Conversion of imidazoles to imidazolones with chloramine-B: kinetic and mechanistic study

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Abstract Oxidative conversion of 1*H*-imidazole (IzIH) and 2-substituted imidazoles viz., 2-ethyl-1*H*-imidazole (2-EtIzIH), 2-methyl-1*H*-imidazole (2-MeIzIH), 1*H*-imidazole-2-ester (2-EsIzIH), and 1*H*-imidazole-2-carbaldehyde (2-CaIzIH) to the corresponding imidazolones with sodium *N*-chlorobenzenesulfonamide or chloramine-B (CAB) were established. This reaction was kinetically investigated at 303 K in HClO₄ medium. Under comparable experimental conditions, the oxidation reactions followed identical kinetics for all the five imidazoles with a first-order dependence of rate on [CAB]₀ and fractional-order dependence each on [imidazole]₀ and [H⁺]. Effects of added benzenesulfonamide, halide ions, NaClO₄, and MeOH on the rate of reaction have been studied. Reaction products were identified and characterized by GC–MS and NMR spectral analysis. The rates are measured at different temperatures and the composite activation parameters have been computed from the Arrhenius plots. Isokinetic temperature (β) was found to be 449 K which is higher than the experimental temperature (303 K), indicating that the rate has been under enthalpy control. Relative reactivity of these imidazoles is in the order: 2-EtIzIH > 2-MeIzIH > IzIH > 2-EsIzIH > 2-CaIzIH. H₂O⁺Cl have been postulated as the reactive oxidizing species. The reaction mechanism and the derived rate law are in good agreement with the observed experimental results. Spectroscopic

studies have been made for an intermediate complex formation between CAB and imidazole. Advantages of the present method include: mild reaction conditions, cost-effectiveness, short reaction time, ease of isolation of products, and the use of eco-friendly reagents. Hence, the methodology developed could be adopted for the facile oxidative conversion of imidazoles to imidazolones and can be scaled up to industrial operation with suitable modification.

Graphical abstract

Keywords Imidazole · Chloramine-B · Oxidation kinetics · Mechanism · Activation parameters · Structure reactivity

Introduction

Oxidation of organic compounds with high selectivity is a foremost transformation in organic synthesis and important in mechanistic chemistry. Chemical kinetics deals with the study of the rates of chemical reactions and with the description of the mechanism by which they proceed. Hence, oxidation-kinetic study is the significant area of research in chemistry to suit the optimum conditions and to unfold the

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mechanistic chemistry of a particular reaction [1, 2]. Imidazole is a five-membered planar ring and it exists in two equivalent tautomeric forms. Imidazoles show amphoteric properties. Imidazole is incorporated into many important biological molecules and the most pervasive is histidine. Imidazoles are common components of a large number of natural products and pharmaceutically active molecules. Imidazole and its derivatives possess a number of versatile properties and pharmaceutical applications include anti-cancer, antiinflammatory, antibacterial, antifungal, antiviral, antitubercular, antidiabetic, and antimalarial ones [3]. Substituted imidazoles are important moieties constituted in pharmaceuticals, pesticides, and bioactive compounds [4]. Many imidazoles with a single heterocyclic substituent in the 2-position serve as key intermediates in the synthesis of pharmaceutically active compounds. Mild oxidation of imidazoles to imidazolones find importance in synthetic organic chemistry and considerable work has been carried out in this direction [5]. Further, various kinds of imidazolones are biologically and pharmaceutically very important, since many of them possess antihypertensive, antidiabetic, and antiinflammatory force [6]. In spite of extensive medicinal applications of imidazoles and imidazolones, no information is available on the oxidative conversion of imidazoles to imidazolones from the kinetic and mechanistic point of view. Therefore, the mechanistic picture and rate law for these redox systems were obscure. Hence, it is very essential to know the kinetic and mechanistic basis for the redox chemistry of these systems. This kind of research knowledge would be very beneficial to synthetic chemists and also kineticists who are working on the mechanistic chemistry of imidazoles in biological systems. For these reasons, in the present research, conversion of imidazoles and 2-imidazoles to the corresponding imidazolones have been developed for our oxidation-kinetic and mechanistic study.

Organic sulfonyl-*N*-haloamines (*N*-haloamines) are mild oxidizing/halogenating/analytical reagents containing a strongly polarized N-bonded halogen in its +1 oxidation state [7]. Kinetics and mechanism of oxidation by these reagents have attracted the attention of chemists due to their diverse properties to act as halonium cations, hypohalites and N-anions [7]. They interact with a wide range of functional groups in aqueous, partially aqueous and non-aqueous media in the presence of an acid or a base. As a result, these reagents have been used as mild and selective oxidizing agents in synthetic organic and mechanistic chemistry [7–12]. The prominent member of this group of compounds is sodium-*N*-chloro-*p*-toluenesulfonamide, commonly known as chloramine-T (CAT), it is a well-known oxidizing/halogenating/analytical agent and the kinetic and mechanistic aspects of many of its reactions have been well documented [7–13]. Sodium-*N*-

chlorobenzenesulfonamide or chloramine-B (CAB) is the benzene analogue of CAT, which can be easily prepared from the reaction of benzenesulfonamide and chlorine in basic solutions. Chloramine-B is a stable compound with slightly higher active chlorine content than CAT. There are but few reports on the synthetic and mechanistic chemistry of CAB [8, 12, 14–16].

