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A mild and efficient method for the conversion of aldehydes into nitriles and thiols into disulfides using an ionic liquid oxidant

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Abstract A simple, mild and high yielding method for the conversion of various aldehydes to nitriles has been developed using an ionic liquid reagent, hexamethylene bis(*N*-methylimidazolium) bis(dichloroiodate) (HMBMIBDCI), in combination with aqueous ammonia in CH_3CN at room temperature. Moreover, the treatment of aromatic and aliphatic thiols with HMBMIBDCI resulted in the corresponding disulfides in solvent-free condition at room temperature.

Keywords Hexamethylene bis(*N*-methylimidazolium) bis(dichloroiodate) · Ionic liquid oxidant · Nitriles · Disulfides · Oxidation

Introduction

Nitriles are important starting materials for the preparation of a series of organic compounds including esters, amides, amidines, carboxylic acids, amines, ketones, and some of the heterocyclic compounds like tetrazoles [1–3]. The nitrile moiety is found in many drugs such as pericyazine [4] and cyamemazine [5, 6] (antipsychotic drugs), citalopram [7] (antidepressant drug), fadrozole [8] and letrozole [9] (breast cancer), etravirine [10] and dapivirine [11, 12] (anti-HIV), and vildagliptin [13] (antidiabetic drug). In addition, aromatic nitriles are utilized as synthetic intermediates for agricultural chemicals and liquid crystals [14].

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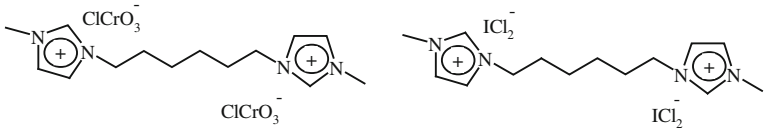
Among several strategies for the preparation of nitriles, the use of ammonia in combination with a suitable oxidant is found to be an expedient procedure for the transformation of aldehydes to their corresponding nitriles. Some of the reported reagents to apply in these methods are $NH_3/NaICl_2(aq)$ [15], tetrabutylammonium tribromide (TBATB)/$NH_3(aq)$ [16], $NH_3/O_2/CuCl_2{\cdot}2H_2O$/MeONa in CH_3OH [17], $NH_3/Pb(OAc)_4$ in dry benzene [18], $Ru(OH)_x/Al_2O_3/NH_3$ [19], NH_3/I_2/MeONa in CH_3OH [20], $NH_3/S_8/NaNO_2$ [21], NH_3/H_2O_2/CuCl in 2-propanol [22], I_2/NH_3 (*aq*) [23], *o*-iodoxybenzoic acid (IBX)/$NH_3(aq)$ [24], and NBS/$NH_3(aq)$ [25]. Some of the other reported procedures for preparation of nitriles include use of aromatic halides/*n*-BuLi/DMF/$NH_3(aq)/I_2$ or 1,3-diiodo-5,5-dimethylhydantoin (DIH) [26], use of alcohols, aldehydes, and amines in the presence of KI/$NH_3(aq)$/*tert*-butyl hydroproxide (TBHP) [27], RCHO/Me_2NNH_2/HOF·CH_3CN [28], use of carboxylic acids/diphosphorus tetraiodide/ammonium carbonate [29], RCHO/$NH_2OH{\cdot}HCl$/KF/Al_2O_3 [30], use of benzylic halides/I_2 or DIH/$NH_3(aq)$ [31], and dehydration of aldoximes with phthalic anhydride [32]. Although some of these methods are efficient [23–25], the others suffer from drawbacks such as long reaction times [4–16, 19, 22, 27, 29, 30], low yield of products [20–22], high reaction temperatures [21, 30, 32], using transition metal catalysts [17–19, 22], sensitive base [26], dry reaction conditions [18, 26, 29, 30], and highly toxic gases in the reaction [28].

On the other hand, selective oxidation of thiols to the corresponding disulfides is an important reaction in biological and synthetic processes [33, 34]. Although several oxidative methods are developed for selective preparation of disulfide compounds in recent years [35–41], a few number of these procedures were carried out in ionic liquids, for example oxidation of thiols with molecular oxygen/cobalt(II) phthalocyanine in [BMIM][BF_4] [42] the synthesis of symmetrical disulfides from thiols using [BMIM][$SeO_2(OCH_3)$] at 60 °C or under microwave irradiation at 30 °C/air [25] metal-free air oxidation of thiols in [BMIM][BF_4] [43], and oxidation of thiols using $K_2S_2O_8$ in [BMIM][Br] at 70 °C [44].

