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Electrophilicity and nucleophilicity of commonly used aldehydes†

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The present approach for determining the electrophilicity (*E*) and nucleophilicity (*N*) of aldehydes includes a kinetic study of $KMNO_4$ oxidation and $NaBH_4$ reduction of aldehydes. A transition state analysis of the $KMNO_4$ promoted aldehyde oxidation reaction has been performed, which shows a very good correlation with experimental results. The validity of the experimental method has been tested using the experimental activation parameters of the two reactions. The utility of the present approach is further demonstrated by the theoretical *versus* experimental relationship, which provides easy access to *E* and *N* values for various aldehydes and offers an at-a-glance assessment of the chemical reactivity of aldehydes in various reactions.

Introduction

Electrophilicity (*E*) and nucleophilicity (*N*) are the two most important concepts to help us to rationalize the electronic aspects of reactivity, selectivity, and substituent effects in a chemical reaction.[1] To date, several methods have been designed to assess the electrophilicity and nucleophilicity scale of molecules using both experimental and theoretical tools.[2] Mayr *et al.* successfully evolved the first experimental scale for both electrophilicity and nucleophilicity from kinetic data using the equation $\log k = s(N + E)$, in which electrophiles are characterized by one parameter (*E*) and nucleophiles are characterized by two parameters (*N*, *s*).[3] Alongside this experimental scale, various theoretical scales have been proposed.[4] Following the establishment of Fukui's frontier molecular orbital theory,[5] the measure of the electrophilicity was based upon the lowest unoccupied molecular orbital (LUMO) eigenvalue, while the energy of the highest occupied molecular orbital (HOMO) characterized the nucleophilicity. However, the whole picture became simpler after Koopmans' theorem, in which the energy of the HOMO is approximately equal to the negative of the ionization potential (IP), and the energy of the LUMO is identified as the negative of the *electron* affinity (EA).[6] Later on, Parr *et al.* defined electrophilicity as the energy of stabilization of a chemical species when it acquires an additional fraction of electronic charge from the environment. They described a global electrophilicity index ω by the equation $\omega = \mu^2/2\eta$, where μ is the electronic chemical potential and η is the chemical hardness.[7] Later on, Ayers *et al.* introduced two sets of equations, based on the IP and EA, to describe both the electrophilicity and nucleophilicity.[8] As an important contribution, Gazquez *et al.* described the electrodonating (ω^-) and electroaccepting (ω^+) powers using two sets of equations.[9] Although some advances have been made in the theoretical description of nucleophilicity and electrophilicity,[10] there exists ample opportunity to expand the experimental determination of the electrophilicity (*E*) and nucleophilicity (*N*) to a wider range of molecules.

During electrophile–nucleophile interactions, an electrophile (and also a nucleophile) will face both attractive and repulsive forces since molecules contain both electrons and nuclei. Depending on the substituent, the predominance of either electron accepting or donating character will arise during the interaction process because of the presence of both the electrophilic and nucleophilic character in a molecule. So, parameters such as net electrophilicity (the electrophilicity of a system relative to its own nucleophilicity) or net nucleophilicity (the nucleophilicity of a system relative to its own electrophilicity) are always preferable to determine the actual electron accepting or donating character of a molecule.[11] A synthetic chemist on the bench is often faced with the challenge to tune the reactivity of an aldehyde and deliver the desired selectivity in a chemical reaction. For this reason, *E* and *N* values would be useful when selecting an aldehyde in order to fine tune the selectivity of any chemical transformation of an aldehyde. In this context, *E* and *N* values of a large class of aldehydes have been evaluated from the rate kinetics of two very simple reactions; the $KMnO_4$ oxidation and $NaBH_4$ reduction of aldehydes (Fig. 1).

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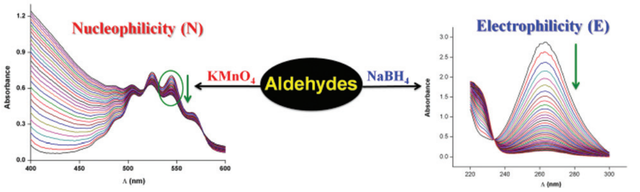

Fig. 1 Electrophilicity (*E*) and nucleophilicity (*N*) from the $KMnO_4$ oxidation and $NaBH_4$ reduction of aldehydes.