Our initial experiments began with the examination of oxidation of the selected imidazoles with CAT in acid medium. These redox systems at different experimental conditions were too sluggish to be measured kinetically. Then we thought of using CAB as an oxidant and we were delighted to see that the reactions proceeded smoothly. Hence, CAB is an excellent oxidant in effectively controlled conversion of 2-imidazoles to corresponding imidazolones. Consequently, in the course of this research, optimum conditions for the facile oxidation of 2-imidazoles to 2-imidazolones with CAB in acid medium were established. The present paper reports the oxidation-kinetics of the imidazoles and substituted imidazoles viz., 2-ethyl-1*H*-imidazole (2-EtIzIH), 2-methyl-1*H*-imidazole (2-MeIzIH), 1*H*-imidazole(IzIH), 1*H*-imidazole-2-ester (2-EsIzIH), and 1*H*-imidazole-2-carbaldehyde (2-CaIzIH) with CAB in acid medium at 303 K. Additionally, these synthesized imidazolones are useful as intermediates for polymers, agrochemicals, and pharmaceutical compounds. Objectives of the present research are to: (a) establish optimum conditions for the facile oxidation of 2-imidazoles to 2-imidazolones; (b) deduce all the possible kinetic data; (c) elucidate the possible reaction mechanism (scheme); (d) put forward kinetic rate law; (e) identify the stoichiometry and oxidation products; (f) ascertain the reactive species; (g) establish the isokinetic relationship through activation parameters; and (h) assess the relative reactivity of imidazoles.

Results and discussion

Reaction stoichiometry

Varying ratios of CAB to imidazoles in the presence of 5.0×10^{-4} mol dm⁻³ HClO₄ were equilibrated at 303 K for 48 h. Determination of the unreacted CAB showed that one mole of the imidazole consumed one mole of CAB in all the cases. Accordingly, the stoichiometric Eq. (1) can be formulated (Scheme 1).

Representative oxidation procedure for the conversion of imidazoles to imidazolones

A mixture of 0.68 g of imidazole, 2.13 g of oxidant (chloramine-B) in presence of 2.5 cm³ (0.01 mol dm⁻³) of

Scheme 1

aqueous perchloric acid was stirred at 303 K for 8–10 h. After completion of the reaction (monitored by TLC), the reaction products were neutralized with alkali and extracted with ether. The organic products were subjected to spot tests and chromatographic analysis (TLC technique). Further, the reaction mixture was extracted with ethyl acetate and dried over sodium sulfate. The solvent was evaporated under reduced pressure to obtain crude products. The crude products were purified on silica gel column by using petroleum ether and ethyl acetate as solvents to get the pure products. Above analyses revealed the formation of corresponding imidazolones as the oxidation products of imidazoles. 3,5-Dihydroimidazol-4-one, 2-methyl-3,5-dihydroimidazol-4-one, 2-ethyl-3,5-dihydroimidazol-4-one, 3,5-dihydro-4-oxoimidazol-2-carbaldehyde, and 3,5-dihydro-4-oxoimidazol-2-ester are the oxidation products of 1*H*-imidazole, 2-methyl-1*H*-imidazole, 2-ethyl-1*H*-imidazole, 1*H*-imidazole-2-carbaldehyde, and 1*H*-imidazole-2-ester, respectively. The mass spectra showed a molecular ion peak at $m/z = 84$ amu (Fig. 1), 99 amu ($M + 1$, Fig. 2), and 112 amu (Fig. 3), clearly confirming 3,5-dihydroimidazol-4-one, 2-methyl-3,5-dihydroimidazol-4-one, and 2-ethyl-3,5-dihydroimidazol-4-one as oxidation products of 1*H*-imidazole, 2-methyl-1*H*-imidazole, and 2-ethyl-1*H*-imidazole, respectively. Further these products were confirmed by NMR data (supplementary material, Figs. 1s–3s). Furthermore, we have succeeded in estimating the products, imidazolones, in case of all the five imidazoles. In some typical experiments, the weight of imidazolones and their percentage yield obtained are recorded in Table 1. The recovery of imidazolones was 87–93 % yields. Further no reaction was noticed between oxidation products and CAB under prevailing experimental conditions.

Kinetic orders

The kinetics of oxidation of imidazole and 2-substituted imidazoles (henceforth abbreviated as imidazole) by CAB

was investigated at several initial concentrations of the reactants in the presence of HClO₄ at 303 K. Similar oxidation-kinetic behavior was observed for all five imidazoles studied under identical experimental conditions.

