Applying TMS-EBX in the presence of tertiary amines, a metal-free alkynylation of various heterocyclic compounds\(^12\) can be realized under mild conditions and affords the corresponding alkynylated heterocyclic compounds\(^134–137\) containing a quaternary carbon in high yields (Figure 48).\(^96\)

In the presence of CsF, cycloaddition between the iodonium ylides\(^139\) and the \(\text{ortho}\)-silyl aryltriflates\(^138\) afforded a series of benzofurans\(^140\) at room temperature in moderate-to-good yields (Figure 49).\(^97\)

Aryliodonium imides in the presence of metal complexes were reported to efficiently introduce another nitrogen atom into the nitrogen-containing heterocycle compounds. Figure 50 depicts the selective addition of the imido moiety to the \(N\) atom of pyridine rings\(^141\) through a Ru-catalyzed \(N\)-\(N\) bond formation.\(^98\)

Arylation of heterocycles with diaryliodonium salts, whether at a carbon or a heteroatom, has drawn much attention from synthetic chemists. One of the most representative examples is the arylation of indole derivatives. In 2006, Deprez et al\(^99\) developed a method to carry out arylation of indoles\(^144\) at C2 through a palladium-catalyzed reaction using diaryliodonium salts (Figure 51). This reaction was proven to be compatible with free N–H indoles\(^144\), such that no by-product from \(N\)-arylation was observed.

As arylation using diaryliodonium salts would inevitably generate one equivalent of an iodoarene as a side product, it makes this approach unattractive with regard to atom economy. Recently, a Cu-catalyzed tandem C–H/N–H arylation of \(\text{N}\)-containing heterocycles by using diaryliodonium salts and metal catalysts. For example, a Pd-mediated arylation of benzotriazol\(^148\) and a Cu-mediated \(N\)-arylation of indole\(^150\), cyclohexylamine\(^152\), and the four-membered lactam\(^154\) were realized. Selected examples are presented in Figure 53.\(^101–105\)

A significant amount of efforts have been devoted to the arylation of \(N\)-containing heterocycles by using diaryliodonium salts and metal catalysts. For example, a Pd-mediated arylation of benzotriazol\(^148\) and a Cu-mediated \(N\)-arylation of indole\(^150\), cyclohexylamine\(^152\), and the four-membered lactam\(^154\) were realized. Selected examples are presented in Figure 53.\(^101–105\)

In 2013, Wang et al\(^106\) realized a Cu(OTf)\(_2\)-catalyzed regioselective synthesis of polysubstituted quinolines from three components including the diaryliodonium salt\(^156\), the nitrile\(^157\), and the alkyn\(^158\) (Figure 54). It is worth noting that the aryl group of the diaryliodonium serves as a C2 building block in this reaction.
Figure 42 Intramolecular carbotrifluoromethylation of alkynes with Togni’s reagent and Cu(I).
Abbreviations: h, hours; DCM, dichloromethane.

Figure 43 Trifluoromethylation of indole derivatives with Togni’s reagent.
Abbreviations: rt, room temperature; h, hours.

Figure 44 (A) Synthesis of biologically important 1-trifluoromethylated isoquinolines with Togni’s reagent. (B) Proposed mechanism.
Abbreviation: h, hours.
Hypervalent iodine (V) reagents

Among the iodine (V) compounds, Dess–Martin periodinane (DMP) and 2-iodoxybenzoic acid (IBX) are the two most practical and therefore most widely applied oxidants for their mild characteristics. A large range of syntheses and functionalization of heterocyclic compounds have been achieved in recent years through the applications of iodine (V) reagents.

Dess–Martin periodinane

DMP was first introduced in 1984. The most special property of it is its ability to realize selective oxidation of primary and secondary alcohols to their respective aldehydes and ketones. Some applications have been formulated based on this property. For example, when treated with DMP in a hydrocarbon solvent, cleavage of the glycol C–C bond in 1,2-diols takes place, leading to the formation of a more complex molecule (Figure 55).110

Another example is the synthesis of the 2-substituted benzothiazoles in high yields, which is facilitated by DMP through an intramolecular oxidative cyclization of the thioformanilides in CH₂Cl₂. The mild reaction environment plays a key role as the reaction proceeds via a thiol radical intermediate (Figure 56).111

Figure 45 Aryltrifluoromethylation of N-phenylcinnamamides by using Togni’s reagent and copper catalyst.