Results and discussion

In this study, the aldehyde functional group was chosen as a model system as its reactivity lies between its reduction product (alcohol) and oxidation product (carboxylic acid) so that it can gain or lose electrons from a reducing or oxidizing agent, respectively. In order to determine the nucleophilicity, the $KMnO_4$ promoted oxidation of various aldehydes was chosen as a model reaction. The progress of the $KMnO_4$ promoted oxidation of various aldehydes was monitored by UV-Vis spectroscopy. The progress of the oxidation reaction was determined from the steady decrease in all four absorbance maxima at specific wavelengths (506, 525, 545, and 566 nm) (Fig. 1). All of the kinetic studies of the $KMnO_4$ promoted oxidation reaction of the aldehydes were performed by monitoring the steady decrease of the absorbance at 545 nm at different time intervals. The nucleophilicity (*N*) of a particular aldehyde was assessed from the pseudo first order rate constant ($\log k$) at 25 °C. Furthermore, to elucidate the mechanism of the oxidation of the aldehyde, Hammett analysis and activation parameter calculations were also performed. Hammett analysis of the oxidation reaction led to a small negative ρ-value (reaction constant = -0.87) (see Fig. S1 in ESI-1†), which indicates the generation of a small positive charge at the aldehyde carbon centre in the transition state (TS).[12] The detailed mode of action of potassium permanganate in neutral solution has been studied previously by Wiberg *et al.*[13] By using isotopic labeling, they showed that the oxidizing agent appears to be the source of the oxygen introduced into the aldehyde. Further evidence from their experiments also suggested that the reaction in neutral solution probably involves the formation of a permanganate ester of the hydrate of the aldehyde, followed by a rate-determining loss of the aldehyde hydrogen. To understand the mechanism of the $KMnO_4$ oxidation of the aldehydes in neutral solution, and also to validate the experimentally observed nucleophilicity of various aldehydes, a transition state (TS) model has been analyzed (Fig. 2).

Geometries of all TSs and intermediates were optimized using the Gaussian 03 suite of quantum chemical programs.[24] Effective core potentials (ECPs) along with valence basis sets (LANL2DZ) were used for manganese, while for other atoms a 6-311+G** basis set was used. The nucleophilic attack of MnO_4^- on the aldehyde carbon leads to the formation of a permanganate ester (*Int.*) intermediate. Improved proximity between the aldehyde C–H bond and the oxygen center in *Int.* would facilitate the transfer of hydrogen towards the oxygen centre. Therefore, the rate determining step involved the cleavage of the aldehyde C–H bond. The overall process involved the transfer of hydrogen from the aldehyde carbon to oxygen with the breaking of the O–Mn bond in the transition state (TS). The optimized transition state and the intermediate geometries, along with some of the important bond lengths for the $KMnO_4$ promoted oxidation of benzaldehyde, have been provided in Fig. 2. The relative enthalpies of formation of the permanganate ester (*Int.*) intermediates for six *para* substituted aldehydes were determined (Fig. 3) using the benz-

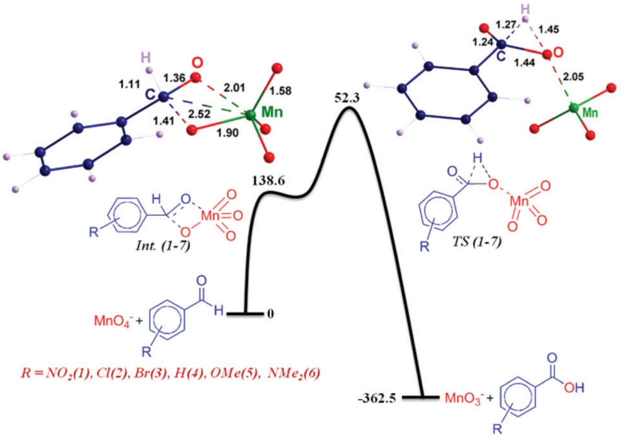

Fig. 2 Gibbs free energy profile (in kJ mol^{-1}) for the $KMnO_4$ promoted oxidation of benzaldehyde to benzoic acid.

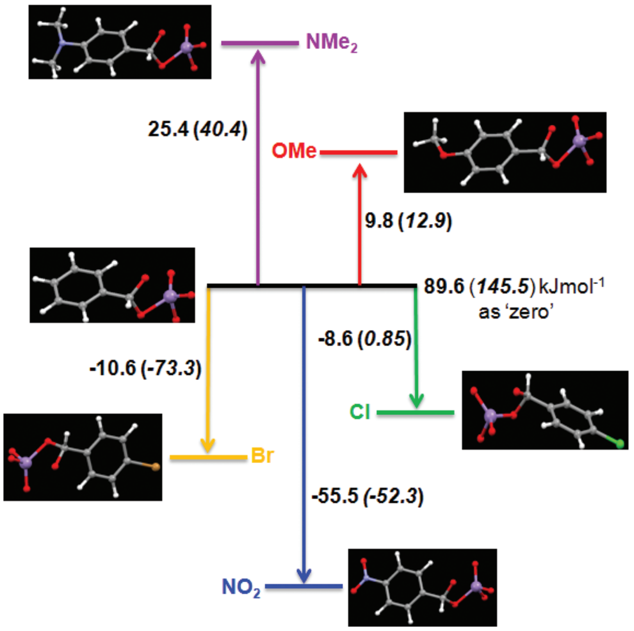

Fig. 3 Relative enthalpies of formation plotted for the permanganate ester intermediates of six different *para* substituted aldehydes in the gas phase and in acetonitrile (in parentheses).

aldehyde intermediate as a reference (89.6 kJ mol^{-1} as 0 kJ mol^{-1}).