Ionic liquids, which are salts with a melting temperature below the boiling point of water (less than 100 °C), have many applications in synthetic transformations [45, 46] electrochemistry [47, 48] extraction and separation processes [49, 50], and catalysts [51, 52]. In addition, they have important roles as non-volatile and reusable solvents in different reactions, for example they have been successfully used as solvent in oxidation reactions [53–57]. Apart from being applied as solvent, they have been shown to serve as reagents in some reactions, but there are only a few examples that ionic liquid was used as an oxidant in organic transformations [58–60]. However, to the best of our knowledge, we have not found any report for dichloroiodate ionic liquid as oxidant for the preparation of nitriles and disulfides.

Recently, we have introduced an ionic liquid oxidant, hexamethylene bis(*N*-methylimidazolium) dichlorochromate (HMBMIDCC), for oxidation of benzylic alcohols [61] and ionic liquid iodinating reagent of hexamethylene bis(*N*-methylimidazolium) bis(dichloroiodate) (HMBMIBDCI) for iodination of aromatic and heteroaromatic amines and terminal alkynes (Scheme 1) [61]. In this study, HMBMIBDCI was utilized in the preparation of nitriles and disulfides as an oxidant and solvent from their corresponding aldehydes and thiols, respectively.



HMBMIDCC **HMBMIBDCI**

Scheme 1 Structures of HMBMIDCC and HMBMIBDCI

Experimental

Materials were purchased from Fluka and Merck. ^{1}H and ^{13}C NMR spectra were obtained on a Bruker Avance instrument at 400 (500) and 100 MHz, respectively, using $CDCl_3$ as solvent. Melting points were determined on an Electro Thermal 9100. All the products were characterized by ^{1}H and ^{13}C NMR data, and some of the products were characterized by GC analyses. GC analyses were performed on a Perkin Elmer 8500 instrument using a capillary column 30 M with a FID detector under helium as carrier gas. GC parameters were quantified by the authentic product samples prior to the analysis. HMBMIBDCI was prepared according to our previously described procedure [61].

General procedure for the conversion of aldehydes into nitriles with HMBMIBDCI and $NH_3(aq)$

The mixture of HMBMIBDCI (0.5 mmol, 322 mg) in CH_3CN (5 ml) was added into a solution of *p*-chlorobenzaldehyde (0.5 mmol, 70 mg) in $NH_3(aq)$ (1.5 ml) and the resulting dark mixture was stirred for the specified time designated in Table 2 at room temperature. The progress of the reaction was followed by TLC and the dark heterogeneous solution gradually changed to a red solution. To the mixture was added $CHCl_3$ (30 ml) and then the organic phase was washed with an aqueous solution of $NaHSO_3$ (5 %, 20 ml). The organic layer was dried over $MgSO_4$ and evaporated under reduced pressure. The crude material obtained was practically pure in most cases with no need for further purification. Otherwise, the crude products were purified by recrystallization or preparative TLC. All the nitrile products were identified by comparing melting point, ^{1}H, and ^{13}C NMR with those of authentic samples reported in the literature.

General procedure for the oxidative coupling of thiols into disulfides with HMBMIBDCI

Thiophenol (0.5 mmol, 55 mg) was treated with HMBMIBDCI (0.25 mmol, 161 mg) in solvent-free conditions at room temperature for the specified time shown in Table 3. After disappearance of the starting material as monitored by GC, the reaction was quenched with water (20 ml) and was extracted with Et_2O (40 ml). The organic layer was washed with aqueous $NaHSO_3$ (5 %, 20 ml), dried over $MgSO_4$, and evaporated under reduced pressure. The crude material obtained was

practically pure in most cases with no need for further purification. Otherwise, the crude products were purified by recrystallization or preparative TLC. All the products were identified by comparing melting point and ^{1}H and ^{13}C NMR with those of authentic samples reported in the literature.

Recovery of HMBMIBDCI

To the separated aqueous layer was added an aqueous solution of $NaICl_2$. The reaction was immediately followed by formation of a yellow precipitate, which was then filtered, washed with Et_2O, and dried under reduced pressure. The obtained yellow solid was identical in all aspects with the parent HMBMIBDCI.

