# A Quantitative Structure–Reactivity Assessment of Phenols by Investigation of Rapid Iodination Kinetics Using Hydrodynamic Voltammetry: Applicability of the Hammett Equation in Aqueous Medium

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ABSTRACT: Halogenations of aromatic substrates in aqueous medium are essentially electrophilic substitutions proceeding at rates concomitant with the nature of the substrates and substituent motifs. Kinetics as an investigatory tool for the quantitative assessment of the structure–reactivity correlation in these reactions for a diverse range of substrates has rarely been reported, presumably due to the rapidity of these reactions in aqueous medium. We have used hydrodynamic voltammetry to investigate the rapid kinetics of uncatalyzed iodination of phenol and eight substituted phenols by iodine monochloride at constant pH in aqueous medium. The Arrhenius plots for these reactions yield comprehensive kinetic and thermodynamic data. The quantitative structure–reactivity correlation stemming from the regio- and

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This paper is dedicated to Professor Dr. T. S. Rao on the occasion of his 82nd birthday, in recognition of his outstanding contributions to chemical kinetics, especially rapid kinetics in aqueous medium.

stereospecificity of the substituent motifs on the substrates has been examined through the Hammett plot, which shows a negative slope of 1.87. The magnitudes of the rate constants, energies of activation, frequency factors, and entropy change obtained for the nine fast reactions reported, reflect the relative ease of the reaction dynamics in quantitative terms thereby ascertaining the relative reactivities of the phenols studied herein. © 2013 Wiley Periodicals, Inc. Int J Chem Kinet 45: 693–702, 2013

## INTRODUCTION

Halogenated aromatic compounds are important in synthetic organic chemistry [1] as key intermediates used in the preparation of organometallic reagents [2,3] and as significant entities in coupling reactions such as Negishi cross-coupling involving transition metals [4]. The halogen functionality accounts for the use of these compounds as medicinal molecules [5–7], herbicides, pesticides, fire retardants, and other commercially valuable products. Halogenations of aromatic substrates are known to be electrophilic aromatic substitution reactions [8]. Iodination of aromatic rings has important applications in synthesizing natural products and pharmaceuticals [9–11]; 4-iodophenol is known to function as an enhancer in horseradish peroxidase–catalyzed luminal chemiluminescence in liposomes [12]. Iodoarene intermediates are used in the synthesis of useful drugs [13]. Therefore, it has always remained the endeavor of chemists to elucidate plausible mechanistic routes for these reactions in terms of substrate reactivity. These being electrophilic substitution reactions, the rates depend on the electrophilicity of the reagent, nucleophilicity of the substrate, and steric compulsions of both. The regiospecificity and nature of the substituent motif on the substrate scaffold coupled with its stereoplanarity operate in unison to determine the substrate reactivity. In aqueous medium, these reactions are rapid and measurements of their rates necessitate special techniques to quantitatively ascertain the reactivity to seek justification of the speculated mechanistic routes involved. A search through the literature reveals the paucity of such quantitative investigations contrary to reports in nonaqueous solutions. Berliner has studied the iodinations of chlorophenol and anisole in acidic solutions [14], whereas Grovenstein and Aprahamain have reported those of dibromo phenols [15]. Schutte and Havinga have studied the base catalysis for the iodination of imidazole and *p*-cresol [16]. Vibhute and Khansole have reported the slow first-order kinetics of iodination of substituted phenols by pyridinium iodochloride in methanol [17].

In contrast to these investigations, we have attempted a comprehensive assessment of the reactivity of phenol and eight substituted phenols in iodination reactions under uniform conditions, by following the fast kinetics, in aqueous medium. These reactions typify electrophilic aromatic substitutions. We have carried out these reactions without using any catalyst. Constant relative proportions of the phenol–phenolate concentrations were ensured by maintaining a pH value of 4.8. Iodine monochloride (ICl) being a polar molecule facilitates the electrophilic attack on the substrates in contrast to the nonpolar iodine molecule. Hence, the reactions under study are remarkably rapid. The use of ICl also minimized the possibility of formation of the tri-iodide anion in these electrophilic substitution reactions besides not being a controversial halogenating species like the protonated hypohalous acid [18]. All the reactions studied herein were found to have half-lives of barely a few seconds. However, these reactions being of the second order, their half-lives were extended by diluting the solutions whereby convenient kinetic measurements became feasible using hydrodynamic voltammetry. The rate of disappearance of ICl, the only electroreducible species among the reactants and products, was measured at a rotating platinum microcathode by the hydrodynamic voltammetry technique. These kinetic investigations confirmed the relative ease of the reaction dynamics speculated on the basis of the substrate structures in these halogenations. Comprehensive kinetic and related thermodynamic data for the iodination of the regioisomers of cresols, nitrophenols, and chlorophenols were obtained and compared with those for phenol. The analysis of the product by the standard technique [19] in each of these nine reactions revealed the regiospecific formation of the monoiodo isomer in these reactions, which was also confirmed from NMR spectra.