The plot shows the facile formation of the permanganate ester (*Int.*) intermediate using the electron withdrawing aldehyde compared to the electron rich aldehyde because of the slightly greater positive charge at the aldehyde centre in the electron withdrawing aldehyde, which will facilitate the attack of MnO_4^- (Fig. 3). The effect of solvent on the TS and intermediate in the $KMnO_4$ promoted oxidation reaction was included using a single point energy calculation in a polarized continuum model (PCM) with acetonitrile as a solvent in same level of theory.[14] Furthermore, to determine the experimental activation parameters of the oxidation reaction, the reaction kinetics of the $KMnO_4$ promoted oxidation of five different *para* substituted benzaldehydes were studied at six different temperatures ranging from 2 to 60 °C.[15,16] The experimental enthalpies of formation followed the order Cl < Br < H < OMe < NMe_2, which correlates well with theoretical results (Table 1).

However, the free energy of activation for the rate determining step is governed by entropy. As is also evident from the Hammett reaction constants, the generation of a slight positive charge at the aldehyde carbon in the TS will occur, which will be stabilized by electron donating substituents. During the rate determining C–H bond loss, the electron density at the oxygen centre will determine the transfer of hydrogen and breaking of the O–Mn bond. Therefore, one would expect a lower transition state (TS) barrier in the case of the electron rich aldehyde, since the electron-donating group could facilitate the overall bond making and breaking process. The computed free energy of activation barriers between the intermediates and TSs of electron rich aldehydes were found to be lower than those of electron deficient aldehydes (Table 2). The experimental free energies of activation ($\Delta G^{\#}$) at 298 K follow the order NMe_2 < OMe < H < Br < Cl, indicative of a more favorable reaction for electron rich aldehydes over electron deficient ones, which is in agreement with the trend in the nucleophilicity of the aldehydes, as well as the computed TSs.

Nucleophilicity Electrophilicity

$$N = \frac{(3I-A)^2}{8(I-A)} \longleftarrow \text{MI} \longrightarrow E = \frac{(I+A)^2}{8(I-A)}$$

$$N = \frac{I^2}{2(I-A)} \longleftarrow \text{MII} \longrightarrow E = \frac{A^2}{2(I-A)}$$

$$N = \frac{(3I+A)^2}{16(I-A)} \longleftarrow \text{MIII} \longrightarrow E = \frac{(I+3A)^2}{16(I-A)}$$

$$\eta = (I-A) \approx E_{HOMO} - E_{LUMO}, \mu = \frac{(I+A)}{2} \approx \frac{(E_{HOMO}+E_{LUMO})}{2}$$

Scheme 1 Equations used to obtain the theoretical *N* and *E* values.

In order to further investigate the relationship between aldehyde nucleophilicity and its theoretical nucleophilicity parameter, various aldehydes have been fully optimized without any symmetry constraints at the B3LYP/6-311+G** level of theory. Three different methods (MI–MIII) using three different sets of equations (Scheme 1)[8,9] have been utilized to evaluate theoretical nucleophilicities and electrophilicities. To check the validity of the observed nucleophilicity data obtained from the three different methods, *para* substituted benzaldehydes were chosen as a test series, and the corresponding calculated *N* values were plotted against the experimental *N* values (Fig. 4). The correlation between the experimental and calculated *N* values obtained using Method I (MI) and II (MII) have been found to be slightly better than MIII. Further correlation between the theoretical *N* values *versus* Hammett substituent constant (σ_p) also suggested the superiority of MI and MIII over MII (Fig. 5). The experimental nucleophilicity was also studied using various mono, di, and hetero aldehydes (please see Fig. S5 in ESI-1†).[18] The nucleophilicity of

Table 1 Activation parameters for the $KMnO_4$ oxidation of five different *para* substituted benzaldehydes

	Cl	Br	H	OMe	NMe_2
$\Delta H^{\#}$ (kJ mol^{-1})	9.1	9.3	11.4	13.6	20.7
$\Delta S^{\#}$ (J K^{-1} mol^{-1})	−276	−274	−265	−254	−219
$\Delta G^{\#}_{298}$ (kJ mol^{-1})	91.1	90.9	90.4	89.3	86.1

