Iodine catalysis: A green alternative to transition metals in organic chemistry and technology

Mekhman S. Yusubov\textsuperscript{a}, Viktor V. Zhdankin\textsuperscript{b,*}

\textsuperscript{a} The Tomsk Polytechnic University, 634050 Tomsk, Russia
\textsuperscript{b} Department of Chemistry and Biochemistry, University of Minnesota Duluth, Duluth, MN 55812, USA

Received 4 May 2015; accepted 21 May 2015
Available online 11 June 2015

Abstract

Iodine and compounds of iodine in higher oxidation states have emerged as versatile and environmentally benign reagents for organic chemistry. One of the most impressive recent achievements in this area has been the discovery of catalytic activity of iodine in numerous oxidative transformations leading to the formation of new C—O, C—N, and C—C bonds in organic compounds. These catalytic transformations in many cases are very similar to the transition metal-catalyzed reactions, but have the advantage of environmental sustainability and efficient utilization of natural resources. Iodine is an environmentally friendly and a relatively inexpensive element, which is currently underutilized in industrial applications. One of the main goals of this review is presenting to industrial researchers the benefits of using catalytic iodine in chemical technology as an environmentally sustainable alternative to transition metals. The present review summarizes catalytic applications of iodine and compounds of iodine in organic synthesis. The material is organized according to the nature of active catalytic species (hypoiodite, trivalent, or pentavalent hypervalent iodine species) generated in these reactions from appropriate pre-catalysts. Numerous synthetic procedures based on iodine(III) or iodine(V) catalytic species in the presence of hydrogen peroxide, Oxone, peroxyacids or other stoichiometric oxidants are summarized. A detailed discussion of catalytic cycles involving hypervalent iodine, hypoiodites, and other active intermediates is presented.

Keywords: Hypervalent catalysis; Iodine catalysis; Hypoiodite catalysis; Hypervalent iodine

1. Introduction

Iodine is one of the heaviest non-radioactive elements in the Periodic Table classified as a non-metal, and it is the largest, the least electronegative, and the most polarizable of the halogens. Iodine can form inorganic and organic derivatives in various oxidation states (−1, 0, +1, +3, +5, +7) and structural features and reactivity pattern of iodine compounds in many aspects are similar to the derivatives of heavy transition metals. Reactions of iodine compounds are commonly discussed in terms of oxidative addition, ligand exchange, reductive elimination, and ligand coupling, which are typical of the transition metal chemistry \cite{1}. In contrast to the heavy metals, iodine is an environmentally friendly and a relatively inexpensive element; iodine bulk price in the last 10 years was within the range of $20–100 per kg, which is orders of magnitude cheaper than platinum, palladium, or osmium. Iodine annual production is about 30,000 tons with estimated world’s total reserves of 15 million metric tons located mainly in Chile and Japan \cite{2}.

Compounds of iodine have found some industrial application. About 16% of iodine world production is utilized in industrial catalysis. Hydroiodic acid is used as a co-catalyst for the production of acetic acid by the Monsanto and Cativa processes. In this technology, which is the main industrial process for the production of acetic acid, hydroiodic acid converts the methanol feedstock into methyl iodide, which then undergoes Rh-catalyzed carbonylation. Hydrolysis of the resulting acetyl iodide regenerates hydroiodic acid and gives acetic acid. Other practical applications of iodine compounds include the use in polymer industry, in liquid-crystal display polarizers, and also numerous applications in food industry, medicine, and pharmaceuticals \cite{3}.

In recent years, organic derivatives of polyvalent iodine (which are known under common name of “hypervalent” iodine compounds) have attracted significant research activity as versatile
and environmentally benign reagents for organic synthesis [1,4,5]. One of the most impressive recent achievements in this area has been the discovery of catalytic activity of iodine in numerous oxidative transformations leading to the formation of new C—O, C—N, and C—C bonds in organic compounds. These catalytic transformations in many cases are very similar to the transition metal-catalyzed reactions, but have the advantage of environmental sustainability and efficient utilization of natural resources.

In the present review, we summarize catalytic applications of iodine and compounds of iodine in organic synthesis. The material is organized according to the nature of active catalytic species (hypoiotide, trivalent, or pentavalent iodine species) generated in these reactions from appropriate pre-catalysts. One of the main goals of this review was to attract attention of the industrial researchers to the benefits of using catalytic iodine in chemical technology as an environmentally sustainable alternative to transition metals.

2. Catalytic cycles involving elemental iodine or iodide anion as pre-catalysts

Catalytic reactions, utilizing iodide anion or elemental iodine as the pre-catalysts, usually involve the iodine cation, hypoiotide acid, or inorganic iodine(III) species as active oxidants. There has been significant recent interest in these reactions since 2010, when first examples of such reactions were reported. The oxidative catalytic reactions utilizing iodide anion or elemental iodine as a catalyst or pre-catalyst have been summarized in several reviews [6–9].

In 2010, Ishihara and co-workers have first reported that tetrabutylammonium iodide can be used as a highly effective pre-catalyst for the oxylactonization of oxocarboxylic acids 1 with aqueous hydrogen peroxide at room temperature (Scheme 1) [10]. Importantly, no Baeyer–Villiger products were obtained under these reaction conditions. Both γ-aryl- and γ-heteroarylcarbonyl-γ-butyrolactones 2 (R = aryl or heteroaryl, n = 1) were obtained in excellent yields, and γ-alkylicarbonyl-γ-butyrolactones 2 (R = alkyl, n = 1) and δ-arylcarbonyl-δ-valerolactones 2 (n = 2), in moderate yields. Lactones are important intermediate products in organic synthesis and in the manufacturing of polyesters, therefore, this simple and environmentally friendly procedure represents interest to industrial chemists.

This catalytic procedure has been further applied to the oxidative coupling of carbonyl compounds with carboxylic acids using Bu4NI as catalyst and tert-butyl hydroperoxide (TBHP) as the terminal oxidant [10]. Various ketones 3 as well as 1,3-dicarbonyl compounds as substrates react with carboxylic acids 4 under these conditions to give the corresponding α-acyloxy ketones 5 in good to excellent yields (Scheme 2) [10]. A similar TBAI-catalyzed oxidative coupling of β-ketoesters with carboxylic acid has been reported in a more recent work [11].

Aldehydes can be α-oxycylated under similar conditions in the presence of piperidine [10]. Thus, aldehydes 6 and acids 7 react upon mild heating in the presence of catalytic amounts of Bu4NI and piperidine and TBHP as the terminal oxidant in ethyl acetate to afford α-acyloxy aldehydes 8 in high yields (Scheme 3). Various functional groups such as terminal or internal alkenyl, benzyl, silyloxy, acetal, halogen, and ester are stable under these conditions.