Under these conditions, the reaction rates solely depended on the nucleophilicity of the substrate, regiospecificity of the substituent, and electrophilicity of the reagent. Consequently, the reaction rates determined are rational indicators of the ease of the plausible mechanistic route considering the substrate structures. The substrate reactivities are determined in quantitative terms from the comprehensive kinetic and relevant thermodynamic data obtained. A Hammett plot [20,21] has been attempted to quantitatively correlate structure and reactivity of the substrates, in view of the dearth of such reports in aqueous medium for the reactions under study.

Microgram quantities of chemicals required in this study, their nonhazardous nature, and very short reaction times of the reactions under study are factors that adhere to green chemistry principles.

## EXPERIMENTAL

### General

All chemicals were purchased from commercial sources and used as supplied. Stock solutions of AR grade 0.001 M ICl, phenol, *o*-cresol, *m*-cresol, *p*-cresol, *o*-chlorophenol, *m*-chlorophenol, *p*-chlorophenol, *m*-nitrophenol, *p*-nitrophenol, and the supporting electrolyte 0.1 M potassium chloride were prepared in double-distilled water. Sodium citrate and citric acid, each 0.1 M, were prepared for the buffer system. Iodine monochloride solution of the required concentration was prepared after determining the exact strength of the stock solution by iodometric titration.

### Kinetic Measurements Using Hydrodynamic Voltammetry

The rotating platinum electrode (RPE) was an inverted "T"-shaped glass tube 30 cm long and 5 mm in diameter, containing mercury. A platinum wire of length 1 cm and diameter 1 mm was fused at the tip of the glass tube such that 0.5 cm of it protruded out. A copper wire was dipped in the glass tube containing mercury for electrical contact. The electrode assembly was mounted on a pair of pulleys and rotated at 600 rpm by a synchronous motor. The inverted "T" shape of the glass tube, to which the platinum electrode was fused, facilitated stirring of the reaction mixture while rotating.

The saturated calomel electrode (SCE) is the positive electrode, which is the reference electrode.

***Calibration of Diffusion Current.*** The iodination of phenol, among the reactions studied, is described. The RPE and SCE were dipped in 50.0 cm$^3$ of $5 \times 10^{-4}$ M potassium chloride, the supporting electrolyte containing the required buffer solutions. A potential of +0.1 V versus the SCE was applied at the RPE by means of a potentiometric arrangement. The galvanometer light spot was ensured to show zero deflection on the scale. The supporting electrolyte solution was then replaced by $5 \times 10^{-6}$ M 50.0 cm$^3$ ICl solution containing $5 \times 10^{-4}$ M potassium chloride and the amount of the buffer components required for pH 4.8. The shunt was adjusted for the deflection of the galvanometer light spot to be within scale limits. 1.0 cm galvanometer light spot deflection on the scale corresponded to a diffusion current value of 1.0 nA. The shunt value was kept constant for all the temperatures studied for the reaction. All the calibration readings were carried out only after the solutions attained the thermostat temperatures at which the kinetic readings were subsequently to be observed. The diffusion current values, in terms of the deflection of the light spot on the scale, were recorded for various ICl concentrations in the range of $1 \times 10^{-6}$ to $5 \times 10^{-6}$ M. The plots of diffusion current in nanoampere versus the concentration of ICl for different temperatures are linear as shown in Table I and Fig. 1. Calibration for the other eight compounds was similarly carried out using the appropriate concentration range of ICl.

**Table I** Calibration of the Diffusion Current of ICl at Various Temperatures for the Uncatalyzed Iodination of Phenol in Aqueous Medium at pH 4.8 (±0.2 nA Error)

| [ICl] | Diffusion Current (nA) | | | | |
|---|---|---|---|---|---|
| (× $10^{-6}$ M) | 10.0°C | 15.0°C | 20.0°C | 25.0°C | 30.0°C |
| 1.0 | 7.7 | 8.2 | 8.5 | 9.0 | 9.4 |
| 2.0 | 15.5 | 16.1 | 17.0 | 18.1 | 18.8 |
| 3.0 | 23.2 | 24.8 | 25.6 | 27.1 | 27.8 |
| 4.0 | 31.0 | 32.2 | 34.1 | 36.5 | 38.0 |
| 5.0 | 38.0 | 41.5 | 42.3 | 44.6 | 46.9 |

Potential applied at the RPE versus SCE is 0.1 V.