Table 2 Computed Gibbs free energies (in kJ mol^{-1}) for important transition states involved in the $KMnO_4$ oxidation of *para* substituted benzaldehydes

Transition state	NO_2 (1)	Cl (2)	Br (3)	H (4)	OMe (5)	NMe_2 (6)
$\Delta G^{\#}$ (kJ mol^{-1})	56.8	53.2	52.1	52.3	52.1	48.0
$\Delta G^{\#}$ (kJ mol^{-1}) in MeCN	n.d.	38.2	n.d.	31.4	25.7	11.6

n.d. = not detected.[17]

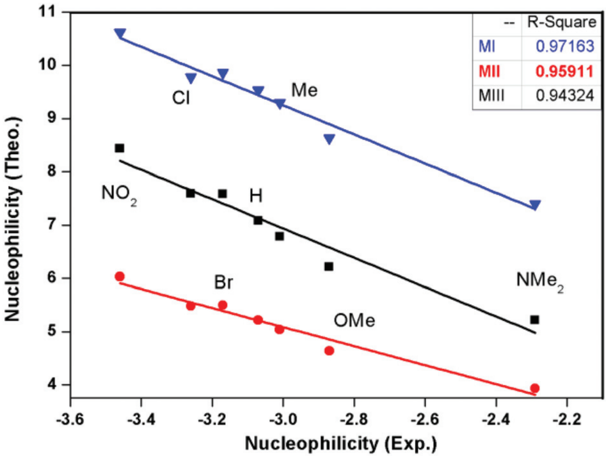

Fig. 4 Plot of theoretical *versus* experimental nucleophilicity for various *para* substituted benzaldehydes obtained using three different methods.

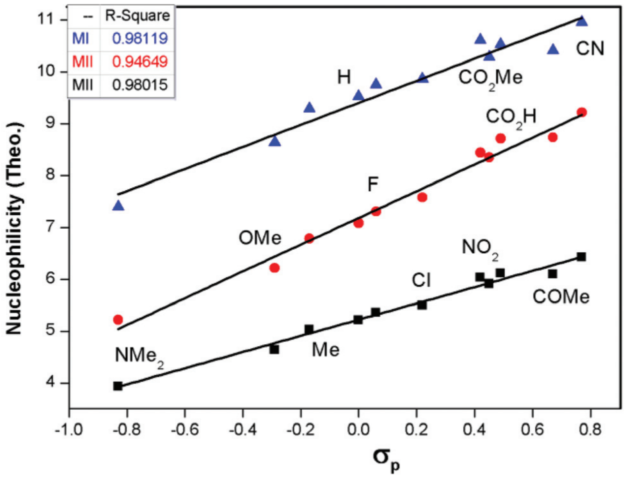

Fig. 5 Nucleophilicity (N) *versus* σ_p plot for different *para* substituted benzaldehydes using all three methods.

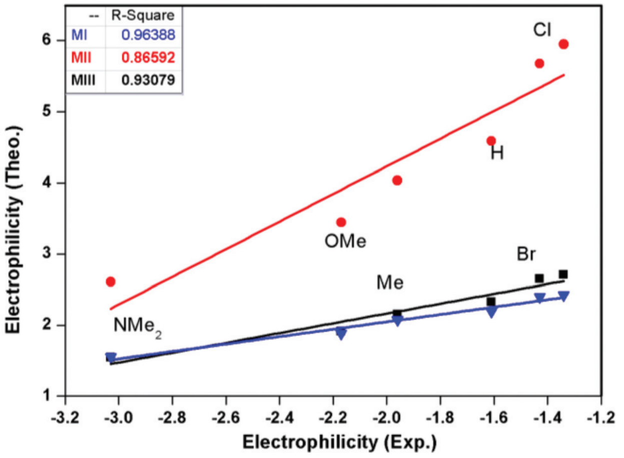

Fig. 6 Plot of the theoretical *versus* experimental electrophilicities of various *para* substituted benzaldehydes obtained using three different methods.

the aldehydes was studied in acetonitrile solvent using a single point energy calculation and a PCM model. When the calculated N values for the aldehydes in acetonitrile were plotted against the experimental N values, MI was found to be superior over MII and MIII (Fig. S3 in ESI-1†).