The Bu4NI/TBHP catalytic system has also been applied toward the α-oxycylation of ethers with carboxylic acids in ethyl acetate at 80 °C [12], possibly, via a radical mechanism. During their studies on the oxylactonization of oxocarboxylic acids 1 (Scheme 1), Ishihara and co-workers discovered that the catalytic oxidative system Bu4NI/H2O2 could be used for the oxidative cycloetherification of oxo-substituted phenols [6]. For example, the oxidation of phenolic substrate 9 with two equivalents of 30% aqueous H2O2 in the presence of Bu4NI as a catalyst in THF or ether at room temperature selectively afforded the corresponding 2-acyldihydrobenzofuran 10 in excellent yield and (Scheme 4).

Based on this reaction (Scheme 4), Ishihara and co-workers have developed a highly enantioselective oxidative cycloetherification of substrates 11 using hydrogen peroxide as the oxidant in the presence of the chiral quaternary ammonium iodide catalyst 12 (Scheme 5) [13]. This cycloetherification leads to the chiral 2-acyl-2,3-dihydrobenzofuran skeleton 13, which is a key structural unit in numerous biologically active compounds, for example, entremirol and entremiridol.

![Scheme 1. Tetrabutylammonium iodide as a pre-catalyst for the oxylactonization of oxocarboxylic acids.](image1)

![Scheme 2. Tetrabutylammonium iodide-catalyzed oxidative coupling of carbonyl compounds with carboxylic acids.](image2)

![Scheme 3. Catalytic α-acyloxylation of aldehydes.](image3)

![Scheme 4. Catalytic oxidative cycloetherification of phenolic substrates.](image4)
In the more recent works by Li and co-workers, the Ishihara’s catalytic cycloetherification has been employed in the synthesis of bisbenzannelated spiro[5], ketals [14], and also used in a new synthetic approach to γ-rubromycin [15]. Several control experiments supported that either tetrabutylammonium hypoiodite (Bu4N\(^{+}\)IO\(^{-}\)) or iodite (Bu4N\(^{+}\)IO\(_2^{-}\)), which are generated in situ from tetrabutylammonium iodide and hydrogen peroxide, are the active species in these oxidations (Schemes 1–5) [10]. The presence of highly unstable iodite anions (IO\(_2^{-}\)) in the reaction mixtures containing Bu4NI/H\(_2\)O\(_2\) was confirmed by the negative ion ESI–MS analysis [16]. Hypoiodite (IO\(^{-}\)) species were also detected in this experiment.

A procedure for the α-tosyloxylation of ketones by the reaction with mCPBA and TsOH\(\cdot\)H\(_2\)O in the presence of catalytic amounts of NH4I and benzene in a mixture of MeCN and trifluoroethanol (8:2) has been reported (Scheme 6) [17]. This method has the advantages of mild reaction conditions with a simple procedure, and it is suitable for preparing various α-sulfonyloxy ketones. It has been suggested that [hydroxyl(tosyloxy)iodo]benzene, generated by the reaction of iodide anion with mCPBA, benzene, and TsOH, is the active oxidant in this reaction [17].

First examples of a hypoiodite-catalyzed oxidative C—N coupling reaction were independently reported by Nachtsheim [18] and Yu and Han [19] in 2011. Nachtsheim and co-workers have found that the reaction of benzoxazoles 14 with various amines in the presence of Bu4NI as a catalyst and 30% aqueous H\(_2\)O\(_2\) or 70% aqueous TBHP as a terminal oxidant afforded the products of C—N coupling (Scheme 7) [18]. The reaction was generally faster and the yield of the products was higher when TBHP was used as an oxidant. The authors suggested that the in situ-generated acetyl hypoiodite is the actual oxidant in this reaction [18].

Yu and co-workers reported the oxidative coupling of 2-aminopyridines 16 with β-ketoesters or 1,3-diones in the presence of 10 mol% of Bu4NI, BF\(_3\)-etherate and two equivalents of 70% aqueous TBHP in acetonitrile (Scheme 8) [19]. The corresponding imidazo[1,2-α]pyridines 17 were obtained as final products in moderate to high yields. The in situ-generated hypoiodite or iodite species are the actual oxidants in this reaction.

The catalytic system I\(^{-}\)/oxidant has also been used for the synthesis of the following heterocycles: (i) 2-imidazolines 18 by the oxidative coupling of benzaldehydes with ethylenediamines [20], (ii) benzimidazoles 19 by a similar oxidative coupling reaction of phenylenediamines with aromatic or aliphatic aldehydes [16], and (iii) oxazole derivatives 20 by the oxidative coupling of β-ketoesters with benzylamines (Scheme 9) [21]. This simple approach to the preparation of oxazoles and imidazoles represents a potentially important new experimental method that can find practical application in the synthesis of heterocyclic compounds.

Yoshimura and coauthors developed an efficient metal-free catalytic procedure for aziridination of alkenes using tetrabutylammonium iodide as a catalyst, m-chloroperoxybenzoic acid, and aqueous hydrogen peroxide [22].
acid as the terminal oxidant, and N-aminophthalimide 21 as a nitrenium precursor (Scheme 10) [22].

The proposed mechanism of this catalytic aziridination is outlined in Scheme 11 [22]. The active species, hypoiodous acid 22 (or iodine 3-chlorobenzoate, IOCOAr), generated from Bu4NI and mCPBA, further react with alkene to give the iodonium ion 23, which is then opened at the benzylic position by N-aminophthalimide 21 (or the corresponding potassium salt, PhthNHK, formed from 21 in the presence of K2CO3). This sequence of reactions gives β-iodo-N-aminophthalimide 24, cyclization of which affords the aziridine product 25 and iodide anion. The regenerated iodide anion continues the catalytic cycle [22].

Li and co-workers reported Bu4NI-catalyzed allylic sulfonylation of α-methyl styrene derivatives with sulfonylhydrazides 27 using TBHP as the terminal oxidant (Scheme 12) [23]. The mechanism of this reaction involves the generation of sulfonyl radicals, Ts’, from sulfonylhydrazides 27 by the Bu4NI/TBHP catalytic system, followed by the addition of Ts’ to α-methyl styrene derivatives 26 to give the corresponding allylic sulfones 28.

This reaction has been further extended to a catalytic procedure for the synthesis of allyl aryl sulfone derivatives 31 from Baylis–Hillman acetates 29 and sulfonylhydrazides 30 using Bu4NI as the catalyst and TBHP as an oxidation agent in water (Scheme 13) [24].