***Kinetic Measurements of Iodination of Phenol.*** The reactants, ICl and phenol, underwent double dilution

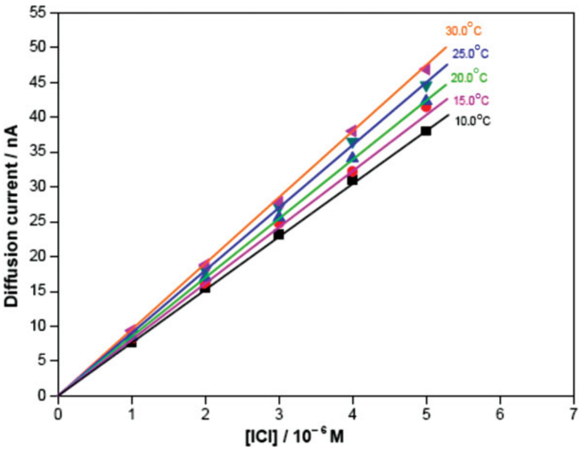


**Figure 1** Calibration of the diffusion current of ICl at various temperatures for the uncatalyzed iodination of phenol in aqueous medium at pH 4.8.

**Table II** Kinetics of Uncatalyzed Iodination of Phenol at 25.0°C by ICl in Aqueous Medium at pH 4.8 (±0.2 nA Error)

| Time (s) | Diffusion Current (nA) | [ICl] ($\times 10^{-6}$ M) | $[\mathrm{ICl}]^{-1}$ ($\times 10^{5}$ $\mathrm{M}^{-1}$) |
|---|---|---|---|
| 20 | 34.5 | 3.85 | 2.60 |
| 30 | 30.0 | 3.45 | 2.90 |
| 40 | 27.5 | 3.08 | 3.25 |
| 50 | 25.0 | 2.82 | 3.55 |
| 60 | 22.5 | 2.63 | 3.80 |
| 70 | 22.0 | 2.39 | 4.20 |

**Table III** Constant Parameters in the Kinetics of Uncatalyzed Iodination of Phenol in Aqueous Medium at All Temperatures at pH 4.8

| Parameter | Value |
|---|---|
| Potential applied at the RPE versus SCE | 0.1 V |
| Initial concentration of iodine monochloride | $5 \times 10^{-6}$ M |
| Initial concentration of phenol | $5 \times 10^{-6}$ M |
| Ionic strength of the reaction medium | $2.55 \times 10^{-2}$ M |
| Concentration of potassium chloride | $5 \times 10^{-4}$ M |
| Concentration of sodium citrate | 0.0125 M |
| Concentration of citric acid | 0.0125 M |
| Total volume of the reaction mixture | 50.0 $\mathrm{cm}^3$ |

after mixing to a total volume of 50 $\mathrm{cm}^3$. Hence, additions of the reactants were made in the following manner: 25 $\mathrm{cm}^3$ of $10 \times 10^{-6}$ M ICl containing $5 \times 10^{-4}$ M potassium chloride and the required buffer components were kept in a flask and maintained at the desired temperature in a thermostat. In another flask, 25 $\mathrm{cm}^3$ of $10 \times 10^{-6}$ M phenol containing $5 \times 10^{-4}$ M potassium chloride and the required buffer components were maintained in the same thermostat. After the thermostat temperature was attained by all the solutions, the two reactant solutions were simultaneously added to the reaction vessel kept in the thermostat in which the RPE was rotating and SCE was dipped. The time at the moment of mixing was noted in a stop clock that was already started, and the decaying diffusion current due to the unreacted ICl was recorded at every ten seconds in terms of the galvanometer light spot on the scale until about one half-life of the reaction under study was completed (Table II). The final initial concentrations of the reactants due to dilution to 50 $\mathrm{cm}^3$ of the reaction mixture are indicated (Table III).

From the calibration plot at the relevant temperature, the unreacted concentrations of ICl at various instants of time were evaluated in the kinetic run. The reaction was of the second order, and equal concentrations of the reactants were used hence the plot of $[\mathrm{ICl}]^{-1}$ versus time was linear, the slope which was the rate constant $k_2$ of the iodination reaction under study (Fig. 2).