On the other hand, the electrophilicity of an aldehyde is directly related to its reducing properties. As in the case of the $NaBH_4$ reduction of aldehydes to alcohols, the reaction rate directly depends on the ability to accept electrons in the form of a hydride nucleophile. Therefore, to obtain E values for the aldehydes, pseudo first order rate constants (k) have been measured for the $NaBH_4$ reduction of different *ortho*, *meta*, and *para* substituted benzaldehydes at 25 °C.[19] The log(k) value of the corresponding aldehyde has been assigned as its electrophilicity. Hammett analysis of the $NaBH_4$ reduction of aldehydes resulted in a positive ρ-value (reaction constant = 1.58), suggesting a small negative charge in the transition state (TS).[20,23] Furthermore, the activation parameter for the $NaBH_4$ reduction of five different *para* substituted benzaldehydes has been determined from the reaction kinetics at 4 different temperatures, ranging from 2 to 25 °C.[21] The activation parameters for the $NaBH_4$ reduction have been given in Table 3. The more positive $\Delta S^{\#}$ and lower $\Delta G^{\#}$ values for the electron deficient aldehydes compared to the electron rich aldehydes implied the higher reducibility of the former towards $NaBH_4$. In order to determine the relationship between experimental electrophilicity and the corresponding calculated electrophilicity, a computational analysis of various aldehydes has been performed at the B3LYP/6-311+G** level of theory. The electrophilicity of the aldehydes was studied using three methods. Interestingly, a good correlation was obtained between the theoretical and experimental electrophilicities of all the *ortho*, *meta*, and *para* substituted aldehydes (please see Fig. S6 in ESI-1†). However, in terms of the correlation coefficient (R^2 value), the *para* substituted benzaldehydes showed better results than all of the other aldehydes. The plot in Fig. 6 shows the superiority of MI compared to MIII and MII. Furthermore, to check the validity of the three methods, calculated E values of different *para* substituted benzaldehydes have been plotted against their corresponding σ_p value. When judged in terms of the correlation coefficient (R^2 value), MI gave a better correlation between the calculated electrophilicity values *versus* σ_p values than MIII and MII (Fig. 7).

Thus, method I (MI) appears to be superior to MII and MIII for both the E and N value calculations.[22] Therefore, MI has been chosen as a model for further calculation of N and E

Table 3 Activation parameters for the $NaBH_4$ reduction of five different *para* substituted benzaldehydes

	NMe$_2$	OMe	H	Br	Cl
$\Delta H^{\#}$ (kJ mol^{-1})	8.9	19.9	16.8	17.0	19.6
$\Delta S^{\#}$ (J K^{-1} mol^{-1})	−272	−219	−219	−214	−204
$\Delta G^{\#}_{298}$ (kJ mol^{-1})	90.2	85.4	82.2	80.9	80.6

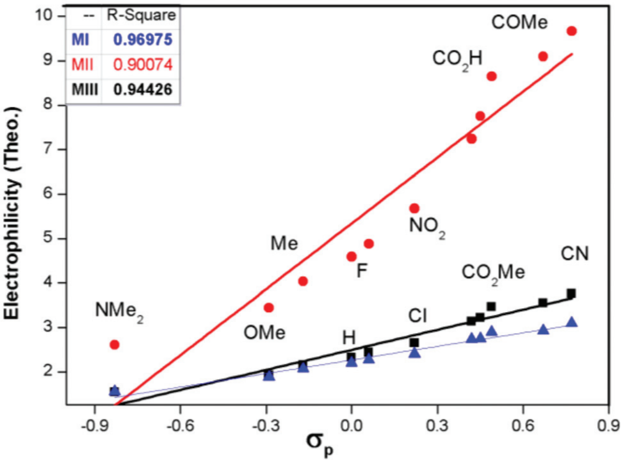

Fig. 7 Electrophilicity *versus* σ_p plot for different *para* substituted benzaldehydes using all three methods.

values for various aldehydes. The two equations,[24] derived from the experimental *versus* theoretical plots (Fig. 4 and 6) were used for the determination of experimental N and E values for various substituted aldehydes (Table 4).[25] The electrophilicity of a molecule dictates its inherent electron accepting character. However, there is also an inherent electron donating character present in a molecule. During E or N value calculation for a molecule, we often considered only one of the parameters in isolation, which is not the actual E or N of the molecule. Therefore, the net electrophilicity (the electrophilicity of a system relative to its own nucleophilicity) would be a better descriptor to explain the electrophilic power of an aldehyde. Finally, the net electrophilicity of a particular aldehyde has been derived from the difference between its E and N values, which will be very useful to predict the actual electron withdrawing capacity of the aldehyde. The N, E, and net E values of various aldehydes are shown in Table 4, which offer an at-a-glance assessment of the chemical reactivity of various aldehydes.

Experimental section

Materials and instruments

Double distilled water was used throughout the experiments. The degassing of oxygen from water and acetonitrile was performed by bubbling argon for 30 minutes. Acetonitrile, the aldehydes, and $KMnO_4$ were of AR grade. All of the reagents were used without further purification. All UV-visible absorption spectra were recorded in a double beam digital spectrophotometer equipped with a chiller.

