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Electrophilicity ω and Nucleophilicity *N* Scales for Cationic and Anionic Species

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Limits of the electrophilicity ω and nucleophilicity *N* scales in DMSO					
	ω			*N*	
	Lower	Upper	Super	Lower	Upper	Super
B3LYP/6-31G(d)	0.85	1.45	3.62	1.61	2.49	3.36
B3LYP/6-311G(d,p)	1.01	1.63	3.84	1.62	2.49	3.37
MPWB1K/6-311G(d,p)	0.75	1.19	2.77	1.66	2.56	3.46
M06-2X/6-311G(d,p)	0.78	1.20	2.68	1.64	2.53	3.41
ωB97-D/6-311G(d,p)	0.62	0.96	2.17	1.58	2.46	3.34

Abstract: The reference electrophilicity ω and nucleophilicity *N* scales for neutral molecules established at the B3LYP/6-31G(d) level in vacuo are herein extended by least squares regressions to cationic and anionic species at the B3LYP/6-31G(d), B3LYP/6-311G(d,p), MPWB1K/6-311G(d,p), M06-2X/6-311G(d,p) and ωB97x-D/6-311G(d,p) levels in DMSO. Excellent linear correlations with coefficients of determination R^2 values of 0.99 are obtained for a series of neutral molecules of different electrophilic/nucleophilic character. In this work, the new lower, upper and superior limits of the electrophilicity ω and nucleophilicity *N* scales are established, enabling the direct classification and quantification of the electrophilic and nucleophilic character of cationic and anionic species

Introduction

Organic reactions are classified as non-polar and polar reactions. Most of the organic reactions exhibit some degree of polar character. The concept of polar reactions in Organic Chemistry was developed at the beginning of the past century. The polar character of the reactions depends on the electrophilicity and the nucleophilicity of the reagents. The electrophile and nucleophile concepts were introduced by K. Ingold, [1] who replaced the terms '*anionoid*' and '*cationoid*' proposed earlier by A. J. Lapworth in 1925.[2] Ingold proposed the nucleophilic (nucleus-seeking) and electrophilic (electron-seeking) species as a generalization of the concepts of bases and acids, defined by Lewis as species whose neutralization involves the donation or acceptance of an electron-pair. However, while nucleophilicity and electrophilicity emphasize the kinetic aspects of reactivity, Lewis's basicity and acidity emphasize the thermodynamic aspects of Lewis adduct formation.

In order to describe the electronic structure of matter in terms of the only physical observable of chemical compounds, namely electron density, Hohenberg and Kohn developed in 1964 the quantum-chemical framework known as Density Functional Theory (DFT),[3] in which the ground-state energy in a given external potential is obtained as a functional of the electron density:

$$E[\rho(\boldsymbol{r})] = \int \rho(\boldsymbol{r})v(\boldsymbol{r})d\boldsymbol{r} + F[\rho(\boldsymbol{r})] \tag{1}$$

Parallel to the development of quantum-chemical models to approach the Hohenberg-Kohn equation (1), Parr and his co-workers developed in the late 1970s and early 1980s the Conceptual Density Functional Theory (CDFT),[4] in which the mathematical framework of DFT is used to provide a quantitative measure for classical reactivity concepts that were established from experimental observations.

CDFT relies on the fact that the ground state energy of an N-electron system can be considered as depending upon the number of electrons N and the external potential $v(\mathbf{r})$, in other words $E[\rho(\mathbf{r})] = E[N;v(\mathbf{r})]$. Thus, the n-th order derivatives of the energy with respect to N and $v(\mathbf{r})$ provide a series of CDFT reactivity indicators. Although many scientists within CDFT have developed a wide number of indices, only three have shown to be useful for experimental organic chemist,[5] namely the electronic chemical potential, μ,[6] which is the

opposite of Mulliken electronegativity, $-\chi$, the chemical hardness, η,[7] which is the inverse of the softness, S, and the electrophilicity ω index [8] (see Computational Methods for their mathematical definition). Later, in 2008, the empirical nucleophilicity N index was proposed.[9] Both, the electrophilicity ω and the nucleophilicity N indices are widely used today in the study of chemical reactivity in Organic Chemistry.[5,10,11]