Only few examples of the C–C bond forming Bu4NI-catalyzed reactions have been reported. In 2011, during their studies on the hypervalent iodine-catalyzed oxidative cyclization of δ-alkynyl β-ketoesters with mCPBA, Moran and co-workers found that treatment of starting material 32 with a catalytic amount of Bu4NI and 30% aqueous H2O2 gave product 33 in moderate yield (Scheme 14) [25]. Although the mechanism is not clear, this is the first example of the hypoiodite-catalyzed C–C coupling reaction. This unique cyclization opens a new approach to 1,3- and 1,4-dicarbonyl compounds, which are useful building blocks in total synthesis. Another example of the hypoiodite-catalyzed C–C coupling reaction is represented by the C3-selective formylation of indoles 34 to products 35 by using N-methylaniline as a formylating reagent in the presence of catalytic Bu4NI and tert-butyl peroxybenzoate as the terminal oxidant (Scheme 15) [26]. Pivalic acid is used as an additive since it has been shown to suppress decomposition of indoles under oxidative conditions. This reaction probably proceeds via a free radical process [26]. The β-formylation of indole (Scheme 15) opens a new approach to a broad range of important for pharmaceutical industry indole derivatives, including serotonin.
Several oxidative catalytic systems utilizing elemental iodine as the catalyst have been developed. Recently, we have reported an efficient synthetic procedure for dicyano cyclopropanation of alkenes using catalytic amounts of molecular iodine as a precatalyst and tert-butyl hydroperoxide (TBHP) as a terminal oxidant under mild conditions (Scheme 16) [27]. This catalytic reaction works especially well for the aryl-substituted double bond affording products of cyclopropanation in high yields. A catalytic cycle based on the generated in situ hypoiodite species has been proposed for this reaction [27].

Wang and co-workers have reported several tandem oxidative cyclization reactions using I₂ as a catalyst and 70% aqueous TBHP as a stoichiometric oxidant (Scheme 17) [28–31]. Heteroaromatic compounds such as oxazoles 36, quinazolines 37, and pyridine derivatives 38 and 39 were synthesized in moderate to high yields under these catalytic conditions. The authors suggested that the I₂/I⁻ catalytic cycle might play an important role in the radical mechanism under these conditions [31]. This simple synthesis of 5- and 6-membered heterocycles from readily available precursors is potentially useful for the development of new resource efficient technologies in chemical industry.

A highly efficient α-amination of various aldehydes 40 using secondary amines 41 as nitrogen source, iodine as the pre-catalyst, and sodium percarbonate as an environmentally benign co-oxidant has been reported (Scheme 18) [32]. This reaction affords synthetically useful α-amino acetals 42 in good yields and tolerates a wide range of functional groups, such as benzyl, allyl, or ester groups, as well as bulky aldehydes and secondary amine derivatives.

Based on control experiments, a mechanism for the α-amination of aldehydes catalyzed by the in situ generated hypoiodite has been proposed (Scheme 19) [32]. In the first step, the active cationic iodine species, hypoiodite acid, which is thought to function as a one-electron oxidizing reagent or electrophilic reagent, is formed by oxidation of iodine (I₂) or iodide (I⁻) with hydrogen peroxide. In the second step, hypoiodite reacts with enamine 43 to provide iminium ion 44, the existence of which was confirmed by a control experiment, in which the hydrolysis of this intermediate led to the corresponding α-iodoaldehyde. In the third step, methanol attacks iminium ion 44 to give the iodo-substituted intermediate 45, which undergoes intramolecular cyclization to afford aziridinium ion 46. Finally, an additional methanol molecule captures the ring-opened intermediate 47 to afford the final product 48 (Scheme 19).

Prabhu and co-workers developed a versatile iodine-based aerobic catalytic system (I₂ and O₂) for the C—H functionalization of tetrahydroisoquinolines 49 with a nucleophile (Nu⁻) (Scheme 20) [33]. This cross-dehydrogenative coupling reaction is performed under mild conditions and gives generally high yields of products with a large number of nucleophiles. The proposed reaction mechanism includes the generation of iminium iodide 52 by the reaction of tetrahydroisoquinoline 49 with molecular I₂ through a radical-cation intermediate 51, followed by the reaction of iminium iodide 52 with the nucleophile and O₂ furnishing the coupled product 50 and regenerating I₂ (Scheme 20) [33].

3. Catalytic cycles based on iodine(III) species

Catalytic reactions of this type involve the reoxidation of iodoarene to aryliodine(III) species in situ using such oxidants...
Oxidative α-functionalization of carbonyl compounds

The first iodonium-catalyzed reaction, a catalytic variant of α-acetoxylation of ketones based on the in situ re-generation of (diacetoxyiodo)benzene from iodonium and m-CPBA, was reported by Ochiai and co-workers in 2005 [36]. The reaction of a ketone with m-CPBA in acetic acid results in the facile oxidation of the iodobenzene by m-CPBA. The protonated iodobenzene intermediate (R¹ = Ph, R² = H) was observed at m/z 383 from the reaction solution, and this ion gave the protonated α-acetoxylation product at m/z 179 in MS/MS by an intramolecular reductive elimination of PhI [37].

A study of the catalytic α-acetoxylation of ketones using m-CPBA as stoichiometric oxidant and iodoniums as catalysts has been reported by Ishihara and co-workers [38]. The reaction is performed by the treatment of a ketocarboxylic acid with iodobenzene (10 mol%), p-toluene sulfonic acid monohydrate (20 mol%), and m-CPBA as a stoichiometric oxidant in nitromethane solution; a representative example of the cyclization of ketocarboxylic acid to ketolactone is shown in Scheme 23.

A similar catalytic procedure for α-oxytosylation of ketones using m-CPBA as stoichiometric oxidant and iodoarenes as catalysts has been reported by Ochiai’s procedure for α-acetoxylation of ketones [34,35].
catalysts in the presence of p-toluenesulfonic acid has been developed. Various α-tosyloxyketones 59 can be efficiently prepared in high yields from the reaction of ketones 58 with mCPBA and p-toluenesulfonic acid in the presence of iodobenzene as a catalyst at moderate warming (Scheme 24) [39]. The mechanism of this reaction includes initial oxidation of PhI by mCPBA in the presence of p-toluenesulfonic acid to generate [hydroxy(tosyloxy)iodo]benzene in situ, which then reacts with the enol form of ketone to give α-tosyloxyketone.

Further modification of this reaction (Scheme 24) involves the use of polystyrene-supported iodobenzene as a recyclable catalyst, which can be recovered by simple filtration of the reaction mixture and reused [40]. Alcohols can be used instead of ketones in this reaction; in this case an excess of mCPBA (2.1 equiv) is employed in the presence of KBr (0.1 equiv) and PhI or poly(4-iodostyrene) as the catalysts [40]. Recyclable ionic-liquid supported iodoarenes have also been used as catalysts in the reaction of α-tosyloxylation of ketones with mCPBA and p-toluenesulfonic acid [41].

Tanaka and Togo have utilized Oxone (2KHSO5·KHSO4·K2SO4) as the stochiometric oxidant in the iodoarene-mediated α-tosyloxylation of ketones [42]. Various alkyl aryl ketones, dialkyl ketones, and cycloheptanone can be converted into the corresponding α-tosyloxyketones in good yields by the reaction with Oxone and p-toluenesulfonic acid in the presence of p-iodotoluene in acetonitrile. In these reactions, p-iodotoluene, 4-MeC6H4I, is the pre-catalyst, and 4-MeC6H4I(OH)OTs is formed in situ as the reactive species for the α-tosyloxylation of ketones. However, catalytic efficiency of this reaction is low, because p-iodotoluene is partially oxidized by Oxone to the iodine(V) species, which are not active in the α-tosyloxylation of ketones [42].