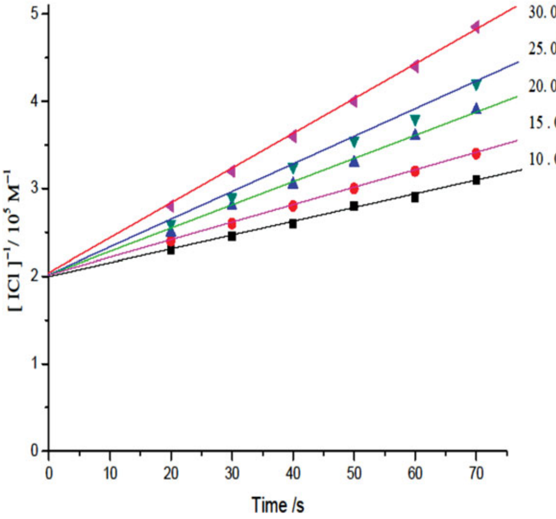


**Figure 2** Kinetics of the uncatalyzed iodination of phenol by ICl in aqueous medium at various temperatures at pH 4.8.

The kinetic runs for the other eight reactions were similarly carried out using appropriate initial reactant concentrations, which facilitated recording of the diffusion current at quick but convenient intervals of time.

***Experimental Errors.*** The above procedure of calibration and kinetic measurements was repeated thrice for checking the reproducibility of the galvanometer measurements, which were found to be within the limits of ±0.2 nA error. The galvanometer sensitivity and response time were such that the error in the determination of the decaying nanocurrents due to iodine monochloride in these studies was $\leq 1\%$.

The error in preparing standard stock solutions of the reactants due to weighing error was $\leq 0.25\%$ considering the sensitivity of the balance used.

The overall experimental error in view of the above in determining $E_a$ and $\Delta S^{\neq}$ was $\leq 2\%$.

## RESULTS AND DISCUSSION

### Optimization of the Reaction Conditions

To assess the relative reactivity of the substrates, optimization of the reaction conditions was essential. Iodinations are the slowest among halogenations but become remarkably rapid when the reagent is dipolar like ICl in contrast to molecular iodine. We have chosen ICl because of its superior potential as an electrophile. The relatively more reactive species between phenol and phenolate anion in these aromatic electrophilic substitution reactions is the phenolate anion; hence constant relative proportions of the phenol–phenolate concentrations have been ensured by maintaining a constant pH value of 4.8 throughout these studies. The citric acid–sodium citrate buffer system is preferred as it is not known to react with aqueous ICl as is the case with other buffer systems.

The hydrodynamic voltammetry technique was employed to measure the diffusion-limited current due to ICl at a rotating platinum cathode in these rapid reactions. This technique necessitated the use of a large concentration of a supporting electrolyte. Potassium chloride was chosen for this purpose, which also suppressed the possible hydrolysis of ICl, due to the common ion effect, according to the equilibrium [22]

$$\mathrm{ICl} + \mathrm{H_2O} \leftrightharpoons \mathrm{IOH} + \mathrm{HCl}$$

The ionic strength is maintained constant in the study.

Under these conditions, the dipolar ICl molecule was the sole iodinating species in the reactions studied. The kinetic and related thermodynamic data obtained have been interpreted on the principles of stereochemistry and electrophilic substitution.

## Thermodynamic and Kinetic Analyses

The kinetics of iodination of phenol, cresols, and the regioisomers of chlorophenol and nitrophenol ICl was studied using the platinum microelectrode (RPE) rotated at 600 rpm by an ac electric motor. A potential of 0.1 V versus a SCE was applied at the RPE. The diffusion-limited current due to unreacted ICl was recorded at every 10 s from the start of the reaction, using a moving coil mirror galvanometer of 1 nA cm$^{-1}$ sensitivity. The galvanometer readings were separately calibrated over a range of ICl concentrations at the temperatures at which the kinetic measurements were to be carried out. From these, the concentrations of unreacted ICl in the reaction at various instants were determined. The kinetic measurements for each reaction were carried out at five different temperatures to determine the energy of activation, as shown in Table IV (see Fig. 3). The specific reaction rates determined were found to be reproducible to within ±2% considering the various sources of errors. Appropriate initial concentrations of the reactants that facilitated convenient kinetic measurements were used in each reaction. The values of energy of activation, frequency factor, and entropy change for each of the nine reactions studied, were evaluated.