In 2002, a comprehensive study on the electrophilic character of a series of common reagents participating in experimental Diels-Alder (DA) reactions allowed the establishment of a single electrophilicity ω scale at the B3LYP/6-31G(d) level,[12] which classified organic molecules into strong electrophiles, with $\omega \geq 1.5$ eV, moderate electrophiles, with $0.8 \leq \omega < 1.5$ eV, and marginal electrophiles, with $\omega < 0.8$ eV (see Table 1). Only strong electrophiles work experimentally, as moderate electrophiles require the participation of strong nucleophiles.[11] Afterwards, in 2005, the definition of superelectrophiles was established for species with $\omega \geq 4.0$ eV.[10]

Table 1. Classification of common reagents involved in DA reactions depending on their B3LYP/6-31G(d) electrophilicity ω indices, in eV.

| Molecules	ω
Strong electrophiles	
$CH_2=N^+(CH_3)_2$	8.25
$(CN)_2C=C(CN)_2$	5.96
$CH_2=CHCHO:BH_3$	3.20
$CH_2=C(CN)_2$	2.82
$CH_2=CHNO_2$	2.61
$CH_2=CHCHO$	1.84
$CH=CHCN$	1.74
$CH_2=CHCOCH_3$	1.65
$CH=CHCO_2CH_3$	1.51
Moderate electrophiles	
$CH_2=CH-CH=CH_2$	1.05
$CH_2=CH(CH_3)-CH=CH_2$	0.94
Cyclopentadiene (C_5H_6)	0.83
Marginal electrophiles	
$CH_3O-CH=CH-CH=CH_2$	0.77
$CH_2=CH_2$	0.73
$(CH_3)_2N-CH=CH-CH_2=CH_2$	0.57
$CH\equiv CH$	0.54
$CH_2=CHOCH_3$	0.42
$CH_2=CHN(CH_3)_2$	0.27

Later, in 2008, the analysis of a series of common nucleophilic species participating in polar organic reactions allowed to establish a further classification of organic molecules as strong nucleophiles, with $N \geq 3.0$ eV, moderate nucleophiles, with $2.0 \leq N < 3.0$ eV, and

marginal nucleophiles, with $N < 2.0$ eV, at the same B3LYP/6-31G(d) level (see Table 2).[13] Recently, supernucleophiles were defined as having $N \geq 4.0$ eV.[10]

Table 2. Classification of common reagents involved in DA reactions depending on their B3LYP/6-31G(d) nucleophilicity N indices, in eV.

Molecules	N
Strong nucleophiles	
$CH_2=CHN(CH_3)_2$	4.28
$C_6H_5NH_2$	3.72
NH_2NH_2	3.65
$CH_2=C(OCH_3)_2$	3.51
$N(CH_3)_3$	3.48
$(CH_3)_2C=C(CH_3)_2$	3.35
$NH(CH_3)_2$	3.26
C_6H_5OH	3.16
NH_2CH_3	3.03
Moderate nucleophiles	
$CH_2=CH-CH=CH_2$	2.98
$C_6H_5CH_3$	2.71
$CH_2=C(CH_3)_2$	2.60
$CH_3C\equiv CCH_3$	2.57
C_6H_6	2.42
H_2O_2	2.41
$C_6H_5COCH_3$	2.39
$CH_2=CHCH_3$	2.32
NH_3	2.25
NH_2OH	2.19
C_6H_5CHO	2.17
$C_6H_5CO_2H$	2.03
Marginal nucleophiles	
CH_3OH	1.92
$CH_2=CH_2$	1.86
$C_6H_5NO_2$	1.53
H_2O	1.20

In 2021, the intramolecular ionic Diels-Alder reactions of iminium cations **I** and **II** were studied within the Molecular Electron Density Theory[14] (MEDT) (see Scheme 1).[15]

I R_1=Me, R_2=Prop
II R_1=R_2=H
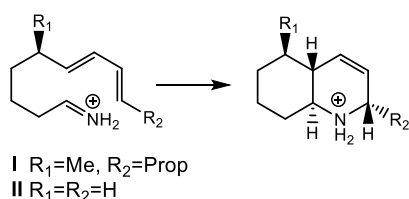
Scheme 1. Intramolecular ionic Diels-Alder reactions of dieniminiums **I** and **II**

The analysis of the electrophilicity ω index of the iminium cations **I** and **II** showed very high values, higher than 25.00 eV. (see Table 3).