Spectroscopic data of some products

*Benzonitrile (Table 2, entry **1**)*

Oil [31]; ^{1}H NMR (400 MHz, $CDCl_3$): δ (ppm) = 7.70–7.67 (m, 2 H), 7.63 (tt, J = 7.7, 2.8 Hz, 1 H), 7.50 (t, J = 7.7 Hz, 2 H). ^{13}C NMR (100 MHz, $CDCl_3$): δ (ppm) = 132.79, 132.18, 129.13, 118.88, 112.45.

*4-Methoxybenzonitrile (Table 2, entry **2**)*

Mp 49–53 °C [Ref. [26] mp 54–55 °C]; ^{1}H NMR (400 MHz, $CDCl_3$): δ (ppm) = 7.59–7.63 (m, 2 H), 6.99–6.95 (m, 2 H), 3.88 (s, 3 H). ^{13}C NMR (100 MHz, $CDCl_3$): δ (ppm) = 162.85, 134.00, 119.24, 114.76, 103.98, 55.55.

*4-Fluorobenzonitrile (Table 2, entry **3**)*

Mp 35–37 °C [Ref. [24] mp 35–37 °C]; ^{1}H NMR (400 MHz, $CDCl_3$): δ (ppm) = 7.73–7.69 (m, 2 H), 7.23–7.18 (m, 2 H). ^{13}C NMR (100 MHz, $CDCl_3$): δ (ppm) = 165.05 (d, J = 254.9 Hz), 134.71 (d, J = 37.6 Hz), 118.07, 116.89 (d, J = 22.6 Hz), 108.57 (d, J = 3.7 Hz).

*4-Chlorobenzonitrile (Table 2, entry **4**)*

Mp 90–92 °C [Ref. [26] mp 92–95 °C]; ^{1}H NMR (400 MHz, $CDCl_3$): δ (ppm) = 7.64–7.61 (m, 2 H), 7.51–7.48 (m, 2 H). ^{13}C NMR (100 MHz, $CDCl_3$): δ (ppm) = 139.58, 133.40, 129.72, 118.00, 110.78.

*4-Bromobenzonitrile (Table 2, entry **5**)*

Mp 108–110 °C [Ref. [24] mp 110–111 °C]; ^{1}H NMR (400 MHz, $CDCl_3$): δ (ppm) = 7.67–7.64 (m, 2 H), 7.57–7.54 (m, 2 H). ^{13}C NMR (100 MHz, $CDCl_3$): δ (ppm) = 133.43, 132.66, 128.05, 118.10, 111.23.

*4-Nitrobenzonitrile (Table 2, entry **6**)*

Mp 140–143 °C [Ref. [32] mp 148–149 °C]; ^{1}H NMR (400 MHz, $CDCl_3$): δ (ppm) = 8.40–8.37 (m, 2 H), 7.93–7.90 (m, 2 H). ^{13}C NMR (100 MHz, $CDCl_3$): δ (ppm) = 150.03, 133.49, 124.32, 118.35, 116.81.

*Terephthalonitrile (Table 2, entry **7**)*

Mp 220–223 °C [Commercial mp 224–227 °C]; ^{1}H NMR (400 MHz, $CDCl_3$): δ (ppm) = 7.82 (s). ^{13}C NMR (100 MHz, $CDCl_3$): δ (ppm) = 132.82, 117.05, 116.72 [62].

*2-Methylbenzonitrile (Table 2, entry **8**)*

Oil [26]; ^{1}H NMR (400 MHz, $CDCl_3$): δ (ppm) = 7.62 (dd, J = 8.0, 1.2 Hz, 1 H), 7.50 (td, J = 8.0 Hz, 1.2 H, 1 H), 7.33 (t, J = 8.0 Hz, 1 H), 7.28 (d, J = 8.0 Hz, 1 H). ^{13}C NMR (100 MHz, $CDCl_3$): δ (ppm) = 141.96, 132.65, 132.53, 130.24, 126.23, 118.19, 112.76, 20.50.

*2-Methoxybenzonitrile (Table 2, entry **9**)*

Oil [26]; ^{1}H NMR (400 MHz, $CDCl_3$): δ (ppm) = 7.59–7.54 (m, 2 H), 7.03 (dd, J = 8.0, 0.8 Hz, 1 H), 7.00 (d, J = 8.0 Hz, 1 H). ^{13}C NMR (100 MHz, $CDCl_3$): δ (ppm) = 161.25, 134.39, 133.77, 120.76, 116.51, 111.29, 101.82, 56.00.