UV-vis study for the $KMnO_4$ oxidation of aldehydes

First, an aqueous homogeneous solution of $KMnO_4$ (2×10^{-4} M) in double distilled oxygen free water was prepared for the study. Separately, 5 ml of an aldehyde stock solution (2×10^{-1} M) was prepared in pre-distilled oxygen free acetonitrile. Then, 200 μL of the aldehyde solution was mixed with a $KMnO_4$ solution (4×10^{-4} M) in a UV-cuvette and the progress of the reaction was recorded. The progress of the reaction was followed by the steady decrease of all four absorbance maxima at specific wavelengths (506, 525, 545, and 566 nm) (Fig. 1). All of the rate measurements for the $KMnO_4$ oxidation of the aldehydes were performed using a time scan option at a fixed absorbance (the 545 nm band of $KMnO_4$).

UV-vis study for the $NaBH_4$ reduction of aldehydes

For the monitoring of the reduction kinetics of the aldehydes, an $NaBH_4$ solution (20 M) in double distilled oxygen free water was prepared. The aqueous $NaBH_4$ solution was admixed with 100 μL of a distilled oxygen free acetonitrile stock solution (2×10^{-1} M) of the corresponding aldehyde. All of the rate measurements for the $NaBH_4$ reduction of the aldehydes were performed using a time scan option at a fixed absorbance band of a particular aldehyde.

Theoretical background

The global reactivity descriptors are defined for the system as a whole. Recently, electrophilicity has been defined by Parr *et al.*[7a] as the energy of stabilization of a chemical species when it attains an additional fraction of electronic charge from the environment. The global electrophilicity index ω is defined as $\omega = \mu^2/2\eta$ where μ is the electronic chemical potential[26] and η is the chemical hardness.[27] In an important contribution, Gazquez *et al.*[9] have defined the *electrodonating power* (ω^-) as

$$\omega^- = \frac{I^2}{2(I-A)} \text{ and } \omega^- = \frac{(3I+A)^2}{16(I-A)} \tag{1}$$

Note that according to this definition, a smaller value of ω^- signifies a better electron donor. In the present work, nucleophilicity has been defined as the inverse of the electrodonating power ($10/\omega^-$) in order to equate with the general notion that "*more is better*". They also defined the *electroaccepting power* (ω^+) as

$$\omega^+ = \frac{A^2}{2(I-A)} \text{ and } \omega^+ = \frac{(I+3A)^2}{16(I-A)} \tag{2}$$

Later on, Ayers *et al.* introduced two sets of equations derived from the IP and EA for both the electrophilicity and nucleophilicity as[8]

$$N = \frac{(3I-A)^2}{8(I-A)} \text{ and } E = \frac{(I+A)^2}{8(I-A)} \tag{3}$$

The electronic chemical potential and the chemical hardness have to be known for the calculation of the electrophilicity (E) and nucleophilicity (N) index. The electronic chemical potential is the negative of the electronegativity χ, defined for an N-electron system with external potential $v(r)$ and total energy E as the partial derivative of the energy to the number of electrons at constant external potential and in absence of a magnetic field:[28]

$$\mu = -\chi = \left(\frac{\partial E}{\partial N}\right)_{v(r)} \approx -\frac{I+A}{2} \tag{4}$$

where I and A are the vertical ionization energy and electron affinity, respectively. These two quantities were calculated in the Gaussian 03 program[29] using the B3LYP methods and the 6-311+G** basis set. Hardness is defined as the corresponding second derivative as proposed by Parr and Pearson.[28]

$$\eta = \frac{1}{2}\left(\frac{\partial^2 E}{\partial N^2}\right)_{v(r)} \approx (I-A) \tag{5}$$

It is now common to exclude the factor 1/2 in the above definition. In this paper we calculated the chemical hardness as the difference between the vertical ionization energy I and the electron affinity A, where $I = E_{\text{HOMO}}$ = ionization potential (IP) and $A = E_{\text{LUMO}}$ = electron affinity (EA).