**Table IV** Variation of the Specific Reaction Rate of Iodination of Phenol by ICl in Aqueous Medium with Temperature at pH 4.8 ($\leq$2%)

| Temperature (K) | $[T]^{-1}$ ($\times 10^{-3}$ K$^{-1}$) | $k_2$ (M$^{-1}$ s$^{-1}$) | log $k_2$ |
|---|---|---|---|
| 283 | 3.53 | 2060 | 3.31 |
| 288 | 3.47 | 3570 | 3.41 |
| 293 | 3.41 | 3160 | 3.50 |
| 298 | 3.36 | 3980 | 3.60 |
| 303 | 3.30 | 4790 | 3.68 |

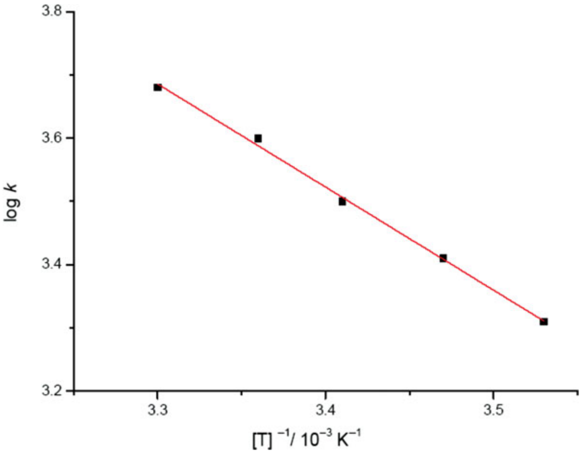


**Figure 3** Variation of the specific reaction rate of iodination of phenol by ICl in aqueous medium at different temperatures at pH 4.8.

The kinetic and thermodynamic data obtained for the iodination of phenol and eight phenol derivatives were examined to study the structure–reactivity correlation of these substrates on a quantitative scaffold. A summary of the kinetic and related thermodynamic data for the reactions studied is presented in Table V.

## Quantitative Determination of the Reactivity Order of Cresols, Chlorophenols, and Nitrophenols

The study ascertained the order of reactivity for the uncatalyzed iodination of phenol and regioisomers of cresol, chlorophenol, and nitrophenol in aqueous medium in quantitative terms. The second-order rate constants $k_2$ were determined using hydrodynamic voltammetry by monitoring the diffusion-limited current due to ICl at a rotating platinum cathode. Under the conditions in this study, the ICl molecule was the sole iodinating species in all the reactions studied. The kinetic and related thermodynamic data obtained under these conditions have been interpreted on the principles of stereochemistry and electrophilic substitution.

**Table V** Quantitative Summary of the Rapid Kinetics of Uncatalyzed Iodination of Phenols in Aqueous Medium at pH 4.8 Using ICl

| Substrate | $k_2$ at 25°C ($M^{-1}$ $s^{-1}$) | $t_{1/2}$ at $25^0$ (s) | Initial Reactant Concentration ($\times$ $10^{-5}$ M) | $E_a$ (kJ $mol^{-1}$) | Frequency Factor, $A$ ($\times$ $10^8$ $M^{-1}$ $s^{-1}$) | $\Delta S^{\neq}$ (J K $mol^{-1}$) |
|---|---|---|---|---|---|---|
| *o*-Cresol | 167 | 60 | 10.0 | 45.0 | 129.0 | −59.7 |
| *m*- Cresol | 6250 | 32 | 0.50 | 28.7 | 6.7 | −84.3 |
| *p*- Cresol | 398 | 50 | 5.0 | 40.0 | 36.7 | −70.1 |
| Phenol | 3162 | 63 | 0.50 | 32.4 | 7.7 | −77.5 |
| *o*-Chlorophenol | 164 | 61 | 10.0 | 41.7 | 33.3 | −70.9 |
| *m*-Chlorophenol | 1698 | 59 | 1.0 | 35.0 | 45.4 | −73.9 |
| *p*-Chlorophenol | 355 | 56 | 5.0 | 43.5 | 149.0 | −58.4 |
| *m*-Nitrophenol | 6 | 33 | 500.0 | 60.0 | 1970.0 | −37.0 |
| *p*-Nitrophenol | 17 | 59 | 100.0 | 54.0 | 494.0 | −48.4 |

## Interpretation of Kinetic and Thermodynamic Data

The kinetic and related thermodynamic data obtained under these uniform conditions have been interpreted on the basis of the principles of stereochemistry and electrophilic substitution. Cresols showed the highest reactivity toward iodination followed by chlorophenols. Nitrophenols showed relatively the lowest reactivity among the three groups of the phenol derivatives studied.