Table 3. B3LYP/6-31G(d) electronic chemical potential μ, chemical hardness η, and electrophilicity ω and nucleophilicity N indices, in eV, of the iminium cations **I** and **II**.

	μ	η	ω	N
I	-7.39	1.02	26.72	1.22
II	-7.65	1.16	25.19	0.89

On the other hand, bimolecular nucleophilic substitution reactions on monosubstituted methyl compounds have recently been studied within MEDT.[16] Standard B3LYP/6-31G(d) reactivity indices of cationic species presented high electrophilicity ω values, while those of anionic species presented also high nucleophilic N values. However, when the reactivity indices were computed at the ωB97X-D/6-311+G(d,p) level in dimethyl sulfoxide (DMSO), the electrophilicity ω and nucleophilic N indices of these ionic species decreased markedly (see the corresponding values in DMSO and in vacuo given in Table 4).

Table 4. ωB97X-D/6-311+G(d,p) electronic chemical potential μ, chemical hardness η, and electrophilicity ω and nucleophilicity N indices, in eV, for the two carbocations and three halide anions in DMSO. In vacuo values are given in parenthesis.

	μ	η	ω	N
CH_3^+	-10.97	13.05	4.61 (11.37)	-6.41 (-12.19)
$C(CH_3)_3^+$	-7.78	11.63	2.61 (6.76)	-2.52 (-6.73)
Br^-	-3.28	10.39	0.52 (0.17)	2.61 (8.56)
Cl^-	-3.11	11.58	0.42 (0.29)	2.18 (8.55)
F^-	-1.46	15.53	0.07 (1.06)	1.86 (9.53)

Very recently, good linear correlations between the electrophilicity ω and nucleophilicity N indices at different DFT computational levels with respect to the standard B3LYP/6-31G(d) ones were found.[17] This behavior facilitated the establishment of the electrophilicity ω and nucleophilicity N scales at DFT levels commonly used today.[17] The corresponding linear regression equations enabled the definition of the lower, upper and superior limits of the new electrophilicity ω and nucleophilicity N scales.

Due to the relevance of superelectrophilic cationic species, and the supernucleophilic anionic species, electrophilicity ω and nucleophilicity N scales involving ionic species are established here at the B3LYP/6-31G(d), B3LYP/6-311G(d,p) MPWB1K/6-311G(d,p), M06-2X/6-311G(d,p) and ωB97X-D/6-311G(d,p) level in DMSO. To this end, the linear correlations between the electrophilicity ω and nucleophilic N indices computed at these levels for twenty neutral molecules were analyzed with respect to the standard B3LYP/6-31G(d) in vacuo (see