Abbreviation: h, hours.

Figure 46 Direct alkynylation of indole and pyrrole heterocycles by using TIPS-EBX.

Abbreviation: TIPS-EBX, [(triisopropylsilyl)ethynyl]benziodoxolone.

Figure 47 Selective cobalt(III)-catalyzed alkynylation of indoles using hypervalent iodine-alkyne reagents.

Abbreviations: TFE, 2,2,2-Trifluoroethanol; h, hours; Cp*, cyclopentadienyl.

Figure 48 Metal-free alkynylation of various heterocyclic compounds with TMS-EBX.
**Figure 49** (A) Cycloaddition of ortho-silyl aryl triflates and iodonium ylides. (B) Proposed mechanism.

**Abbreviation:** rt, room temperature.

**Figure 50** Ru-catalyzed nitrogen atom transfer.

**Abbreviations:** h, hours; DCM, dichloromethane.

**Figure 51** Diaryliodonium salts-mediated arylation of indoles at C2.

**Abbreviations:** rt, room temperature; h, hours.

**Figure 52** Cu-catalyzed tandem C–H/N–H arylation of indoles with diaryliodonium salts.

**Abbreviations:** eq., equivalent; DMEDA, N,N’-Dimethyl-1,2-ethanediamine.
Hypervalent iodine reagents

Iodoxybenzoic acid

Certain heterocyclic compounds such as isoxazolines, [1,2]oxazinanes, and 3,5-disubstituted isoxazolines could be synthesized through radical cyclization by using IBX as a single-electron transfer (SET) oxidant. The cyclizations brought about with this protocol could occur in an intramolecular as well as intermolecular manner.

In 2005, Janza and Studer described the generation of alkoxiamidyl radicals initiated by IBX as an SET oxidant from the acylated alkoxyamines. The stereoselective 5-exo and 6-exo reactions with these N-heteroatom-centered radicals led to the isoxazolidines 166a and the [1,2]oxazinanes 166b in good-to-excellent yields (Figure 57).

In 2004, Das et al reported the preparation of the 3,5-disubstituted isoxazolines 169, achieved via an SET reaction consisting of multiple components of 167 and 168 using IBX as an oxidant (Figure 58). The reaction proceeded through a substituted aldoxime intermediate followed by a 1,3-dipolar addition of an alkene.

Recently, Bredenkamp et al reported a new example of IBX-promoted direct functionalization of the indoles 170 to the isatins 172. The reagent mixture containing a substituted sulfonyl of IBX was employed to trigger this oxidative process (Figure 59).

Conclusion

During the past several decades, hypervalent iodine reagents have been widely used in the syntheses and functionalization of heterocycles. The low production cost has made many of them commercially available, and the low toxicity, being transition metal-free, renders them environmentally friendly. But most importantly, it is their powerful oxidizing properties under mild reaction conditions along with high chemoselectivity that have driven hypervalent iodine chemistry to expand its territory in the field of synthetic chemistry.

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Figure 53 Arylation of N-containing heterocycles with diaryliodonium salts.
Abbreviations: rt, room temperature; h, hours.

Figure 54 A Cu(OTf)2-catalyzed, three-component regioselective synthesis of polysubstituted quinolones.
Abbreviations: eq., equivalent; DCE, 1,2-dichloroethane.

Figure 55 Oxidative cleavage of the glycol C–C bond with DMP.
Abbreviations: DMP, Dess–Martin periodinane; rt, room temperature; h, hours.

Figure 56 Synthesis of 2-substituted benzoisoxazoles with DMP.
Abbreviations: DMP, Dess–Martin periodinane; rt, room temperature; min, minutes.
Author contributions
All authors contributed toward data analysis, drafting and critically revising the paper and agree to be accountable for all aspects of the work. All authors read and approved the final version of the manuscript.

Disclosure
The authors report no conflicts of interest in this work.

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