The –OH group in cresols is ortho and para directing in electrophilic substitutions, whereas the –$CH_3$ group is ortho directing. Both these effects operate in unison in *m*-cresol, which indeed are confirmed from the highest rate of iodination observed for this compound. The other two cresols manifest relatively lower reactivity in terms of the rates of iodination due to the lack of this additive activation effect of the two substituent groups. There is steric congestion of the hydroxyl and methyl groups in *o*-cresol, resulting in the lack of coplanarity of the benzene ring with one of these substituents. This causes deteriorated aromaticity of the substrate, manifested from the lowest specific reaction rate for the iodination of *o*-cresol among the three regioisomers (see Table V).

The –Cl group is electron withdrawing due to the inductive effect and also electron donating due to the electron rich nature of the halogen atom. However, halogens show a stronger mesomeric effect than inductive. Thus the reactivity order of the three regioisomers of chlorophenol is similar to that of cresols albeit the rates for iodination are slower than those of cresols. The nitro group is plainly electron withdrawing unlike the halo group. This is clearly evident from the lowest specific reaction rate for the iodination of *m*-nitrophenol among all the substrates studies.

***Typical Calculations.*** Iodination of phenol by ICl

(i) *Specific Reaction Rate*, $k$. The graph of $[ICl]^{-1}$ versus time is a straight line at all temperatures for both the reactions; hence both the reactions follow the second-order kinetics and the specific reaction rates are the slopes of these lines.

(ii) *Energy of activation*, $E_a$

$$\begin{aligned} E_a &= -2.303 \times R \times \text{slope of the plot} \log k\ VsT^{-1} \\ &= -2.303 \times 8.314 \times (-1692.16) \\ &= 32.4\,\text{kJ mol}^{-1} \end{aligned}$$

(iii) Preexponential or frequency factor, $A$
Iodination of phenol by ICl

$$\begin{aligned} k &= A \exp(-E_a/RT) \\ \log A &= \log k + E_a/2.303\,RT \\ A &= 7.7 \times 108\ M^{-1}s^{-1} \end{aligned}$$

(iv) Entropy of activation , $\Delta S^{\neq}$

$$\begin{aligned} \Delta S^{\neq} &= 2.303R \log k - 2.303\,R \log(ek{*}T/h) \\ &\quad + E_a/T \\ \Delta S^{\neq} &= 19.15 \log k - 253.25 + E_a/T \\ \Delta S^{\neq} &= -77.5\,\text{JK}^{-1}\text{mol}^{-1} \end{aligned}$$

where $e = 2.713$, $h$ = Planck constant, and $k*$ = Boltzmann constant.

Similar mathematics for the calculation of $k$, $E_a$, $A$, and $\Delta S^{\neq}$ for the other eight substrates was adopted.

**Table VI** Hammett Constants for the Substituents and Reactions Studied and Their Correlation with the Rate Constants Observed at 25.0°C (≤2%)

| Compound | $k_2$ ($M^{-1}$ $s^{-1}$) | log $k_2$ | p$K_a$ | $\sigma_x$ | $\Delta S^{\neq}$ (J $K^{-1}$ $mol^{-1}$) |
|---|---|---|---|---|---|
| Phenol | 3162 | 3.5000 | 9.94 | 0.00 | −77.52 |
| *m*-Cresol | 6250 | 3.7959 | 10.08 | −0.14 | −84.25 |
| *p*-Cresol | 398 | 2.6000 | 10.19 | −0.25 | −70.11 |
| *m*-Chlorophenol | 1698 | 3.2300 | 9.02 | 0.92 | −73.94 |
| *p*-Chlorophenol | 355 | 2.5502 | 9.38 | 0.56 | −58.44 |
| *m*-Nitrophenol | 6 | 0.7782 | 8.35 | 0.75 | −37.00 |
| *p*-Nitrophenol | 17 | 1.2304 | 7.14 | 1.23 | −48.48 |

## Applicability of the Hammett Equation to the Data in the Study

A correlation between the structure of a molecule and its chemical reactivity is a challenging feature of physical organic chemistry, and quantification of such a correlation is even more intriguing. The structure of a molecule is an intrinsic property and is independent of the solvent effect. However, the experimentally measured observable, the reaction rate, is affected by the nature of the solvent. The structure of a molecule determines its physical properties, chemical reactivity, and consequently its biological activity. Speculations on the reactivity of molecules from their structures cannot be generalized since correlation between chemical reactivity and structure cannot be deduced from any known laws but depends on several factors that have to be experimentally verified. The Hammett equation nonetheless is a rational indicator of the structure and reactivity on a quantitative scaffold.

A fit of the Hammett equation to the data in the study has been attempted to further elucidate the structure–reactivity correlation in the reactions studied (Table VI).