Effect of varying reactant concentrations on the reaction rate

The reactions performed in the presence of HClO₄, under pseudo-first-order conditions of $[\text{imidazole}]_0 \gg [\text{CAB}]_0$, gave linear plots of $\log [\text{CAB}]$ vs. time ($R^2 > 0.9884$). The linearity of these plots, together with the constancy of the slopes for various $[\text{CAB}]_0$, indicating a first-order dependence of the rate on $[\text{CAB}]_0$. The pseudo-first-order rate constants (k'/s^{-1}) obtained are listed in Table 2. Under the same experimental conditions, an increase in $[\text{imidazole}]_0$ increased the k' values (Table 2). Plots of $\log k'$ vs. $\log [\text{imidazole}]$ were linear ($R^2 > 0.9900$) with fractional slopes (0.27–0.51), showing a fractional-order dependence of the rate on $[\text{imidazole}]_0$. Further, plots of k' vs. $[\text{imidazole}]$ were linear ($R^2 > 0.9900$) with a y-intercept, confirming a fractional-order dependence of rate on $[\text{imidazole}]_0$. The rate increased with increase in $[\text{HClO}_4]$ (Table 2) and plots of $\log k'$ vs. $\log [\text{HClO}_4]$ were linear ($R^2 > 0.9707$) with fractional slopes (0.26–0.54), thus illustrating a fractional-order dependence of rate on $[\text{H}^+]$. Further, plots of k' vs. $[\text{H}^+]$ were linear ($R^2 > 0.9900$) with a y-intercept corresponding to a rate law of the type: $\text{rate} = a + b [\text{H}^+]$ and confirming the order to be less than unity with respect to $[\text{H}^+]$.

Effect of varying benzenesulfonamide (BSA) on the reaction rate

Addition of benzenesulfonamide (BSA) to the reaction mixture retards the rate (Table 3) while keeping other experimental conditions constant. Plots of $\log k'$ vs. $\log [\text{BSA}]$ were linear ($R^2 > 0.9924$) with negative fractional slopes (0.10–0.42), indicating the involvement of BSA with oxidant in a pre-equilibrium step prior to the rate-limiting step (rls).

Effect of varying ionic strength of the medium on the reaction rate

The effect of ionic strength of the medium on the reaction rate was carried with 0.2 mol dm⁻³ NaClO₄ solution by keeping other experimental conditions constant. It was found that ionic strength had negligible effect on the reaction rate indicating that non-ionic species are involved in the rls. Subsequently, the ionic strength of the reaction mixture was not kept constant for kinetic runs.

Fig. 1 Mass spectrum of 3,5-dihydroimidazol-4-one with its parent molecular ion peak at $m/z = 84$ amu

Effect of varying dielectric constant of the medium on the reaction rate

The dielectric constant (D) of the medium was varied using different proportions of MeOH and H₂O (0–15 %, v/v), keeping other experimental conditions constant. The reaction rate increased with increase in methanol content (Table 4) and plots of $\log k'$ vs. $1/D$ were found to be linear ($R^2 > 0.9933$) with positive slopes. Values of dielectric constant of MeOH–H₂O reported in the literature [17] were employed. Blank experiments performed showed that MeOH was not oxidized by CAB under the prevailing experimental conditions.

Effect of varying temperature on the reaction rate

To calculate the activation parameter, the reaction was studied over a range of temperatures (288–323 K), keeping other experimental conditions constant. From the linear

Arrhenius plots of $\log k'$ vs. $1/T$ ($R^2 > 0.9988$), values of activation parameters (E_a , $\Delta H^\ddagger$, $\Delta S^\ddagger$, $\Delta G^\ddagger$, and $\log A$) for the composite reactions were calculated. These data are tabulated in Table 5.

Effect of Cl[−] ion on the reaction rate

The effect of Cl[−] ion on the rate of the reaction was studied using 0.2 M NaCl. There was no significant effect of Cl[−] on the rate, suggesting no interhalogen or free chlorine was formed during the reaction sequence.

Polymerization study

Addition of acrylamide solution to the reaction mixture did not initiate polymerization, showing the absence of free radical species. This clearly ruled out the possibility of free radical mechanism.

Fig. 2 Mass spectrum of 2-methyl-3,5-dihydroimidazol-4-one with its parent molecular ion peak at $m/z = 99$ amu ($M + 1$)

Oxidizing species of CAB

Chloramine-B, ($\text{PhSO}_2\text{NClNa}$) like chloramine-T, is a mild and effective oxidizing agent in both acidic and alkaline media due to its versatile behavior [7]. In general, CAB undergoes a two electron change in its reactions forming the reduction products BSA and NaCl [18]. The redox potential of CAB/BSA is pH dependent and decreases with increases in pH of the medium.