*2-Bromobenzonitrile (Table 2, entry **10**)*

Mp 48–50 °C [Ref. [63] mp 52–55 °C]; ^{1}H NMR (400 MHz, $CDCl_3$): δ (ppm) = 7.73–7.68 (m, 2 H), 7.51–7.43 (m, 2 H). ^{13}C NMR (100 MHz, $CDCl_3$): δ (ppm) = 134.34, 133.88, 133.22, 127.63, 125.36, 117.14, 115.92.

*2-Chlorobenzonitrile (Table 2, entry **11**)*

Mp 41–43 °C [Ref. [16] mp 42–44 °C]; ^{1}H NMR (400 MHz, $CDCl_3$): δ (ppm) = 7.70 (ddd, J = 7.6, 1.6, 0.4 Hz, 1 H), 7.60–7.53 (m, 2 H), 7.40 (ddd, J = 6.4, 1.6, 0.8 Hz, 1 H). ^{13}C NMR (100 MHz, $CDCl_3$): δ (ppm) = 136.92, 134.04, 133.87, 130.07, 127.14, 115.98, 113.45.

*3-Chlorobenzonitrile (Table 2, entry **12**)*

Mp 37–40 °C [Ref. [16] mp 39–40 °C]; ^{1}H NMR (400 MHz, $CDCl_3$): δ (ppm) = 7.66 (t, J = 1.4 Hz, 1 H), 7.61 (ddd, J = 7.8, 1.4, 0.8 Hz, 1 H), 7.58 (dt, J = 7.8, 1.4 Hz, 1 H), 7.45 (t, J = 7.8 Hz, 1 H). ^{13}C NMR (100 MHz, $CDCl_3$): δ (ppm) = 135.27, 133.26, 131.95, 130.50, 130.31, 117.45, 113.99.

*Cinnamonitrile (Table 2, entry **13**)*

Oil [24]; ^{1}H NMR (400 MHz, $CDCl_3$): δ (ppm) = 7.49–7.43 (m, 5 H), 7.43 (d, J = 16.6 Hz, 1 H), 5.91 (d, J = 16.6 Hz, 1 H). ^{13}C NMR (100 MHz, $CDCl_3$): δ (ppm) = 150.63, 133.52, 131.25, 129.14, 127.38, 118.19, 96.35.

*1-Naphthonitrile (Table 2, entry **14**)*

[Ref. [26] mp 35–36 °C]; ^{1}H NMR (400 MHz, $CDCl_3$): δ (ppm) = 8.25 (d, J = 8.4 Hz, 1 H), 8.09 (d, J = 8.4 Hz, 1 H), 7.93 (t, J = 7.6 Hz, 2 H), 7.71 (td, J = 7.4, 1.2 Hz, 1 H), 7.67–7.60 (m, 1 H), 7.53 (t, J = 8.0 Hz, 1 H). ^{13}C NMR (100 MHz, $CDCl_3$): δ (ppm) = 133.32, 132.92, 132.66, 132.36, 128.69, 128.63, 127.58, 125.15, 124.95, 117.87, 110.16.

*2-Naphthonitrile (Table 2, entry **15**)*

Mp 60–64 °C [Ref. [26] mp 68–70 °C]; ^{1}H NMR (400 MHz, $CDCl_3$): δ (ppm) = 8.26 (d, J = 0.8 Hz, 1 H), 7.93 (t, J = 9.2 Hz, 3 H), 7.68 (dd, J = 1.2 Hz, 1 H), 7.66–7.61 (m, 2 H). ^{13}C NMR (100 MHz, $CDCl_3$): δ (ppm) = 134.66, 134.19, 132.25, 129.22, 129.07, 128.44, 128.08, 127.68, 126.37, 119.30, 109.37.

*9-Anthracenecarbonitrile (Table 2, entry **16**)*

Mp 170–172 °C [Ref. [64] mp 173–175 °C]; IR: 2210 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$): δ (ppm) = 8.71 (s, 1 H), 8.45 (dd, J = 8.4, 0.8 Hz, 2 H), 8.11 (d, J = 8.4 Hz, 2 H), 7.75 (td, J = 8.4, 5.6 Hz, 2 H), 7.61 (td, J = 8.4, 1.2 Hz, 2 H).

*4-Cyanopyridine (Table 2, entry **17**)*

Mp 73–76 °C [Commercial mp 77–81 °C]; IR: 2240 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$): δ (ppm) = 8.84 (dd, J = 4.4, 1.6 Hz, 2 H), 7.56 (dd, J = 4.4, 1.6 Hz, 2 H). ^{13}C NMR (100 MHz, $CDCl_3$): δ (ppm) = 150.81, 125.27, 120.46, 116.40 [65].