Togo and co-workers have found that alkyl aryl ketones and dialkyl ketones could be converted into the corresponding α-tosyloxyketones in generally low yields by treatment with mCPBA and p-toluenesulfonic acid in the presence of catalytic molecular iodine in a mixture of acetonitrile and 2,2,2-trifluoroethanol (Method A, Scheme 25) [43]. A similar conversion of ketones into the corresponding α-tosyloxyketones could be carried out by the reaction with mCPBA and TsOH·H2O in the presence of catalytic amounts of iodine and tert-butylbenzene (Method B). In both reactions, p-iodotoluene 60 (Method A) or 4-tert-butyl-1-iodobenzene 61 (Method B) are initially formed followed by conversion to the corresponding [hydroxy(tosyloxy)iodo]arenes, ArI(OH)OTs by the reaction with mCPBA and TsOH·H2O. [Hydroxy(tosyloxy)iodo]arenes are the actual reagents for the α-tosyloxylation of ketones in this catalytic cycle. Oxone can also be used as the oxidant for α-tosyloxylation of ketones in the presence of catalytic I2 (0.7 equiv) [44].

Wirth and co-workers have reported an enantioselective α-oxytosylation of ketones; in this case the enantiopure chiral iodoarene 62 is used as a catalyst in a reaction leading to the enantioenriched α-tosyloxyketones 63 (Scheme 26) [45]. The authors have tested numerous chiral iodoarenes as catalysts, but the enantioselectivity of this reaction was low [45–47].

Chi Zhang and co-workers have achieved better levels of enantioselectivity by using spirobiindane-based chiral iodoarenes as the catalysts. In particular, the use of chiral catalyst 64 (Scheme 27) allowed to obtain α-tosyloxylated ketones in up to 58% enantiomeric excess [48]. Moran and Rodriguez have prepared several chiral aryl iodides (e.g., structures 65 and 66) and tested them as catalysts in the enantioselective α-oxytosylation of propiophenone and in the oxidative cyclization of 5-oxo-5-phenylpentanoic acid to 5-benzoyldihydrofuran-2(3H)-one [49]. The highest

![Scheme 23. Hypervalent iodine-catalyzed cyclization of ketocarboxylic acid.](image)

![Scheme 24. Hypervalent iodine-catalyzed α-tosyloxylation of ketones.](image)

![Scheme 25. Catalytic α-tosyloxylation of ketones.](image)

![Scheme 26. Enantioselective catalytic α-oxytosylation of ketones.](image)
enantioselectivities obtained were 18% for the α-oxytosylation
using catalyst 65 and 51% ee for the oxidative cyclization
using catalyst 66. Legault and co-workers have developed a
family of iodooxazoline catalysts (e.g., structure 67) for the
iodine(III)-mediated α-tosyloxylation of ketone derivatives
[50]. The use of catalyst 67 (10 mol%) in dichloromethane
solution gives the best levels of enantioselectivity (up to 54%
ee). The observed enhancement in catalytic activity was
explained by the introduction of steric hindrance ortho
to the iodine atom of the catalyst (e.g., methyl group in catalyst 67)
[51]. Enantioselective tosyloxylation of carbonyl compounds is
a potentially important methodology for pharmaceutical
research.

Similarly to the α-oxytosylation, an effective catalytic method
for the α-phosphoryloxylation of ketones has been developed [52].
The treatment of ketones with phosphates 68 in the presence of
iodobenzene as the catalyst and mCPBA as the oxidant in
acetonitrile at room temperature affords respective keto
phosphates 69 in moderate to good yields (Scheme 28) [52].

3.2. Oxidative functionalization of alkenes and alkynes

Several examples of hypervalent iodine-catalyzed reactions
of alkenes and alkynes have been reported. A method for the
organocatalytic syn diacetoxylation of alkenes has been
developed using aryl iodides as efficient catalysts and hydrogen
peroxide or mCPBA as terminal oxidants (Scheme 29) [53].
Various substrates, including electron-rich as well as electron-
deficient alkenes, are smoothly transformed by this procedure
to the respective diacetoxylation products 70 in good to
excellent yields with high diastereoselectivity (up to >19:1 dr).

Iodobenzene of 4-iodotoluene have been used as the catalysts in
this reaction.

Braddock and co-workers have demonstrated that suitably ortho-substituted iodobenzenes act as organocatalysts for the
transfer of electrophilic bromine from N-bromosuccinimide to
alkenes via the intermediacy of bromoiodinanes [54]. Particularly
active catalyst is the ortho-substituted iodoarene 71, as illustrated
by a bromolactonization reaction shown in Scheme 30. An
alternative procedure for the bromolactonization of alkenoic acids
employs iodobenzene as a catalyst, sodium bromide as the source
of bromine, and Oxone as the terminal oxidant in trifluoroethanol
at room temperature [55].

Based on the hypervalent iodine-catalyzed bromocarbocyclization of appropriate alkenoic precursors 73, Gulder and co-workers have developed an efficient synthetic approach to 3,3-disubstituted oxindoles 74 (Scheme 31) [56].

These cyclizations are catalyzed by 2-iodobenzamide 72 at room
temperature using NBS as the source of electrophilic bromine. Alternatively, KBr can be used as the source of bromine in the

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\begin{align*}
\text{R}^1 & = \text{Ph, 4-} \text{MeC}_6\text{H}_4, 4-\text{ClC}_6\text{H}_4, 4-\text{BrC}_6\text{H}_4, 4-\text{NO}_2\text{C}_6\text{H}_4, 3-\text{NO}_2\text{C}_6\text{H}_4, \text{Me, Et} \\
\text{R}^2 & = \text{H, Me}
\end{align*}
\]

\[
\begin{align*}
\text{NBS} & = \text{N-bromosuccinimide}
\end{align*}
\]

**Scheme 27.** Chiral aryl iodides used as catalysts in the enantioselective α-oxytosylation of ketones.

**Scheme 28.** Hypervalent iodine-catalyzed α-phosphoryloxylation of ketones.

**Scheme 29.** Organocatalytic syn diacetoxylation of alkenes.

**Scheme 30.** Catalytic bromolactonization of alkenoic acids.

**Scheme 31.** Catalytic synthesis of 3,3-disubstituted oxindoles.
presence of Oxone as a terminal oxidant. Synthetic utility of this cyclization has been demonstrated by preparation of product 75, which is the key intermediate in the formal synthesis of the acetylcholinesterase inhibitor physostigmine [56].

A catalytic procedure for the (diacetoxyiodo)benzene-mediated oxidative iodolactonization of penentoic, pentyenoic, and hexynoic acids in the presence of tetrabutylammonium iodide has been reported [57]. In this procedure, (diacetoxyiodo)benzene is generated in situ using a catalytic amount of iodobenzene with sodium perborate monohydrate as the stoichiometric oxidant. A variety of unsaturated acids including δ-pentenoic acids 76, δ-pentyenoic acids 78 and δ-hexynoic acid afforded the respective lactones (e.g., 77 and 79) using this organocatalytic methodology (Scheme 32) [57].