Table 4 Experimental and theoretical nucleophilicity (*N*), electrophilicity (*E*), and net *E* values of various aldehydes from kinetic and theoretical analysis

	Theoretical[a]		Experimental		
Compound	*E*	*N*[b]	*N*[c]	*E*[d]	Net *E*
2-Nitro benzaldehyde	3.76	11.42	−3.80	1.28	5.09
3-Nitro benzaldehyde	3.44	11.35	−3.78	0.67	4.45
4-Cyano benzaldehyde	3.09	10.96	−3.63	0.01	3.64
4-Chloroisophthalaldehyde	2.99	10.68	−3.53	−0.20	3.33
2-Formyl benzonitrile	2.91	10.67	−3.53	−0.35	3.18
Phthalaldehyde	2.95	10.41	−3.43	−0.26	3.17
4-Acetyl benzaldehyde	2.93	10.41	−3.43	−0.31	3.12
4-Formyl benzoic acid	2.90	10.53	−3.47	−0.37	3.10
3,4-Dichloropicolinaldehyde	2.87	10.62	−3.51	−0.43	3.08
Ethylglyoxalate	2.85	10.58	−3.49	−0.46	3.03
5-Nitro-1*H*-indole-3-carbaldehyde	2.96	9.97	−3.27	−0.25	3.02
3-Formyl benzonitrile	2.77	10.62	−3.51	−0.61	2.90
4-Trifluoromethyl benzaldehyde	2.77	10.52	−3.47	−0.62	2.85
4-Nitro benzaldehyde	2.73	10.61	−3.51	−0.69	2.82
2,4,5-Trifluorobenzaldehyde	2.74	10.51	−3.47	−0.68	2.79
4-Chloronicotinaldehyde	2.77	10.30	−3.39	−0.62	2.78
Methyl-4-formylbenzoate	2.74	10.28	−3.39	−0.67	2.72
4-Chloropicolinaldehyde	2.72	10.35	−3.41	−0.72	2.70
Isophthalaldehyde	2.72	10.29	−3.39	−0.72	2.67
2,3-Dichlorobenzaldehyde	2.66	10.14	−3.33	−0.82	2.51
4-Chlorofuran-2-carbaldehyde	2.63	9.90	−3.24	−0.88	2.36
3-Acetyl benzaldehyde	2.61	10.02	−3.29	−0.93	2.36
3-Formyl benzoic acid	2.58	10.15	−3.34	−0.99	2.35
2,6-Dichlorobenzaldehyde	2.60	9.89	−3.24	−0.93	2.31
2-Formyl benzoic acid	2.60	9.87	−3.24	−0.95	2.29
3-Phenyl propynal	2.60	9.78	−3.20	−0.95	2.25
2-Acetyl benzaldehyde	2.52	9.64	−3.15	−1.10	2.05
Methyl-3-formylbenzoate	2.46	9.95	−3.26	−1.22	2.05
3-Chloro benzaldehyde	2.46	9.89	−3.24	−1.21	2.03
2-Chloro aldehyde	2.45	9.91	−3.25	−1.23	2.02
Cinnamaldehyde	2.53	9.48	−3.09	−1.08	2.01
3-Fluoro benzaldehyde	2.43	9.98	−3.27	−1.26	2.01
3-Bromo benzaldehyde	2.46	9.78	−3.20	−1.20	2.00
2-Bromo benzaldehyde	2.46	9.82	−3.21	−1.22	2.00
Picolinaldehyde	2.45	9.83	−3.22	−1.23	1.99
4-Bromo benzaldehyde	2.42	9.78	−3.20	−1.28	1.92
2-Fluoro benzaldehyde	2.40	9.87	−3.24	−1.33	1.91
4-Chloro benzaldehyde	2.40	9.86	−3.23	−1.33	1.90
Methyl-2-formylbenzoate	2.43	9.61	−3.14	−1.27	1.86
Thiophene-2-carbaldehyde	2.33	9.57	−3.13	−1.46	1.67
Biphenyl-4-carbaldehyde	2.40	9.07	−2.94	−1.32	1.62
4-Fluoro benzaldehyde	2.27	9.76	−3.19	−1.57	1.62
Biphenyl-2-carbaldehyde	2.40	9.06	−2.94	−1.33	1.61
2-(Thiophen-3-yl) benzaldehyde	2.42	8.97	−2.91	−1.30	1.61
Benzaldehyde	2.19	9.53	−3.11	−1.73	1.38
2-Naphthaldehyde	2.29	8.90	−2.88	−1.54	1.34
2-Methyl benzaldehyde	2.18	9.39	−3.06	−1.75	1.31
Furan-2-carbaldehyde	2.17	9.38	−3.05	−1.77	1.28
2-Chloro-3,4-dihydroxybenzaldehyde	2.23	8.97	−2.90	−1.65	1.25
3-Methyl benzaldehyde	2.12	9.33	−3.04	−1.87	1.17
3-Hydroxy benzaldehyde	2.17	9.03	−2.93	−1.76	1.16
4-*Tert*-butyl-2-hydroxybenzaldehyde	2.17	8.97	−2.91	−1.76	1.14
4-Methyl benzaldehyde	2.07	9.30	−3.02	−1.96	1.07
4-Ethyl benzaldehyde	2.07	9.28	−3.02	−1.97	1.05
4-Propyl benzaldehyde	2.05	9.26	−3.01	−1.99	1.02
4-Formylphenylboronic acid	2.05	9.23	−3.00	−2.00	1.00
Thiophene-3-carbaldehyde	2.02	9.33	−3.04	−2.07	0.97
3-Chloro-4-hydroxy-5-methoxybenzaldehyde	2.08	8.66	−2.79	−1.93	0.86
3-Methoxy benzaldehyde	2.07	8.74	−2.82	−1.97	0.85
2-Methoxy benzaldehyde	2.04	8.72	−2.81	−2.02	0.79
Formaldehyde	1.87	9.54	−3.11	−2.34	0.77
2-(Naphthalen-2-yl)benzaldehyde	2.13	8.10	−2.59	−1.85	0.74
4-Mercapto benzaldehyde	2.06	8.43	−2.71	−1.99	0.72
4-Hydroxy benzaldehyde	1.97	8.90	−2.88	−2.16	0.72
Furan-3-carbaldehyde	1.90	9.14	−2.97	−2.29	0.68
3,4-Dihydroxybenzaldehyde	1.97	8.50	−2.73	−2.15	0.58
3-Amino benzaldehyde	2.00	8.23	−2.63	−2.10	0.53