*Thiophene-2-carbonitrile (Table 2, entry **18**)*

Oil [24]; ^{1}H NMR (400 MHz, $CDCl_3$): δ (ppm) = 7.67 (dd, J = 4.0, 1.2 Hz, 1 H), 7.64 (dd, J = 4.0, 1.2 Hz, 1 H), 7.16 (dd, J = 4.0, 1.2 Hz, 1 H). ^{13}C NMR (100 MHz, $CDCl_3$): δ (ppm) = 137.43, 132.57, 127.65, 114.25, 110.00.

*Diphenyldisulfide (Table 3, entry **1**)*

Mp 58–60 °C [Ref. [42] mp 57–59 °C]; ^{1}H NMR (500 MHz, $CDCl_3$): δ (ppm) = 7.61 (d, J = 8.3 Hz, 2 H), 7.57 (d, J = 8.3 Hz, 2 H), 7.40–7.35 (m, 4 H), 7.31–7.26 (m, 2 H).

*Bis(4-methylphenyl)disulfide (Table 3, entry **2**)*

Mp 44–47 °C [Ref. [39] mp 44–45 °C]; ^{1}H NMR (500 MHz, $CDCl_3$): δ (ppm) = 7.42 (d, J = 8.1 Hz, 4 H), 7.15 (d, J = 8.1 Hz, 4 H), 2.36 (s, 6 H).

*Bis(4-methoxyphenyl)disulfide (Table 3, entry **3**)*

^{1}H NMR (400 MHz, CDCl3): δ (ppm) = 7.43 (d, J = 8.8 Hz, 2 H), 6.86 (d, J = 8.8 Hz, 2 H), 3.82 (s, 3 H); ^{13}C NMR (100 MHz, $CDCl_3$): δ (ppm) 159.92, 132.71, 128.43, 114.63, 55.41.

*Bis(4-bromophenyl)disulfide (Table 3, entry **4**)*

Mp 95–97 °C [Ref. [66] mp 94–95 °C]; ^{1}H NMR (500 MHz, $CDCl_3$): δ (ppm) = 7.47 (d, J = 8.4 Hz, 4 H), 7.38 (d, J = 8.4 Hz, 4 H).

*Bis(2-methylphenyl)disulfide (Table 3, entry **5**)*

^{1}H NMR (400 MHz, $CDCl_3$): δ (ppm) 7.57–7.55 (m, 1 H), 7.21–7.17 (m, 3 H), 2.47 (s, 3 H); ^{13}C NMR (100 MHz, $CDCl_3$): δ (ppm) 137.34, 135.41, 130.35, 128.53, 127.32, 126.73, 20.05.

*Bis(2-hydroxyphenyl)disulfide (Table 3, entry **6**)*

Oil [65]; ^{1}H NMR (400 MHz, $CDCl_3$): δ (ppm) = 7.37 (td, J = 8.0, 1.6 Hz, 1 H), 7.25 (dd, J = 8.0, 1.6 Hz, 1 H), 7.03 (dd, J = 8.0, 1.2 Hz, 1 H), 6.86 (td, J = 8.0, 1.2 Hz, 1 H). ^{13}C NMR (100 MHz, CDC_3): δ (ppm) = 156.93, 136.27, 133.30, 121.08, 119.98, 115.77.

*Bis(2-naphthyl)disulfide (Table 3, entry **7**)*

^{1}H NMR (400 MHz, $CDCl_3$): δ (ppm) 8.01 (d, J = 1.2 Hz, 1 H), 7.83–7.80 (m, 2 H), 7.77–7.75 (m, 1 H), 7.65 (dd, J = 2.0, 8.0 Hz, 1 H), 7.51–7.45 (m, 2 H). ^{13}C NMR (100 MHz, $CDCl_3$): δ (ppm) 134.27, 133.48, 132.51, 129.00, 127.79, 127.49, 126.76, 126.55, 126.26, 125.67.

*Dibenzyldisulfide (Table 3, entry **8**)*

^{1}H NMR (400 MHz, $CDCl_3$): δ (ppm) 7.37–7.33 (m, 2 H), 7.32–7.25 (m, 3 H), 3.62 (s, 2 H); ^{13}C NMR (100 MHz, $CDCl_3$): δ (ppm) 137.37, 129.44, 128.51, 127.45, 43.27.