Chloramine-B behaves as a strong electrolyte [19] in aqueous solutions and depending upon the pH of the medium it furnishes following types of reactive species in solutions [19–21] (Scheme 2).

Chloramine-B dissociates to give an anion $\text{PhSO}_2\text{NCl}^-$ as shown in reaction (2). The anion picks up a proton in acid medium to give the free acid PhSO_2NHCl according to reaction (3). This free acid undergoes disproportionation [20] via reaction (4) giving rise to dichloramine-B and the

parent amide. Dichloramine-T and the free acid undergo hydrolysis according to reactions (5) and (6). PhSO_2NHCl further protonates to give diprotonated species as shown in reaction (7). This diprotonated species hydrolyzed to yield PhSO_2NH_2 and $\text{H}_2\text{O}^+\text{Cl}$ species, reaction (8). Finally hypochlorous acid ionizes according to reaction (9). Therefore, the possible oxidizing species in acidified CAB solutions are PhSO_2NHCl , $\text{PhSO}_2\text{NCl}_2$, HOCl , and $\text{H}_2\text{O}^+\text{Cl}$.

If $\text{PhSO}_2\text{NCl}_2$ were to be the reactive species, then the rate law predicts a second-order dependence of rate on $[\text{CAB}]_0$, see Eq. (4) but experimentally clear first-order plots were obtained for the disappearance of CAB. Soper [22] reported that $[\text{HOCl}]$ is very small in acidified CAB solution and is independent of the $[\text{CAB}]$. On the basis of the above facts, the role of $\text{PhSO}_2\text{NCl}_2$ and HOCl in the present case can be ignored. Further, Swain and Crist [23] have pointed out in their studies that hypochlorite ion

Fig. 3 Mass spectrum of 2-ethyl-3,5-dihydroimidazol-4-one with its parent molecular ion peak at $m/z = 112$ amu

formed in a prior equilibrium before the rate-limiting step is a better electrophile than HOCl . Formation of the species of the type $\text{PhSO}_2\text{N}^+\text{H}_2\text{Cl}$ has been reported with CAB in acid medium (Eq. (7)). In the present investigations, the rate of the reaction increases with increase in $[\text{H}^+]$ but it is retarded by the added BSA (PhSO_2NH_2). This indicates that Eqs. (7) and (8) play a dominant role in the present case. Furthermore, CAB contains a polar N-Cl bond as the source of positive chlorine Cl^+ species, which forms the conjugate acid, PhSO_2NHCl in acidic solutions. The conjugate acid with N-Cl bond in fact interacts with the hydronium ion (H_3O^+), to form the reactive oxidant species $\text{H}_2\text{O}^+\text{Cl}$ and the BSA (PhSO_2NH_2) [24]. Hence, the most reactive oxidizing species in the present case is $\text{H}_2\text{O}^+\text{Cl}$.

Spectroscopic measurements were made for imidazole, CAB, and a mixture of both. Absorption maxima of 214, 220, and 216 nm for imidazole, CAB and a mixture of both were noticed in acidic solutions (Fig. 4). A hypsochromic

shift of 4 nm from 220 to 216 nm of CAB was observed. This can be probably attributed to complexation between CAB and imidazole.

In the light of these considerations, a mechanism (Scheme 3) is formulated for the oxidation of imidazole and 2-substituted imidazoles with CAB in acid medium to substantiate the observed experimental results.

A detailed mechanistic interpretation for the Scheme 3 has been worked out in Scheme 4. In Scheme 4, an initial equilibrium step involves protonation of CAB forming an active oxidizing species, $\text{H}_2\text{O}^+\text{Cl}$ with the elimination of PhSO_2NH_2 as shown in step (i). In the next pre-equilibrium fast step (ii) an electrophilic attack of the positive chlorine of the oxidizing species $\text{H}_2\text{O}^+\text{Cl}$ at the 5-position of the imidazole followed by the elimination of a proton and addition of a proton at the 4-position may give chloro substituted intermediate complex. In the next slow and rls step the intermediate complex undergoes a nucleophilic attack at the iminium carbon by H_2O followed by loss of a

Table 1 Percentage yield of imidazolones obtained from the oxidation of imidazoles with CAB in acid medium

Imidazoles	Imidazolones	Weight of imidazolone / g (found)	Weight of imidazolone / g (expected)	Yield of imidazoles / %
1.20	1.23	89.4
1.10	1.20	91.6
1.12	1.19	93.6
0.98	1.11	87.8
1.03	1.16	88.8

Experimental conditions: equimolar quantities of CAB and imidazoles were taken to calculate the percentage yield of imidazolones

molecule of HCl to give the final product imidazolone as shown in step (iii).