Chart 1) After establishing the strong linear correlations between those obtained in DMSO and the standard B3LYP/6-31G(d) indices in vacuo, the lower, upper and superior (super) limits were proposed, enabling the establishment of new electrophilicity ω and nucleophilicity *N* scales for cationic and anionic species.
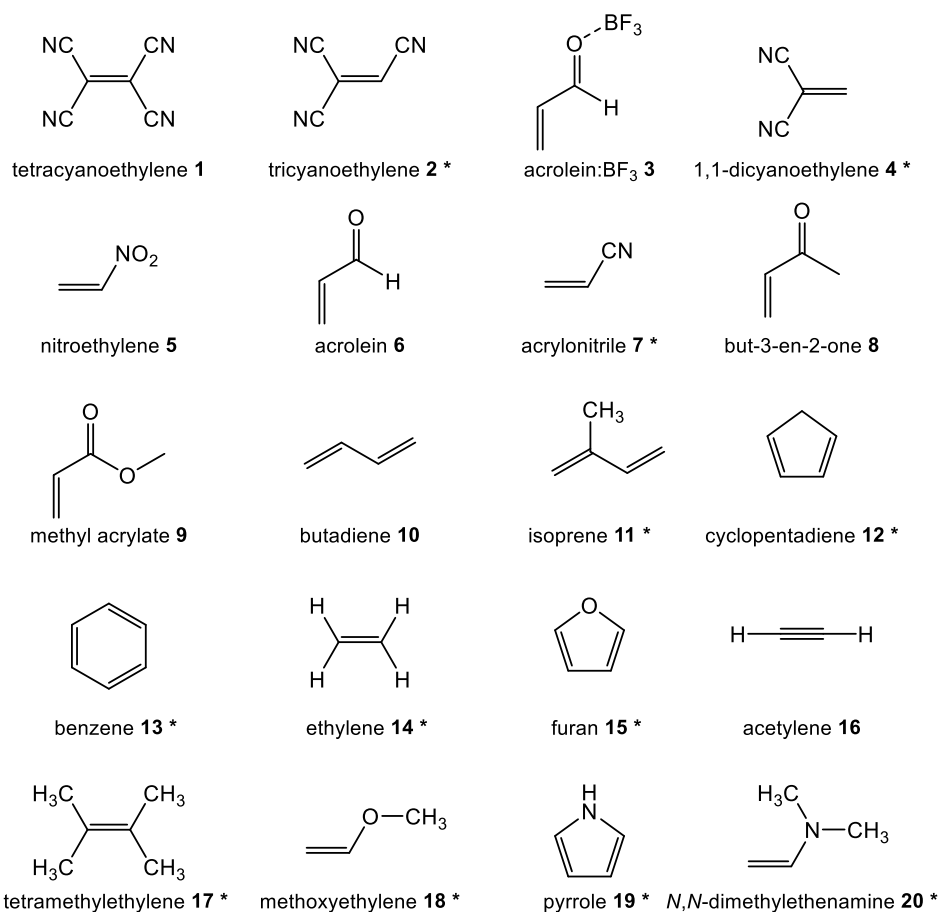

Chart 1. Common organic molecules used in the present study to establish the electrophilicity ω and nucleophilicity *N* scales in DMSO. The twelve molecules selected for the nucleophilicity *N* scales are marked with an asterisk.

Results and discussion

This study has been divided into four sections: i) first, the DFT-based reactivity indicators for the twenty selected molecules displayed in Chart 1 are obtained at the five selected computational levels; ii) second, the electrophilicity ω and nucleophilicity *N* indices at the different computational levels in DMSO are plotted with respect to the reference B3LYP/6-31G(d) ones, obtaining the corresponding linear regressions; iii) third, the lower, upper and superior limits of the electrophilicity ω and nucleophilicity *N* scales at the different computational levels in DSMO are established; and finally, iv) the proposed

electrophilicity ω and nucleophilicity N scales in DMSO are applied to a series of five cationic and five anionic species.

Electrophilicity ω Nucleophilicity N indices in DMSO at different computational levels

First, the electrophilicity ω and nucleophilicity N indices for the twenty selected molecules of increased electrophilic/nucleophilic character displayed in Chart 1 were computed at the five selected computational levels. The corresponding values are presented in Tables 4 and 5, while the total electronic energies E, the ε_H and ε_L energies, the electronic chemical potentials μ, and the chemical hardnesses η are gathered in Tables S1-S5 in the Supporting Information.

The data given in Tables 4 and 5 are ordered by decreasing values of the electrophilicity ω and nucleophilicity N indices at the B3LYP/6-31G(d) level in vacuo. Only slight changes in this order are observed for the indices calculated in DMSO.

Table 4. Electrophilicity ω indices, in eV, of the twenty chosen molecules (Chart 1) at the five selected computational levels.