*Dicyclohexyldisulfide (Table 3, entry **9**)*

Oil [39]; ^{1}H NMR (500 MHz, $CDCl_3$): δ (ppm) = 2.74–2.69 (m, 2 H), 2.09–2.07 (m, 4 H), 1.86–1.81 (m, 4 H), 1.67–1.64 (m, 2 H), 1.39–1.24 (m, 10 H).

*Di(2-hydroxyethyl)disulfide (Table 3, entry **10**)*

Oil [36]; ^{1}H NMR (400 MHz, $CDCl_3$): δ (ppm) = 3.94 (t, J = 5.6 Hz, 2 H), 2.91 (t, J = 5.6 Hz, 2 H). ^{13}C NMR (100 MHz, $CDCl_3$): δ (ppm) = 60.35, 41.21.

*Dipentyldisulfide (Table 3, entry **11**)*

Oil [44]; ^{1}H NMR (400 MHz, $CDCl_3$): δ (ppm) = 2.70 (t, J = 7.4, 2 H), 1.70 (quin, J = 7.4 Hz, 2 H), 1.40–1.34 (m, 4 H), 0.93 (t, J = 7.2 Hz, 3 H). ^{13}C NMR (100 MHz, $CDCl_3$): δ (ppm) = 39.18, 30.71, 28.93, 22.33, 13.99.

*Dioctyldisulfide (Table 3, entry **12**)*

Oil [36]; ^{1}H NMR (400 MHz, $CDCl_3$): δ (ppm) = 2.70 (t, J = 7.4 Hz, 2 H), 1.69 (quin, J = 7.4 Hz, 2 H), 1.40 (quin, J = 7.4 Hz, 2 H), 1.32–1.30 (m, 8 H), 0.91 (t, J = 7.0 Hz, 3 H). ^{13}C NMR (100 MHz, $CDCl_3$): δ (ppm) = 39.23, 31.82, 29.24, 29.21, 29.19, 28.55, 22.66, 14.10.

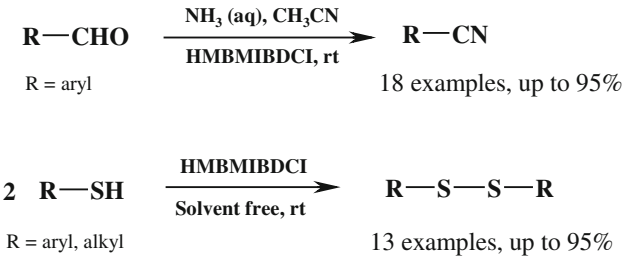
*Diisopropyl disulfide (Table 3, entry **13**)*

Oil [commercial]; ^{1}H NMR (400 MHz, $CDCl_3$): δ (ppm) = 2.99 (sep, J = 6.8 Hz, 1 H), 1.32 (d, J = 6.8 Hz, 6 H).

Results and discussion

In continuation of our work using bis imidazolium reagents in organic reactions [61, 67–70], we report here another useful application of hexamethylene bis(*N*-methylimidazolium) bis(dichloroiodate) as an ionic liquid oxidant in the preparation of nitriles from aldehydes in the presence of aqueous ammonia and disulfides from the corresponding thiols (Scheme 2).

HMBMIBDCI, is an yellow-orange solid that is prepared according to our previous procedures from 1,6-dichlorohexane, *N*-methylimidazol, and $NaICl_2$ or ICl [61].



Scheme 2 Conversion of aldehydes and thiols into nitriles and disulfides using HMBMIBDCI

Table 1 Conversion of 4-chlorobenzaldehyde into 4-chlorobenzonitrile using HMBMIBDCI/aqueous ammonia

Entry	Cosolvent	Time (min)	Yield (%)[a]
1	–	120	80
2	CH_3CN	90	92
3	CH_3OH	90	56
4	CH_2Cl_2	90	Trace

[a] Yields refer to isolated products

For optimization studies, a mixture of *p*-chlorobenzaldehyde (0.5 mmol), HMBMIBDCI (0.5 mmol) and aqueous ammonia (1.5 ml) was stirred at room temperature. The progress of the reaction was monitored by TLC analysis. Also, the effect of cosolvents, such as CH_3CN, CH_2Cl_2, and CH_3OH on promoting of the reaction of ammonia with *p*-chlorobenzaldehyde in the presence of HMBMIBDCI were examined (Table 1). It is noteworthy that the reaction did not proceed in the absence of the reagent even in a long reaction time.