An efficient catalytic method for sulfonyloxylactonization of alkenoic acids using (diacetoxyiodo)benzene as a catalyst in combination with m-chloroperoxybenzoic acid as an oxidant in the presence of a sulfonic acid has been reported [58]. The cyclization of alkenoic acids 80 is performed in dichloromethane at room temperature giving tosyloxylactones 81 in good yields (Scheme 33).

A similar catalytic phosphoryloxylactonization of penentoic acids has been developed. The cyclization of 4-pentenoic acids 82 with phosphates using iodobenzene as a catalyst in combination with mCPBA as the terminal oxidant in trifluoroethanol at room temperature affords phosphoryloxylactones 83 in good yields (Scheme 34) [59].

Iodobenzene has been shown to catalyze the 5-exo-dig cyclization of δ-alkynyl β-ketoesters 84 under oxidative conditions that generate hypervalent iodine species in situ (Scheme 35) [25]. The cyclopentane products 85 contain adjacent quaternary and tertiary stereocenters, which are formed with excellent diastereoselectivity (up to over 20:1 dr).

Ochiai and co-workers have developed an efficient iodoarene-catalyzed oxidative cleavage of alkenes and alkynes using mCPBA as a terminal oxidant [60]. Various cyclic and acyclic alkenes as well as aliphatic and aromatic alkenes are smoothly cleaved to carboxylic acids under these organocatalytic conditions (Scheme 36) [60].

A convenient procedure for the aminobromination of electron-deficient olefins using N-bromosuccinimide/tosylamide (Scheme 37) or Bromamine-T promoted by (diacetoxyiodo)benzene has been reported [61,62]. This efficient metal-free protocol affords the vicinal bromamines 86 with excellent stereoselectivities. A similar (diacetoxyiodo)benzene-catalyzed aminochlorination can be performed by using Chloramine-T as nitrogen and chlorine source [63].

Wirth and co-workers have published in 2007 a detailed study of the aziridination of alkenes with the PhI(OAc)2/N-substituted hydrazine system (Scheme 38) and, in particular, reported tentative evidence that this reaction proceeds through the formation of an aminoiodane that reacts directly with the alkene [64]. Furthermore, the authors of this publication have analyzed the requirements to make this reaction catalytic in iodoarene. This reaction requires an oxidant that will oxidize iodoarenes but that does not oxidize alkenes, and it is possible that no such oxidant actually exists [64]. Despite this prediction, the catalytic variant of a similar aziridination reaction has been developed later employing iodoide–hypoiodite catalytic cycle [22].

Scheme 32. Hypervalent iodine-catalyzed oxidative iodolactonization reactions.

Scheme 33. Catalytic sulfonyloxylactonization of alkenoic acids.

Scheme 34. Catalytic phosphoryloxylactonization of penentoic acids.

Scheme 35. Catalytic cyclization of δ-alkynyl β-ketoesters.

Scheme 36. Iodoarene-catalyzed oxidative cleavage of alkenes and alkynes.

Scheme 37. Catalytic aminobromination of electron-deficient olefins.
3.3. Oxidative bromination of aromatic compounds

Oxidative bromination of arenes can be achieved by using a source of bromide anion and an appropriate iodine(III) oxidant, possibly via intermediate formation of electrophilic bromoiodanes. An efficient and regioselective monobromination of electron-rich aromatic compounds has been developed, in which iodobenzene is used as the catalyst in combination with mCPBA as the terminal oxidant. The bromination of arenes with lithium bromide readily proceeds in THF at room temperature affording regioselective monobrominated products in good yields (Scheme 39) [65].

The proposed catalytic cycle for this reaction includes the initial formation of [hydroxyl(tosyloxy)iodo]benzene by oxidation of iodobenzene in the presence of toluenesulfonic acid followed by its conversion to the bromoiodane via ligand exchange, and then the bromination of arene gives aryl bromide (Scheme 40). The reduced by-product, iodobenzene, is again reoxidized into hypervalent iodine reagent by the oxidation with mCPBA [65].

3.4. Oxidative amination of aromatic compounds

Aromatic C—H bond can be aminated in intermolecular or intramolecular mode using amides as the nitrogen source, catalytic iodoarene, and an appropriate oxidant, such as peroxycarboxylic acid. Antonchick and co-workers have developed an atom-efficient and environmentally friendly direct oxidative intermolecular procedure for amination and hydrazination of nonfunctionalized arenes [66]. A wide range of arenes, including simple benzene, can be aminated using N-methoxybenzamide as amination reagent in the presence of peracetic and trifluoroacetic acids giving products as illustrated by Scheme 41. Even electron-poor arenes like chlorobenzene and fluorobenzene can be selectively functionalized in the para-position using this mild method. The reactions of electron-rich arenes afford products of amination in the highest yield. Out of several catalysts tested, 2,2’-diiodo-4,4’,6,6’-tetramethylbiphenyl has shown the highest catalytic activity in this reaction.

This procedure has been extended to organocatalytic hydrazination of arenes to products using N-(1,3-dioxoisooindolin-2-yl)acetamide as the nitrogen source (Scheme 42) [66]. This new approach to acetanilides may find practical use in the synthesis of isocyanates from substituted benzenes.

The mechanism of this reaction involves initial oxidation of aryl iodide by peracetic acid to the active hypervalent iodine species, which undergo oxidative fragmentation to form nitrenium ions. Reaction of an arene with the electron-deficient nitrenium ion affords final products of amination and the reduced intermediate, which is reoxidized to the species (Scheme 43) [66].

Several examples of hypervalent iodine-catalyzed cyclizations leading to intramolecular C—N bond formation have been reported. Antonchick and co-workers have developed an efficient catalytic method for the preparation of carbazoles through oxidative C—N bond formation [67]. The best yields of products were obtained in hexafluoro-2-propanol as a solvent using 2,2’-diiodo-4,4’,6,6’-tetramethylbiphenyl as a catalyst and peracetic acid as the oxidant, as illustrated by a reaction shown in Scheme 44.
Togo and Moroda have reported a (diacetoxyiodo)benzene-catalyzed cyclization of 2-aryl-N-methoxyethanesulfonamides using iodobenzene as a catalyst and m-CPBA as the stoichiometric oxidant (Scheme 45) [68]. A similar catalytic cyclization has also been performed using Oxone in acetonitrile [69].

In a similar fashion, the oxidative C–H amination of N″-aryl-N′-tosyl/N′-methylsulfonylamidines and N,N′-bis(aryl)amidines has been accomplished using iodobenzene as a catalyst to give 1,2-disubstituted benzimidazoles in the presence of mCPBA as a terminal oxidant at room temperature (Scheme 46) [70]. This is a general reaction affording benzimidazoles in moderate to high yields.

3.5. Oxidation of phenolic substrates to quinones and quinols

Oxidation of phenols or o- and p-hydroquinones with stoichiometric [bis(acyloxy)iodo]arenes to the corresponding benzoquinones is one of the most typical synthetic applications of hypervalent iodine reagents. The catalytic version of this reaction was first reported by Yakura and Konishi in 2007 [71]. In this work, the reaction of p-alkoxyphenols 102 in the presence of catalytic amounts of 4-iodophenoxycetic acid with Oxone as the terminal oxidant in aqueous acetonitrile at room temperature affords p-quinones 103 in high yields (Scheme 47) [71]. 4-Iodophenoxycetic acid is a readily available, water-soluble aromatic iodide that has a particularly high catalytic activity in this reaction.