Deduction of rate law

From the slow and rate-limiting step (iii) of Scheme 3,

$$\text{Rate} = k_3[\text{Complex}] \quad (10)$$

The value of the complex can be determined as follows: the total concentration of CAB is given as

$$[\text{CAB}]_t = [\text{PhSO}_2\text{NHCl}] + [\text{H}_2\text{O}^+\text{Cl}] + [\text{Complex}] \quad (11)$$

From steps (i) and (ii) of Scheme 3,

$$[\text{PhSO}_2\text{NHCl}] = \frac{[\text{PhSO}_2\text{NH}_2][\text{Complex}]}{K_1 K_2 [\text{H}_3\text{O}^+][\text{Imidazole}]} \quad (12)$$

$$[\text{H}_2\text{O}^+\text{Cl}] = \frac{[\text{Complex}]}{K_2 [\text{Imidazole}]} \quad (13)$$

By substituting for $[\text{PhSO}_2\text{NHCl}]$ and $[\text{H}_2\text{O}^+\text{Cl}]$ from Eqs. (12) and (13) into Eq. (11) and solving for $[\text{Complex}]$, we get

$$[\text{Complex}] = \frac{K_1 K_2 [\text{CAB}]_t [\text{Imidazole}] [\text{H}_3\text{O}^+]}{[\text{PhSO}_2\text{NH}_2] + K_1 [\text{H}_3\text{O}^+] + K_1 K_2 [\text{Imidazole}] [\text{H}_3\text{O}^+]} \quad (14)$$

Upon substituting for $[\text{Complex}]$ from Eq. (14) into Eq. (10), one obtains

$$\text{Rate} = \frac{K_1 K_2 k_3 [\text{CAB}]_t [\text{Imidazole}] [\text{H}_3\text{O}^+]}{[\text{PhSO}_2\text{NH}_2] + K_1 [\text{H}_3\text{O}^+] + K_1 K_2 [\text{Imidazole}] [\text{H}_3\text{O}^+]} \quad (15)$$

Rate law (15) is in accordance all observed kinetic data, in which a first-order dependence of rate on $[\text{CAB}]_t$, fractional-order dependence each on $[\text{imidazole}]_o$ and $[\text{H}^+]$, and an inverse-fractional-order on $[\text{PhSO}_2\text{NH}_2]$ was noticed.

Evaluation of reaction constants

Since $\text{rate} = k' [\text{CAB}]_t$, under pseudo-first-order conditions of $[\text{CAB}]_o \ll [\text{imidazole}]_o$, Eq. (15) can be transformed as:

$$k' = \frac{K_1 K_2 k_3 [\text{Imidazole}] [\text{H}_3\text{O}^+]}{[\text{PhSO}_2\text{NH}_2] + K_1 [\text{H}_3\text{O}^+] + K_1 K_2 [\text{Imidazole}] [\text{H}_3\text{O}^+]} \quad (16)$$

$$\frac{1}{k'} = \frac{[\text{PhSO}_2\text{NH}_2]}{K_1 K_2 k_3 [\text{Imidazole}] [\text{H}_3\text{O}^+]} + \frac{1}{K_2 k_3 [\text{Imidazole}]} + \frac{1}{k_3} \quad (17)$$

$$\frac{1}{k'} = \frac{1}{[\text{Imidazole}]} \left\{ \frac{[\text{PhSO}_2\text{NH}_2]}{K_1 K_2 k_3 [\text{H}_3\text{O}^+]} + \frac{1}{K_2 k_3} \right\} + \frac{1}{k_3} \quad (18)$$

In order to deduce equilibrium and decomposition constants, according to Eqs. (17) and (18), the reaction was studied at constant $4.0 \times 10^{-4} \text{ mol dm}^{-3}$

Table 2 Effect of varying CAB and imidazole concentrations of the reaction rate at 303 K

[CAB] _o × 10 ⁴ /mol dm ⁻³	[imidazole] × 10 ³ /mol dm ⁻³	[HClO ₄] × 10 ⁴ /mol dm ⁻³	[BSA] × 10 ⁴ /mol dm ⁻³	<i>k'</i> × 10 ⁴ /s ⁻¹				
				2-EtIzIH	2-MeIzIH	IzIH	2-EsIzIH	2-CaIzIH
0.20	1.00	5.00	–	9.15	6.35	5.32	4.93	2.63
0.50	1.00	5.00	–	9.20	6.41	5.30	4.89	2.62
1.00	1.00	5.00	–	9.21	6.39	5.35	4.96	2.65
2.00	1.00	5.00	–	9.25	6.41	5.29	4.94	2.71
4.00	1.00	5.00	–	9.23	6.38	5.38	4.95	2.68
1.00	0.10	5.00	4.0	1.96 (1.85)	1.60 (1.55)	1.45 (1.30)	1.32 (1.15)	1.20 (1.02)
1.00	0.50	5.00	4.0	5.50 (4.70)	4.25 (3.74)	3.35 (2.84)	3.05 (2.31)	2.00 (1.47)
1.00	1.00	5.00	4.0	9.21 (7.93)	6.39 (4.72)	5.35 (3.74)	4.96 (2.75)	2.65 (1.59)
1.00	2.00	5.00	4.0	13.4 (11.8)	8.67 (6.02)	6.81 (5.12)	5.90 (3.31)	3.90 (1.75)
1.00	4.00	5.00	4.0	18.9 (13.2)	14.5 (8.74)	8.67 (6.05)	8.32 (4.01)	5.87 (1.85)
1.00	1.00	1.00	4.0	2.81 (2.87)	2.06 (2.42)	1.86 (2.05)	1.95 (1.65)	1.72 (1.05)
1.00	1.00	3.00	4.0	5.56 (5.05)	4.25 (3.92)	3.07 (3.49)	2.80 (2.41)	2.37 (1.29)
1.00	1.00	5.00	4.0	9.21 (7.93)	6.39 (4.72)	5.35 (3.74)	4.96 (2.75)	2.65 (1.59)
1.00	1.00	10.0	4.0	11.2 (10.9)	9.38 (5.75)	6.20 (4.56)	5.75 (3.15)	3.62 (2.33)
1.00	1.00	15.0	4.0	13.4 (13.0)	12.3 (6.89)	7.98 (4.92)	7.42 (3.55)	4.19 (2.89)