Table 4 *(Contd.)*

	Theoretical[a]		Experimental		
Compound	*E*	*N*[b]	*N*[c]	*E*[d]	Net *E*
3,4,5-Trimethoxybenzaldehyde	1.97	8.25	−2.64	−2.14	0.50
4-Methoxy benzaldehyde	1.88	8.63	−2.78	−2.33	0.45
5-Chloro-1*H*-indole-3-carbaldehyde	1.87	8.46	−2.72	−2.34	0.37
4-Hydroxy-3-methoxybenzaldehyde	1.86	8.20	−2.62	−2.36	0.26
3-(Dimethylamino) benzaldehyde	1.86	7.63	−2.42	−2.36	0.05
Phenyl acetaldehyde	1.64	8.77	−2.83	−2.79	0.04
4-Amino benzaldehyde	1.71	7.99	−2.55	−2.65	−0.11
Acetaldehyde	1.54	8.88	−2.87	−2.98	−0.11
3-Phenyl propanal	1.55	8.56	−2.75	−2.95	−0.20
2-(Dimethylamino) benzaldehyde	1.73	7.57	−2.39	−2.61	−0.22
Heptanal	1.46	8.65	−2.79	−3.13	−0.34
4-(Dimethylamino) benzaldehyde	1.55	7.40	−2.33	−2.95	−0.62

[a] Theoretical calculation performed at the B3LYP/6-311+G** level of theory in the gas phase. [b] The more positive *N* value indicates less electron donating ability. [c] For nucleophilicity (*N*), N (Theo.) = $-2.73 \times N$ (Exp.) + 1.04 has been used. [d] For electrophilicity (*E*), E (Theo.) = $0.52 \times E$ (Exp.) + 3.09 has been used.

Conclusions

In summary, the nucleophilicity (*N*) and electrophilicity (*E*) of various aldehydes have been determined from the kinetics of two simple reactions; namely, the $KMnO_4$ oxidation and $NaBH_4$ reduction reactions of aldehydes. The validity of the experimental method has been checked using the activation parameters of the two reactions. The mechanism of the $KMnO_4$ oxidation of the aldehydes has been studied with the help of transition state analysis. Furthermore, theoretical *N* and *E* values of various aldehydes have been calculated at the B3LYP/6-311+G** level of theory with three different equations. The validity of the methods was evaluated from the linear relationship between the experimental *versus* theoretical plots, and theoretical *versus* σ_p plots for different *para* substituted benzaldehydes. Finally, *N*, *E*, and net *E* values for a variety of aldehydes have been evaluated, which offer an at-a-glance assessment of the chemical reactivity of various aldehydes. The concept can be applied further to determine the nucleophilic and electrophilic power of molecules like ketones and alkenes *etc.*, with reactivities that lie between their oxidation and reduction products.

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22 It should be noted that while Method I (MI) has been successfully utilized for this set of molecules, providing good correlation between the experimental and computed results, other methods can also be equally useful to rationalize the reactivity for other sets of molecules.

23 Both E and N values of all the aldehydes have been calculated in acetonitrile solvent using a PCM model. The N and E values are given in Table S8 in ESI-1†

24 The two equations E (Theo.) = $0.52 \times E$ (Exp.) + 3.09 and N (Theo.) = $-2.73 \times N$ (Exp.) + 1.04 from the theoretical *versus* experimental plots have been utilized for the calculation of N, E and net E values for the aldehydes.

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