	B3LYP/ 6-31G(d)	B3LYP/ 6-31G(d)	B3LYP/ 6-311G(d,p)	MPWB1K/ 6-311G(d,p)	M06-2X/ 6-311G(d,p)	ωB97X-D / 6-311G(d,p)
	in vacuo	in DMSO				
1	5.96	5.22	5.47	3.90	3.72	2.97
2	4.39	3.86	4.08	2.94	2.84	2.30
3	3.29	3.07	3.31	2.42	2.36	1.93
4	2.82	2.50	2.70	1.98	1.96	1.60
5	2.61	2.65	2.82	2.01	1.96	1.65
6	1.84	1.83	2.02	1.45	1.45	1.16
7	1.74	1.66	1.84	1.37	1.37	1.13
8	1.66	1.69	1.89	1.37	1.37	1.09
9	1.51	1.59	1.76	1.32	1.33	1.09
10	1.04	1.09	1.29	0.93	0.96	0.76
11	0.99	1.04	1.24	0.90	0.93	0.73
12	0.83	0.88	1.06	0.76	0.80	0.62
13	0.80	0.86	1.04	0.80	0.85	0.67
14	0.73	0.77	0.94	0.71	0.75	0.62
15	0.58	0.63	0.79	0.63	0.59	0.48
16	0.54	0.58	0.75	0.59	0.62	0.52
17	0.43	0.45	0.56	0.41	0.45	0.35
18	0.43	0.48	0.62	0.46	0.51	0.39
19	0.31	0.35	0.48	0.33	0.37	0.30
20	0.27	0.31	0.44	0.32	0.37	0.27

Table 5. Nucleophilicity *N* indices, in eV, of the twenty chosen molecules (Chart 1) at the five selected computational levels.

	B3LYP/ 6-31G(d)	B3LYP/ 6-31G(d)	B3LYP/ 6-311G(d,p)	MPWB1K/ 6-311G(d,p)	M06-2X/ 6-311G(d,p)	ωB97X-D / 6-311G(d,p)
	in vacuo	in DMSO				
1	0.00	0.00	0.00	0.00	0.00	0.00
2	0.33	0.26	0.26	0.26	0.26	0.25
3	0.00	0.03	0.02	-0.01	0.01	-0.03
4	0.65	0.51	0.51	0.52	0.51	0.47
5	1.07	0.55	0.55	0.22	0.21	0.26
6	2.12	1.63	1.66	1.29	1.21	1.47
7	1.25	0.95	0.93	0.92	0.91	0.85
8	2.38	1.83	1.82	1.46	1.40	1.65
9	1.72	1.12	1.10	0.92	0.90	0.88
10	2.89	2.43	2.37	2.49	2.47	2.37
11	2.97	2.50	2.46	2.57	2.55	2.46
12	3.37	2.88	2.81	2.90	2.85	2.76
13	2.42	1.92	1.87	1.97	1.95	1.86
14	1.87	1.41	1.34	1.31	1.29	1.19
15	3.01	2.53	2.48	2.59	2.56	2.45
16	1.45	0.92	0.76	0.66	0.64	0.57
17	3.19	2.75	2.77	2.87	2.84	2.77
18	3.18	2.66	2.63	2.60	2.57	2.56
19	3.64	3.07	3.00	3.12	3.09	2.98
20	4.00	3.50	3.51	3.55	3.51	3.49