Values in parentheses refer to the effect of [imidazole] and [HClO₄] in presence of 4.0 × 10⁻⁴ mol dm⁻³ BSA

Table 3 Effect of varying benzenesulfonamide concentration on the reaction rate at 303 K

[BSA] × 10 ⁴ /mol dm ⁻³	<i>k'</i> × 10 ⁴ /s ⁻¹				
	2-EtIzIH	2-MeIzIH	IzIH	2-EsIzIH	2-CaIzIH
0	9.21	6.39	5.35	4.96	2.65
2.0	8.73	5.24	4.68	3.62	2.02
4.0	7.93	4.72	3.74	2.75	1.59
8.0	7.29	3.83	3.09	2.02	1.15

[CAB]_o = 1.0 × 10⁻⁴ mol dm⁻³, [imidazole]_o = 1.0 × 10⁻³ mol dm⁻³, [HClO₄] = 5.0 × 10⁻⁴ mol dm⁻³

benzenesulfonamide by varying concentrations of imidazole and HClO₄ in the concentration range given in Table 2.

From Eq. (17), plots of 1/*k'* vs. 1/[H⁺] at constant [imidazole] and [PhSO₂NH₂] were linear (Fig. 5; *R*² > 0.9900) with

$$\text{Slope} = \frac{[\text{PhSO}_2\text{NH}_2]}{K_1 K_2 k_3 [\text{Imidazole}]}$$

$$\text{and Intercept} = \frac{1}{K_3 k_3 [\text{Imidazole}]} + \frac{1}{k_3}$$

From Eq. (18), plots of 1/*k'* vs. 1/[imidazole] at constant [H⁺] and [PhSO₂NH₂] were linear (Fig. 6; *R*² = 0.9905) with

$$\text{Slope} = \frac{[\text{PhSO}_2\text{NH}_2]}{K_1 K_2 k_3 [\text{H}_3\text{O}^+]} + \frac{1}{K_2 k_3} \text{ and Intercept} = \frac{1}{k_3}$$

From the slopes and intercepts of the above plots, the values of equilibrium constants *K*₁ and *K*₂, and the decomposition constant *k*₃ were evaluated for all the imidazoles. These values are recorded in Table 6. The proposed mechanism and the derived rate law are supported by the experimental findings given below.

The proposed reaction mechanism is also evinced by the observed zero effect of ionic strength on the rate of the reaction. This can be justified by Brønsted and Bjerrum theory of salt effects [25]. According to this concept, the effect of ionic strength (*μ*) on the rate for a reaction involving two ions A and B is given by the relationship:

$$\log k' = \log k_0 + 1.018 Z_A Z_B \mu^{1/2} \quad (19)$$

Here, *Z*_A and *Z*_B are the values of the ions A and B, and *k'* and *k*₀ are the rate constants in the presence and in the absence of the added electrolyte, respectively. Above equation shows that a plot of log *k'* vs. *μ*^{1/2} should be linear with a slope of 1.018 *Z*_A*Z*_B and an intercept of log *k*₀. As the slope of the line depends on *Z*_A*Z*_B, i.e., charges of the reacting ions, three special cases may arise: (a) if A and B have similar signs, then *Z*_A*Z*_B will be positive and the rate constant *k'* increases with *μ*^{1/2}; (b) if A and B have dissimilar charges, then *Z*_A*Z*_B will be negative and the rate constant *k'* decreases with *μ*^{1/2}; and (c) if either A or B is uncharged or neutral then *Z*_A*Z*_B is equal to zero and *k'* is independent of the ionic strength of the solution. In the present case, variation of ionic strength of the medium does not alter the rate of reaction, this clearly signifies that one