Hammett has summarized quantitatively the ability of a meta or para substituent group to donate or withdraw electrons in the equation

$$log\ k_x = log\ k_H + \rho\sigma_x$$

where $k_x$ is a rate constant of the substituted substrate, $k_H$ is the rate constant of the unsubstituted substrate, $\rho$ is a reaction constant, and $\sigma_x$ is a substituent constant:

$$\sigma_x = \log[K_x/K_H] = (pK_a)_H - (pK_a)$$
$$= (pK_a)_{phenol} - (pK_a)_{substituted\ phenol}$$

where $K_x$ is a dissociation constant of substituted phenol (substituted carbolic acid) and $K_H$ is a dissociation constant of unsubstituted phenol (carbolic acid)

The ability of a substituent to donate or withdraw electrons was estimated by Hammett on the basis of the p$K_a$ or p$K_b$ value of the acid or base from which the substrate is derived. If the substituent has no effect, $\sigma$ is zero. If the substituent is electron withdrawing, $\sigma$ is positive and if the substituent is electron donating it is $\sigma$ negative.

The reaction constant $\rho$ is a measure of the sensitivity of a reaction to the electronic substitution effect and is unity for the dissociation of benzoic acid in water. For acid-anion equilibrium, electron-donating groups decrease the extent of dissociation and electron-withdrawing groups increase the extent of dissociation due to the effect of stability of the anion. Electron-donating groups retard hydrolysis rates, whereas withdrawing groups accelerate hydrolysis. A nucleophile bearing an electron-donating group makes the carbon atom of the carbonyl group of an ester more reactive. The solvent of the reaction affects the reaction rate and thus the reactivity of the substrates [22]. If the transition state has more electrons than the reactants then $\rho$ has a positive value. If the transition state has lesser electrons than the reactants then $\rho$ has a negative value.

That ortho-substituted aromatic compounds do not conform to Hammett plots is well known and accepted. This is attributed to the possible steric hindrance that ortho substituents may exert resulting in noncoplanarity of the substituent with the aromatic ring leading to hampered delocalization, hence Hammett plots are restricted to meta- and para-substituted compounds [23,24]. In the studies carried out herein, the slope of the Hammett plot, log $k$ versus $\sigma_x$ (Fig. 4), is negative (–1.87), signifying the electrophilic substitution nature of the reactions.

## Moderate Negative Values of ΔS≠ Are Indicative of Bimolecular Reactions

Such a fit of the observed kinetics for these nine substitution reactions of phenol derivatives in the Hammett plot was lacking for aqueous medium. The present studies have attempted such a fit of the experimentally observed values.