As indicated in Table 1, the addition of CH_3CN improved the yield of *p*-chlorobenzonitrile up to 92 %, while CH_3OH and CH_2Cl_2 showed less effectiveness as cosolvent.

In the next step, a wide variety of aldehydes such as aromatic, heterocyclic, and α, β-unsaturated aldehydes were oxidized to the corresponding nitriles in good to excellent yields using HMBMIBDCI in a combination of $NH_3(aq)$ and CH_3CN. The results are presented in Table 2.

It was observed that benzaldehyde, *p*-methoxy, *p*-fluoro, *p*-chloro, *p*-bromo, and *p*-nitrobenzaldehyde could be converted into corresponding nitriles in high yields under the optimized reaction conditions (Table 2, entries **1**–**6**). The same treatment of terephthalaldehyde provided terephthalonitrile in excellent yield (Table 2, entry **7**). Also, the use of sterically hindered aldehydes such as *o*-methyl, *o*-methoxy, *o*-bromo, and *o*-chlorobenzaldehyde resulted in the corresponding nitriles in high yields (Table 2, entries **8**–**11**). *m*-Chlorobenzaldehyde and cinnamaldehyde were converted into *m*-chlorobenzonitrile and cinnamonitrile in good yields, respectively (Table 2, entries **12**, **13**). 1-Naphthaldehyde, 2-naphthaldehyde and anthracene-9-carbaldehyde under the same reaction conditions were also transformed to the corresponding nitriles in 54, 85 and 70 % yields, respectively (Table 2, entries **14**–**16**). Similarly, the heterocyclic aldehyde such as 4-pyridinecarboxaldehyde was converted into 4-pyridinecarbonitrile in excellent yield (Table 2, entry **17**). However, a lower yield was observed in the case of 2-thiophenecarboxaldehyde (Table 2, entry **18**).

The use of HMBMIBDCI was also studied for oxidation of thiols to disulfides (Scheme 2). Our investigation showed that the effect of the solvents, such as CH_3CN, CH_2Cl_2 and H_2O, in the reaction of thiophenol with HMBMIBDCI is negligible. Quantitative conversion was also observed when the reaction was conducted in solvent-free conditions.

Table 2 Conversion of aldehydes into nitriles with HMBMIBDCI in aqueous ammonia and CH_3CN

Entry	Substrate	Product	Time (min)	Conversion[a]/ yield[b,c] (%)	Mp [(Ref.) (°C)]
1	Ph-CHO	Ph-CN	90	99/91	Oil [30]
2	4-MeO-Ph-CHO	4-MeO-Ph-CN	90	89/81	49–53 (54–55) [26]
3	4-F-Ph-CHO	4-F-Ph-CN	90	99/90	35–37 (35–37) [24]
4	4-Cl-Ph-CHO	4-Cl-Ph-CN	90	99/92	90–92 (92–95) [26]
5	4-Br-Ph-CHO	4-Br-Ph-CN	90	98/91	108–110 (110–111) [24]
6	4-NO_2-Ph-CHO	4-NO_2-Ph-CN	60	99/93	140–143 (148–149) [32]
7	4-CHO-Ph-CHO	4-CN-Ph-CN	60	99/92	220–223 (224–227) [Commercial]
8	2-CH_3-Ph-CHO	2-CH_3-Ph-CN	75	99/90	Oil [26]
9	2-MeO-Ph-CHO	2-MeO-Ph-CN	90	99/95	Oil [26]
10	2-Br-Ph-CHO	2-Br-Ph-CN	50	98/91	48–50 (52–55) [63]
11	2-Cl-Ph-CHO	2-Cl-Ph-CN	50	99/94	41–43 (42–44) [16]
12	3-Cl-Ph-CHO	3-Cl-Ph-CN	60	97/89	37–40 (39–40) [16]
13	Cinnamaldehyde	Cinnamonitrile	30	97/89	Oil [24]
14	1-Naphthyl-CHO	1-Naphthyl-CN	2.45 h	88/80	(35–36) [26]
15	2-Naphthyl-CHO	2-Naphthyl-CN	70	93/85	60–64 (68–70) [26]
16	9-Anthracenyl-CHO	9-Anthracenyl-CN	3 h	72/70	170–172 (173–175) [64]
17	4-Pyridyl-CHO	4-Pyridyl-CN	60	99/90	73–76 (77–81) [Commercial]
18	2-Thienyl-CHO	2-Thienyl-CN	4.5 h	87/80	Oil [24]

[a] Conversion based on ^1H NMR

[b] Isolated products

[c] All products were identified by comparing ^1H and ^{13}C NMR with those of authentic samples reported in the literature

To show the generality of this methodology, a wide variety of thiol derivatives were tested under solvent-free conditions. The results as shown in Table 3 reveal that thiols with electron-donating groups and also aliphatic thiols were efficiently converted to the disulfide products in the presence of HMBMIBDCI at room temperature (Table 3).