Table 4 Effect of varying dielectric constant of the medium on the reaction rate at 303 K

% MeOH (v/v)	<i>D</i>	$k' \times 10^4/\text{s}^{-1}$				
		2-EtIzIH	2-MeIzIH	IzIH	2-EsIzIH	2-CaIzIH
0	76.73	9.21	6.39	5.35	4.96	2.65
5	74.50	13.1	9.31	8.42	6.29	3.40
10	72.37	18.2	12.9	11.1	9.24	5.36
15	69.75	25.8	18.4	16.4	12.8	7.22

$[\text{CAB}]_0 = 1.0 \times 10^{-4} \text{ mol dm}^{-3}$, $[\text{imidazole}]_0 = 1.0 \times 10^{-3} \text{ mol dm}^{-3}$, $[\text{HClO}_4] = 5.0 \times 10^{-4} \text{ mol dm}^{-3}$

Table 5 Effect of varying temperature on the reaction rate and activation parameters for the oxidation of imidazoles by CAB in acid medium

Temperature/K	$k' \times 10^4/\text{s}^{-1}$				
	2-EtIzIH	2-MeIzIH	IzIH	2-EsIzIH	2-CaIzIH
288	3.09	2.32	1.89	1.75	1.01
293	4.60	3.19	2.57	2.48	1.31
298	6.34	4.68	3.87	3.58	1.89
303	9.21	6.39	5.35	4.96	2.65
308	13.5	9.69	7.92	6.95	3.80
313	18.5	13.2	11.0	10.1	5.32
318	26.5	18.9	15.7	14.2	7.94
323	34.5	25.8	21.9	21.4	10.5
$E_a/\text{kJ mol}^{-1}$	49.8	52.6	54.7	57.6	64.3
$\Delta H^\ddagger/\text{kJ mol}^{-1}$	48.0	50.1	52.2	55.1	58.2
$\Delta G^\ddagger/\text{kJ mol}^{-1}$	89.6	92.9	93.5	93.7	95.1
$\Delta S^\ddagger/\text{J K}^{-1} \text{mol}^{-1}$	−140	−135	−131	−126	−120
Log <i>A</i>	10.0	9.77	9.61	10.0	10.3

$[\text{CAB}]_0 = 1.0 \times 10^{-4} \text{ mol dm}^{-3}$, $[\text{imidazole}]_0 = 1.0 \times 10^{-3} \text{ mol dm}^{-3}$, $[\text{HClO}_4] = 5.0 \times 10^{-4} \text{ mol dm}^{-3}$

Scheme 2

of the reactant species is a neutral molecule as seen in slow/rls of Scheme 4. Hence, the observed ionic strength effect is in agreement with the above theory.

The effect of changing solvent composition on the rate of reaction has been described in detail in various

Fig. 4 UV-Vis spectra of (A) imidazole, (B) CAB, and (C) a mixture of both in an acid medium

monographs [26–30]. The dependence of the rate constant on the dielectric constant of the medium is given by the following relationship:

$$\ln k' = \ln k'_0 \left(\frac{NZ_A Z_B e^2}{DRT r_{\#}} \right) \quad (20)$$

In this equation, k'_0 is the rate constant in a medium of infinite dielectric constant, $Z_A e$ and $Z_B e$ are the total charges on the ions A and B, $r_{\#}$ is the radius of the activated complex, R , T , and N have their usual meanings. The equation predicts a linear plot of $\log k'$ vs. $1/D$ with a negative slope if the charges on the ions are of the same sign and a positive slope if they are opposite sign. The positive dielectric effect observed in the present study (Table 4) clearly supports the involvement of dissimilar charges in the rate-limiting step (Scheme 4).

Scheme 3

Scheme 4

Fig. 5 Plots of $\log 1/k'$ vs. $1/[H^+]$ at constant [BSA]

Fig. 6 Plots of $\log 1/k'$ vs. $1/[\text{imidazole}]$ at constant [BSA]

Table 6 Values of equilibrium and decomposition constants

Substrate	$K_1 \times 10^2$	$K_2 \times 10^3$ /dm ⁻³ mol ⁻¹	$k_3 \times 10^4$ /s ⁻¹
2-EtIzIH	25.0	2.66	12.5
2-MeIzIH	14.5	6.50	7.70
IzIH	14.8	3.50	7.14
2-EsIzIH	50.8	25.0	3.84
2-CaIzIH	41.7	14.2	1.69

It can be seen from the Table 5 that the rate of oxidation of imidazoles by CAB in presence of HClO₄ increases in the order: 2-EtIzIH > 2-MeIzIH > IzIH > 2-EsIzIH > 2-CaIzIH. This trend due to combined effect of the electronic and steric factors of the substituents attached to the 2-position of imidazole ring. The higher reactivity of

2-EtIzIH in comparison with 2-MeIzIH can be endorsed due to the differences in the electron donating effect of the -C₂H₅ and -CH₃ groups and also through the positive inductive effect, thereby enhancing the electron density by imidazolium ring make the reaction very fast. Furthermore, 2-CaIzIH have least reactive assessment with 2-EsIzIH because the attached electron withdrawing group in 2-CaIzIH rapidly decreases the nucleophilicity on the aromatic ring than electron withdrawing group present in 2-EsIzIH.