Yakura and Konishi proposed a catalytic cycle based on the iodine(V) species was proposed for this reaction (Scheme 47) [71]; however, the more recent studies have demonstrated that the oxidation of iodoarenes with Oxone at room temperature generates active iodine(III) species, and heating to about 70 °C or the presence of ruthenium catalyst is required to oxidize ArI to ArIO₂ [72].

Several modifications of the procedure shown in Scheme 47 have been reported [73–75]. The reaction of p-dialkoxybenzenes 104 with a catalytic amount of 4-iodophenoxycetic acid in the presence of Oxone as the oxidant in aqueous trifluoroethanol affords the corresponding p-quinones 105 in excellent yields (Scheme 48) [73,75].

The catalytic oxidation of p-substituted phenols bearing an alkyl or aryl group in the para position gives the corresponding p-quinols. In particular, the reaction of p-substituted phenols 106 with a catalytic amount of 4-iodophenoxyacetic acid and Oxone as the oxidant affords p-quinols 107 in generally high yields (Scheme 49) [75,76].
3.6. Oxidative spirocyclization of aromatic substrates

The oxidative dearomatization of phenolic substrates resulting in intramolecular cyclization with the formation of spirocyclic products represents one of the most powerful synthetic tools in modern organic synthesis. Kita and co-workers have reported the first example of catalytic oxidative spirocyclization reaction based on the in situ regeneration of a [bis(trifluoroacetoxy)iodo]arene from iodoarene with mCPBA as a terminal oxidant [77]. In a specific example, the oxidation of the phenolic substrate 108 with mCPBA in dichloromethane in the presence of a catalytic amount of p-[bis(trifluoroacetoxy)iodo]toluene (1 mol%) and trifluoroacetic acid at room temperature affords the respective spirolactone 109 in good yield (Scheme 50). A variety of other [bis(trifluoroacetoxy)iodo]arenes [e.g., PhI(OCOCF₃)₂, 4-MeOC₆H₄I(OCOCF₃)₂ and 2,4-F₂C₆H₃I(OCOCF₃)₂] and different acidic additives (acetic acid, BF₃·OEt₂, TMSOTf, molecular sieves) have been tested as catalysts in this reaction; however, the 4-MeC₆H₄I(OCOCF₃)₂/trifluoroacetic acid system generally provides the best catalytic efficiency. Under optimized conditions, various phenolic substrates 108 have been oxidized to spirolactones 111 in the presence of catalytic amounts of p-iodotoluene (Scheme 50) [77]. A modification of this catalytic procedure involves the use of peracetic acid as the oxidant in fluoroalcohol solvents [78].

In a more recent work, the Kita’s catalytic spirocyclization has been tested in the synthesis of bioactive polyspirocyclohexa-2,5-dienones, as shown in Scheme 51 [79]. The target product 113 was isolated in a low yield, probably due to the competitive oxidation of substrate 112 directly by mCPBA to give unwanted side products.

Ngatimin et al. have developed a procedure for the iodobenzene-catalyzed synthesis of spirofurans and benzopyrans by oxidative cyclization of vinylogous esters [80]. Vinylogous esters bearing para or meta methoxy benzyl groups undergo oxidative cyclization with 5–20 mol% iodobenzene and mCPBA to give spirofuran or benzopyran containing heterocycles as illustrated by two specific examples shown in Scheme 52. These cyclizations allow rapid synthesis of skeletally complex products in good to excellent yields [80].

A similar procedure allows catalytic oxidation of the amide derivatives of phenolic substrates 114 to the respective N-fused spirolactams 115 using p-iodotoluene as the catalyst and mCPBA as the terminal oxidant (Scheme 53) [81].

The catalytic spirocyclization procedure has been further improved by using 2,2′-diido-4,4′,6,6′-tetramethylbiphenyl 93 as the catalyst instead of p-iodotoluene. Diiodide 93 has demonstrated a high catalytic activity in this reaction in the presence of peracetic acid as the terminal oxidant, as illustrated by Scheme 54 [82]. It has been proposed that the in situ generated μ-oxo-bridged hypervalent iodine(III) species are the actual active species in this catalytic cycle [82].
The catalytic spirocyclization of phenolic substrates can be performed as an enantioselective reaction using chiral, non-racemic organic iodides as the catalysts [83–85]. In particular, the chiral iodoarene 117 with a rigid spirobiindane backbone has been found to catalyze enantioselectively the dearomatization of naphtholic substrates 116 in a highly selective manner giving optically active products 118 with up to 69% ee (Scheme 55) [83]. Ishihara and co-workers have designed a conformationally flexible C2-symmetric iodoarene catalyst 120 for a similar enantioselective oxidative spirolactonization [84,86,87]. For example, hydroxynaphthalenyl propanoic acid derivatives 119 undergo dearomatization in the presence of catalyst 120 to give the corresponding spirolactones 121 in yields up to 94% with enantioselectivity up to 90% (Scheme 55) [84].

3.7. Carbon–carbon bond forming reactions

In the 2005 seminal work, Kita and co-workers reported the first example of an intermolecular C–C bond formation reaction catalyzed by an iodoarene [77]. Specifically, the oxidative coupling of phenolic ether 122 using [bis(trifluoroacetoxy)iodo]benzene as a catalyst and mCPBA as a terminal oxidant afforded product 123 in moderate yield (Scheme 56). More recently, this C–C coupling reaction was extended to a selective coupling of N-methanesulfonyl anilides with aromatic hydrocarbons [88].

Kita and co-workers have developed an H2O2/acid anhydride system for the iodoarene-catalyzed intramolecular C–C cyclization of phenolic derivatives; an example of this catalytic cyclization is shown in Scheme 57 [89]. In a similar fashion, the intramolecular oxidative coupling of substituted 4-hydroxyphenyl-N-phenylbenzamides 124 has been performed by using iodobenzene as a catalyst and m-chloroperoxybenzoic acid or urea·H2O2 as the oxidant (Scheme 58). This reaction provides an efficient synthetic approach to spirooxindoles 125 [90].
3.8. Hofmann rearrangement of carboxamides

Hypervalent iodine reagents have been employed in numerous synthetic works as oxidants for the Hofmann-type rearrangements, including the preparation of pharmaceutical products on an industrial scale [91]. Synthetic procedures for Hofmann rearrangement using stoichiometric organo-hypervalent iodine species generated in situ from iodoarenes and appropriate oxidants have also been reported [92,93]. In particular, alkylcarboxamides can be converted to the respective amines by Hofmann rearrangement using hypervalent iodine species generated in situ from stoichiometric amounts of iodobenzene and Oxone in aqueous acetonitrile [92]. Likewise, the Hofmann-type rearrangement of aromatic and aliphatic imides using a hypervalent iodine(III) reagent generated in situ from stoichiometric PhI, mCPBA, and TsOH·H2O has also been reported [93].