It is noticeable that the oxidation of thiols into disulfides was performed without over-oxidation of disulfides (Table 3, entries **1**–**13**). The oxidation of the SH functional group in the presence of the hydroxyl group can be carried out to the corresponding disulfide without oxidation of the hydroxyl group (Table 3, entries **6**, **10**). Aliphatic substrates such as cyclic and acyclic thiols were also converted to the corresponding disulfides in good yields (Table 3, entries **9**–**13**). In spite of the ability of this reagent in iodination of activated aromatic compounds [61], no iodinated thiophenols were detected during the oxidation of aromatic thiols to their corresponding disulfides (Table 3, entries **1**–**8**).

Another advantage of this protocol is reusability of this ionic liquid reagent (HMBMIBDCI) which can be reproduced from the reaction residue and be reused.

Table 3 Conversion of thiols to disulfides using HMBMIBDCI in solvent-free conditions

Entry	Substrate	Product	Time (min)	Conversion[a]/ yield[b,c] (%)	Mp [(Ref.) (°C)]
1	Ph-SH	(Ph-S-)$_2$	10	99/94	58–60 (57–59) [42]
2	4-Me-Ph-SH	(4-Me-Ph-S-)$_2$	10	89/84	44–47 (44–45) [39]
3	4-MeO-Ph-SH	(4-MeO-Ph-S-)$_2$	10	87/82	34–36 (42–43) [43]
4	4-Br-Ph-SH	(4-Br-Ph-S-)$_2$	10	78/73	95–97 (94–95) [66]
5	2-Me-Ph-SH	(2-Me-Ph-S-)$_2$	10	93/88	34–37 (35–37) [39]
6	2-OH-Ph-SH	(2-OH-Ph-S-)$_2$	10	80/78	Oil (75) [65]
7	2-Naphthyl-SH	(2-Naphthyl-S-)$_2$	20	83/80	139–141 (144–145) [71]
8	Ph-CH_2-SH	(Ph-CH_2-S-)$_2$	20	96/91	70–72 (70–71) [39]
9	Cyclohexyl-SH	(Cyclohexyl-S-)$_2$	30	99/95	Oil [39]
10	$HOCH_2CH_2SH$	($HOCH_2CH_2S$-)$_2$	15	60/58	Oil [36]
11	1-Pentyl-SH	(1-Pentyl-S-)$_2$	10	86/81	Oil [44]
12	1-Octyl-SH	(1-Octyl-S-)$_2$	15	97/85	Oil [36]
13	*i*-Propyl-SH	(*i*-Propyl-S-)$_2$	10	50/44	Oil [Commercial]

[a] Conversion based on GC

[b] Isolated products

[c] All products were identified by comparing mp, ^{1}H and ^{13}C NMR with those of authentic samples reported in literature

To regenerate the reagent, after completion of the oxidation reaction, the mixture was washed with diethylether and the residue was dissolved in water which, in treatment with aqueous solution of $NaICl_2$, afforded HMBMIBDCI. The recovered reagent was successively reused three times in the conversion of *p*-chlorobenzaldehyde to *p*-chlorobenzonitrile and thiophenol to diphenyl disulfide without appreciable loss in its activity.

Conclusion

In conclusion, a mild and efficient method has been developed for the direct conversion of aldehydes to the corresponding nitriles using HMBMIBDCI in combination with aqueous ammonia at room temperature. The significant advantages of this method are simplicity, considerably fast reaction, easy and simple work-up procedure, and high yields of products with no need for further purification. In addition, oxidation of thiols to the corresponding disulfides was also achieved using HMBMIBDCI in solvent-free conditions at room temperature. This procedure is mild and gave good to excellent yields of disulfides in the case of both aliphatic and aromatic substrates with no overoxidation to the sulfone and sulfoxide products. Furthermore, we have demonstrated that the ionic liquid oxidant can be recovered and reused for three runs without any significant loss of oxidation activity.

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