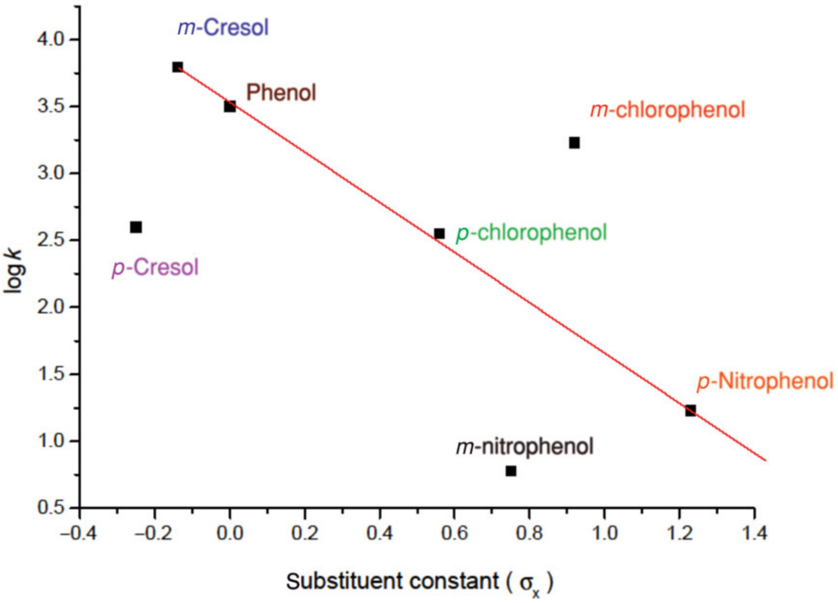


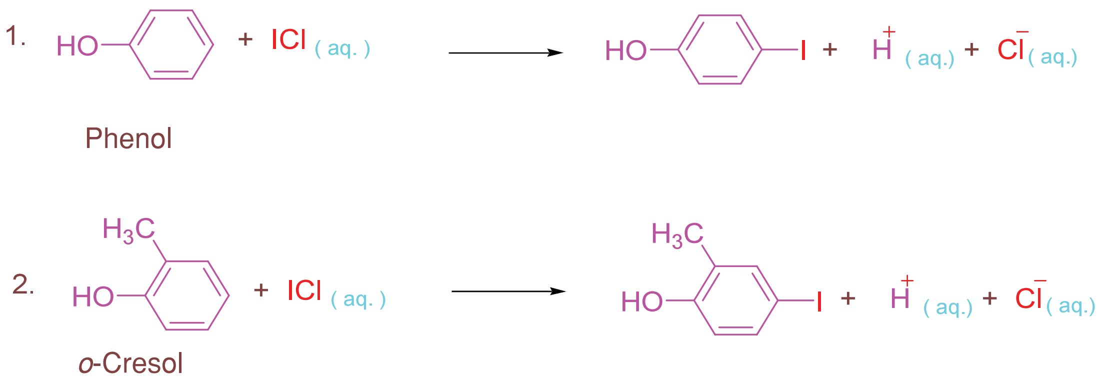
**Figure 4** Hammett plot for the iodination reactions studied.

## CONCLUSIONS

The observed trends of the reaction rates for the iodination of nitrophenols, chlorophenols, and cresols are complemented with those for the energies of activation, frequency factors, and entropy changes for these reactions (Table I). The activated complex has lower entropy of activation than the reactants; hence, it is unstable and decays into products. Increasing magnitudes of the rate constants are seen to accompany decreasing frequency factors, decreasing activation energies, and increasing magnitudes of entropy of activation. These trends are a quantitative measure of the reactivity order of the substrates in these reactions and clearly manifest the subtleties of the reactivity of these substrates stemming from the contribution of the various factors that affect the mechanistic route. The Hammett plot confirms the nonconformity of the ortho isomers while is seen to hold good for the other isomers.

The electron-donating inductive effect of the $CH_3$ group, the electron-donating mesomeric effects of the substituents OH and Cl, the electron-withdrawing mesomeric effect of the $NO_2$ group, all depend on their nature and the position they occupy on the aromatic ring along with steric compulsions. These factors operating in unison determine the reactivity of the substrates studied in these electrophilic substitutions using the iodine monochloride reagent. The quantitative structure–reactivity assessment of the phenols studied herein, by investigating the rapid iodination kinetics ascertained by applying the Hammett equation, has been plausible using the hydrodynamic voltammetry technique.

The nine reactions under study are as follows:



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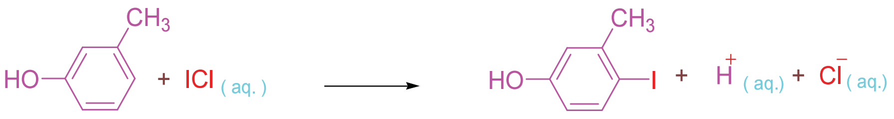
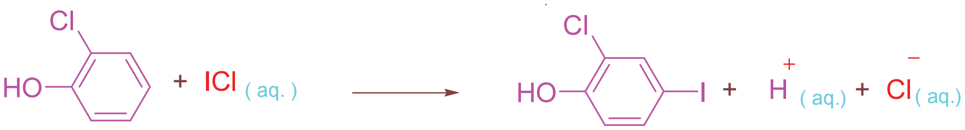


*m*-Cresol

4.

*p*-Cresol

5.

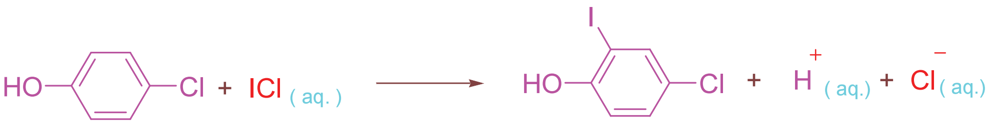


*o*-Chlorophenol

6.

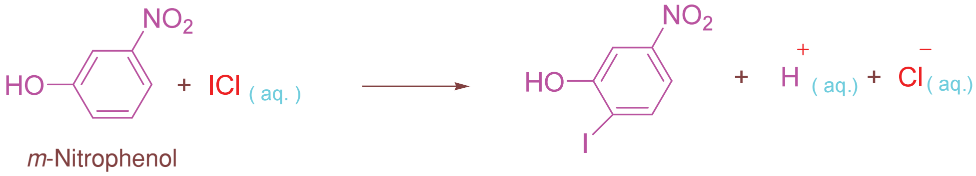
*m*-Chlorophenol

7.



*p*-Chlorophenol

8.



*m*-Nitrophenol

9.

*p*-Nitrophenol

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