The first truly catalytic version of Hofmann rearrangement using aryl iodides as catalysts and mCPBA as terminal oxidant was reported by Ochiai and co-workers in 2012 [94]. Catalytic efficiency of several substituted iodobenzenes and aliphatic alkyl iodides in Hofmann rearrangement of benzylic carboxamides has been tested to demonstrate that iodobenzene is the best catalyst. Introduction of electron-donating (4-methyl, 3,5-dimethyl and 2,4,6-trimethyl) or electron-withdrawing groups (4-Cl and 4-CF3) into iodobenzene decreased the yield of products. Aliphatic iodides such as methyl, trifluoroethyl, and 1-adamantyl iodides showed no catalytic efficiency. Under optimized reaction conditions, various linear, branched, and cyclic aliphatic carboxamides afford alkylammonium chlorides in high yields (Scheme 59). These catalytic conditions are compatible with the presence of various functionalities such as halogens (F, Cl, Br), sulfonamides, amines and methoxy and nitro groups. Bicyclic amide affords endo-ammonium chloride stereoselectively in a good yield, which suggests retention of stereochemistry of the migrating groups in the catalytic rearrangement of carboxamides, same as observed in the classical Hofmann rearrangement. This procedure for the preparation of various amines from commercially available amides represents a potentially useful resource efficient technology for organic synthesis.

The catalytic cycle for this reaction probably involves in situ generation of a tetracoordinated square planar bis(aqua)(hydroxy)phenyliodine(III) complex as an active oxidant formed from iodobenzene by the reaction with mCPBA in the presence of aqueous HBF4 (Scheme 60). Complex promotes the Hofmann rearrangement of carboxamides, probably via intermediate formation of N-(phenyliodanyl)carboxamides [94].

Our group has reported the hypervalent iodine-catalyzed Hofmann rearrangement of carboxamides to carbamates using Oxone as the oxidant [95]. This reaction involves hypervalent iodine species generated in situ from catalytic amounts of PhI and Oxone in the presence of hexafluoroisopropanol (HFIP) in aqueous methanol solutions. Under these conditions, Hofmann rearrangement of various carboxamides affords corresponding carbamates in high yields (Scheme 61). The addition of small amount of water is required to dissolve Oxone in the reaction mixture, and the presence of HFIP in the mixture dramatically improves the yield of carbamates. Iodobenzene is the most active pre-catalyst in this reaction; the use of other iodine containing pre-catalysts (2,4,6-Me3C6H2I, 4-MeC6H4I, 4-CF3C6H4I, 3-HO2CC6H4I, Bu4NI) instead of PhI gives poor results. In general, the reactions of benzylcarboxamides with either electron-donating or electron-withdrawing substituents give corresponding carbamates in good yields. Various aliphatic amides, including primary, secondary, tertiary and cyclic alkylcarboxamides, also smoothly react under these conditions.

Compared to the previous reported method of Hofmann rearrangement with the in situ-generated stoichiometric hypervalent iodine species [92], the catalytic method affords carbamates in comparable yields.
The catalytic cycle for this reaction involves the reactive species 134 generated from PhI and Oxone in aqueous HFIP, which further react with carboxamide 132 to give the hypervalent amidoiodane 135 via ligand exchange (Scheme 62). Amidoiodane 135 then undergoes the reductive elimination of iodobenzene and the 1,2-shift at the electron-deficient nitrenium nitrogen atom to give isocyanate 136. Subsequently, the addition of methanol to isocyanate 136 gives the final carbamate 133. The regenerated PhI continues catalytic cycle. The presence of HFIP may help to generate more electron-deficient active species 134 and 135 via ligand exchange with hydroxy(phenyl)iodonium ion or hypervalent aminoiodine, which help to accelerate further steps of the catalytic cycle, such as ligand exchange and 1,2-shift.

3.9. Oxidation of anilines

Anilines can be oxidized to azobenzenes under hypervalent iodine catalysis using peracetic acid as the oxidant (Scheme 63) [96]. 2-Iodobenzoic acid has the best catalytic effect compared to other aryl iodides (PhI, 4-MeOC₆H₄I, 4-NO₂C₆H₄I, 3-IC₆H₄CO₂H, 4-IC₆H₄CO₂H). This metal-free oxidation system demonstrates wide substituent tolerance, and the corresponding products are formed in generally good yields. The large-scale preparation of azo compounds also could be carried out successfully by this method. Azobenzenes are key compounds in the dye industry, so this catalytic technology is important from the industrial viewpoint.

The asymmetrical azo compounds 140 have also been prepared under these conditions in moderate yields by coupling 3-ethynylaniline 139 with excessive amounts of a less reactive aniline (Scheme 64) [96].

3.10. Generation of nitrile oxides from oximes

Hypervalent iodine catalyzed oxidation of aldoximes 141 using oxone as a terminal oxidant generates nitrile oxides 142, which react with alkenes and alkynes to give the corresponding isoxazolines 143 and isoxazoles 144 in moderate to good yields (Scheme 65) [97]. This reaction involves active hypervalent iodine species formed in situ from catalytic iodoarene and oxone in the presence of hexafluoroisopropanol in aqueous methanol solution.

4. Catalytic cycles based on iodine(V) species

Hypervalent iodine(V) reagents, such as 2-iodoxybenzoic acid (IBX) and Dess–Martin periodinane (DMP), have found widespread synthetic application as stoichiometric oxidants for the facile and selective oxidation of alcohols to respective carbonyl compounds and also for some other important oxidative transformations. Catalytic application of iodine(V) species in oxidation of alcohols has previously been reviewed by Uyanik and Ishihara [98,99]. First examples of a catalytic application of the iodine(V) species such as IBX in the oxidation of alcohols using Oxone as the oxidant were independently reported by the groups of Vinod [100] in 2005 and Giannis [101] in 2006. In particular, Vinod’s group employed 20–40 mol% of 2-iodobenzoic acid in a water–acetonitrile biphasic solvent.
system; under these conditions primary and secondary alcohols were oxidized to carboxylic acids and ketones, respectively (Scheme 66) [100].

In a similar catalytic oxidation, Giannis’ group utilized a water–ethyl acetate biphasic solvent system in the presence of 10 mol% of 2-iodobenzoic acid and tetrabutylammonium hydrogen sulfate as a phase-transfer catalyst. In this system, primary benzylic alcohols were oxidized to the corresponding aldehydes, which, in contrast to Vinod’s procedure, did not undergo further oxidation (Scheme 67) [101].

Page and co-workers have demonstrated that primary and secondary alcohols can be oxidized to the respective aldehydes and ketones under reflux conditions in acetonitrile or dichloroethane in the presence of catalytic amount of 2-iodobenzoic acid and using tetrphenylphosphonium monoperoxysulfate, Ph₄P⁻HSO₅⁻, as the oxidant (Scheme 68) [102]. Tetrphenylphosphonium monoperoxysulfate is prepared from Oxone by treatment with tetrphenylphosphonium chloride. This catalytic system is useful for the oxidation of primary alcohols to the corresponding aldehydes without further oxidation to the carboxylic acids.