Isokinetic relationship

The rate constants and activation energies in Table 5 reveal that activation energy is highest for the slowest reaction and vice versa as expected indicating that the reaction is under enthalpy control. This is verified by calculating the isokinetic temperature (β) from the slope of the linear plot of $\Delta H^\ddagger$ vs. $\Delta S^\ddagger$ (Fig. 7; $R^2 = 0.9987$). The value β found is 453 K, which is higher than the experimental temperature (303 K) employed in the present work. The genuine nature of isokinetic relationship was also tested through the Exner criterion [31] by plotting $\log k'_{(303\text{K})}$ vs. $\log k'_{(293\text{K})}$ (Fig. 7; $R^2 = 0.9993$). The isokinetic temperature β can be evaluated from the expression: $\beta = T_1 T_2 (q - 1) / (q T_2 - T_1)$ where q is the slope of the Exner plot; β was found to be 449 K. The proposed mechanism is also supported by the moderate values of energy of activation and other activation parameters. The fairly high negative $\Delta S^\ddagger$ values reflect a greater degree of ordering in the transition state than the initial state, due to an increase in solvation during the solvation process. The near constancy of $\Delta G^\ddagger$ values indicates that the same types of reaction mechanism could be operative for all the five imidazoles studied.

Conclusion

In the course of this research, optimum conditions for the facile oxidative conversion of imidazole (IzIH) and 2-substituted imidazoles viz., 2-ethyl-1*H*-imidazole (2-EtIzIH), 2-methyl-1*H*-imidazole (2-MeIzIH), 1*H*-imidazole-2-ester (2-EsIzIH), and 1*H*-imidazole-2-carbaldehyde (2-CaIzIH) to the corresponding imidazolones with chloramine-B have been developed in acid medium. These reactions follow identical kinetics with a rate law:

$$-d[\text{CAB}]/dt = k[\text{CAB}]_o[\text{imidazole}]_o^x[\text{H}^+]^y[\text{BSA}]^{-z}$$

where x , y , and $z < 1$; BSA is benzenesulfonamide. Activation parameters and reaction constants have been deduced. The isokinetic temperature was evaluated. The rate of oxidation of imidazoles follows the order: 2-EtIzIH > 2-MeIzIH > IzIH > 2-EsIzIH > 2-CaIzIH. A

Fig. 7 Isokinetic plots of
(a) $\log k'_{(303\text{K})}$ vs. $\log k'_{(293\text{K})}$
(b) $\Delta H^\ddagger$ vs. $\Delta S^\ddagger$

suitable reaction scheme is proposed and an appropriate rate law is deduced to account for the observed experimental results. The present method offers many advantages including high yield, simplicity, short reaction times, cost-effectivity and involvement of non-toxic reagents which make the reaction process is simple, smooth, and environmentally benign. Hence, this redox system can be scaled up to industrial process with suitable modification.

Experimental

Sigma make chloramine-B was purified by the method of Morris et al. [20]. An aqueous solution of CAB was prepared and standardized by iodometric method. 2-Ethyl-1*H*-imidazole and 1*H*-imidazole-2-carbaldehyde (Sigma), 2-methyl-1*H*-imidazole (SRL Pvt. Ltd., India), 1*H*-imidazole (SD Fine Chem. Ltd., India) and 1*H*-imidazole-2-ester (Avra Synthesis Pvt. Ltd., India) were of acceptable grades of purity and were used as received. Aqueous solutions of the compounds were used for kinetic studies. Reagent grade chemicals and doubly distilled water were used throughout the experiment. SL 159 Elico UV–Vis spectrophotometer was used for studying the formation of intermediate complex. GC–MS data were obtained on a 17A Shimadzu gas chromatograph with a QP-5050A Shimadzu mass spectrometer. NMR spectra were obtained on a Bruker WH 400-MHz nuclear magnetic resonance spectrometer.

Kinetic measurements

The kinetic runs were performed under pseudo-first-order conditions with a known excess of [substrate]₀ over

[oxidant]₀ in acid medium at 303 K. The progress of the reaction was monitored by the iodometric method. The experimental procedure we followed here was identical to that reported earlier [15]. The course of the reaction was studied for at least two half-lives. The pseudo-first-order rate constants (k'/s^{-1}) calculated from the linear plots of $\log$ [CAB] vs. time. All the kinetic runs were carried out twice to check the reproducibility. The values are found to be reproducible within ± 3 –6 % error. Regression coefficient (R^2) were calculated using $fx - 100$ W scientific calculator.

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