All these catalytic oxidations (Schemes 66–68) utilize catalytic cycle involving IBX 146 as the reactive species generated in situ from 2-iodosylbenzoic acid (IBA, 145) and monoperoxysulfate salts as terminal oxidants (Scheme 69) [99]. The synthetic value of this iodine(V)-based catalytic cycle is limited by the reoxidation step of IBA to IBX, which proceeds relatively slowly even at temperatures above 70 °C.

Several modified catalysts for the iodine(V)-mediated oxidation of alcohols have been developed based on the IBX derivatives and analogs (Scheme 70). In particular, the “fluorous IBX” 147 efficiently works as a catalyst for oxidation of various alcohols to the corresponding carbonyl compounds in good to high yields [103]. Fluorous IBX 147 can be regenerated from “fluorous IBA”, which is readily recovered from the reaction mixture by simple filtration. The recovered reagent 147, without further purification, retains its catalytic activity for at least five cycles.

The “twisted” dimethyl-IBX 148 and tetramethyl-IBX 149 have especially high catalytic activity and are capable to catalyze the oxidations of alcohols and sulfides with Oxone at room temperature in common organic solvents [104]. The ortho-methyl...
groups in reagents 148 and 149 lower the activation energy corresponding to the rate-determining hypervalent twisting, and also the steric relay between successive methyl groups twists the structure, which manifests in significant solubility in common organic solvents.

Ishihara and co-workers have found that 2-iodobenzenesulfonic acid (IBS 150) [105] is an extremely active catalyst in the oxidations of alcohols with Oxone as the terminal oxidant [106]. Methyl substituted IBS derivatives 151 and 156 have even slightly higher catalytic activity. Catalysts 150–152 can be conveniently generated in situ by using sodium or potassium salts of the respective 2-iodobenzenesulfonic acids and Oxone in such solvents as acetonitrile, ethyl acetate, or nitromethane. The catalytic oxidation of alcohols using IBS and Oxone is illustrated by Scheme 71. Primary alcohols are oxidized to aldehydes, when smaller quantity of Oxone (0.6–0.8 equiv) is used, or to carboxylic acids in the presence of excessive Oxone (1.2 equiv) [106]. This reaction (Scheme 71) has been used for a selective larger scale oxidation of 4-bromobenzyl alcohol (6 g) to the corresponding aldehyde or carboxylic acid in excellent yields by controlling the amount of Oxone added in the presence of 1 mol% of the precatalyst, potassium 2-ido-5-methylbenzenesulfonate [99].

Konno and co-workers investigated in detail the oxidation of various fluoroalkyl-substituted alcohols in the presence of a catalytic amount of sodium 2-iodobenzenesulfonate and Oxone in acetonitrile or nitromethane [107]. The efficiency of this oxidation was also evaluated by comparison to other oxidations, such as the Dess–Martin, pyridinium dichromate, and Swern oxidations. It was demonstrated that the hypervalent iodine(V)-catalyzed oxidation could be applied for almost all types of fluorinated alcohols, and it was comparable to Dess–Martin oxidation, while pyridinium dichromate and Swern oxidations could not be employed for allylic and propargylic alcohols as well as the alcohols having an aliphatic side chain. Moreover, the hypervalent iodine-catalyzed oxidation could be applied for a larger scale reaction as demonstrated for the oxidation of fluoroalcohol 153 to the respective ketone 154 (Scheme 72) [107].

Ishihara and co-workers have developed an oxidative rearrangement of tertiary allylic alcohols 155 to enones 156 with Oxone promoted by catalytic quantities of sodium 2-iodobenzenesulfonate (Scheme 73) [108]. Under these conditions, 5-methyl-IBS 95 is generated in situ and serves as the actual catalyst for the oxidation. Cyclic and acyclic substrates afford the corresponding enones in moderate to high yields. Notably, sterically demanding steroidal alcohol 157 has been converted into enone 158 in high yield [108].

During the course of research on the oxidation of cycloalkanols, Ishihara and co-workers have also found that the selective oxidation of 4-tert-butylcyclohexanol 159 to 4-tert-butyl-2-cyclohexenone 160 can be achieved in excellent yield in the presence of a catalytic amount of sodium 2-iodobenzenesulfonate and 2 equivalents of Oxone (Scheme 74) [106]. Using this procedure, five- and six-membered cycloalkanols can be transformed into the corresponding enones 161–165 in good yields [106].

Vinod and co-workers have first developed a selective procedure for oxidation of benzylic C—H bonds to the corresponding carbonyl functionalities using a catalytic amount of 2-iodobenzoic acid and Oxone as a stoichiometric oxidant in aqueous acetonitrile under reflux conditions (Scheme 75) [109]. The authors hypothesized that the active hypervalent iodine oxidant generated in situ might not be IBX, but a soluble derivative of IBX 166, incorporating a peroxysulfate ligand. This intermediate is believed to oxidize a benzylic C—H bond via a single electron transfer (SET) mechanism [109].
Zhang and co-workers have further improved the procedure for catalytic oxidation of benzylic C—H bonds using IBS as a catalyst, which is generated in situ by the oxidation of sodium 2-iodobenzenesulfonate (5 mol%) by Oxone in the presence of a phase-transfer catalyst, tetrabutylammonium hydrogen sulfate, in anhydrous acetonitrile at 60 °C [110]. Various alkylbenzenes, including methyl- and ethylarenes, substituted alkylbenzenes containing acetoxy or cyclic acetal functionalities, and a cyclic benzylic ether could be efficiently oxidized. The same catalytic system can also be applied to the oxidation of alkanes as illustrated by Scheme 76 [110]. This catalytic procedure may serve as an alternative method for the existing industrial technology of preparation of cyclohexanone.

Ishihara and co-workers have reported the first example of hypervalent iodine(V)-catalyzed regioselective oxidation of phenols to α-quinoines [111]. Various phenols could be oxidized to the corresponding α-quinoines in good to excellent yields using catalytic amounts of sodium 2-iodo-5-methylbenzenesulfonate and stoichiometric amounts of Oxone as a co-oxidant under mild conditions; a representative example is shown in Scheme 77 [111].

5. Conclusions

This review demonstrates an active current interest in catalytic applications of iodine compounds. Compounds of iodine possess similar to transition metals reactivity, but have the advantage of environmental sustainability and efficient utilization of natural resources. Iodine is an environmentally friendly and a relatively inexpensive element, which is currently underutilized in industrial applications. We hope that this review will attract attention of industrial researchers to the benefits of using catalytic iodine in chemical technology as an environmentally sustainable alternative to transition metals.

Acknowledgment

Our own research in the area of iodine chemistry was supported by a research grant from the National Science Foundation (CHE-1262479). M.S.Y. is also thankful to the Ministry of Education and Science of the Russian Federation (project ‘Science’ No. 4.2569.2014/K).

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