Obtaining of linear regression equations

Next, the electrophilicity ω and nucleophilicity *N* indices computed at the B3LYP/6-31G(d), B3LYP/6-311G(d,p) MPWB1K/6-311G(d,p), M06-2X/6-311G(d,p) and ωB97X-D /6-311G(d,p) levels in DMSO were plotted with respect to the references computed at the B3LYP/6-31G(d) in vacuo (see Figures 1-3).
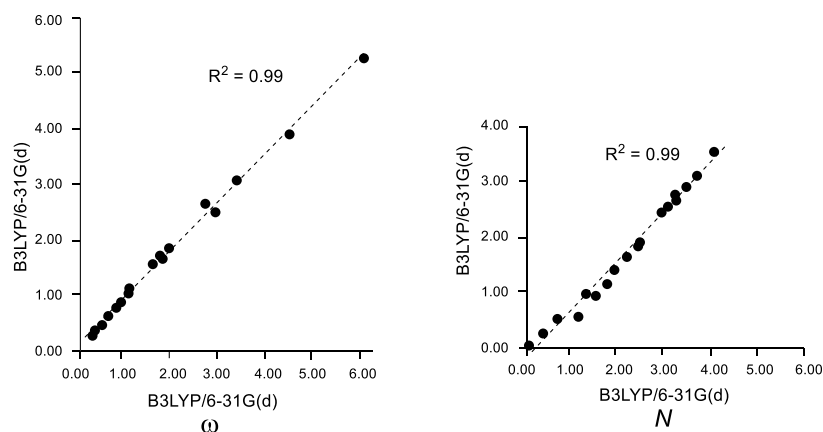

Fig. 1. Plot of the B3LYP/6-31G(d) electrophilicity ω and nucleophilicity *N* indices in DMSO versus the standard B3LYP/6-31G(d) electrophilicity ω and nucleophilicity *N* indices in vacuo of molecules **1 – 20**.
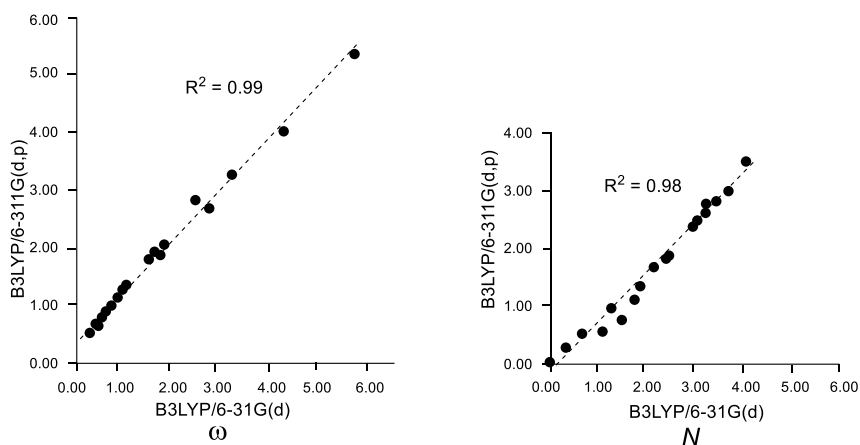
Fig. 2. Plot of the B3LYP/6-311G(d,p) electrophilicity ω and nucleophilicity *N* indices in DMSO versus the standard B3LYP/6-31G(d) electrophilicity ω and nucleophilicity *N* indices in vacuo of molecules **1** − **20**.
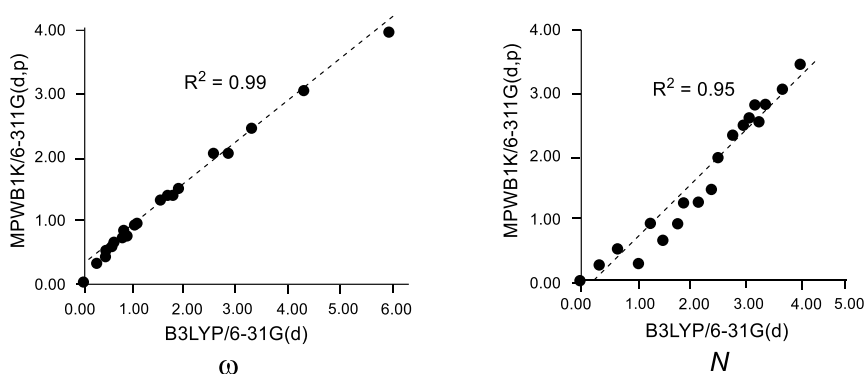
Fig. 3. Plot of the MPWB1K/6-311G(d,p) electrophilicity ω and nucleophilicity *N* indices in DMSO versus the standard B3LYP/6-31G(d) electrophilicity ω and nucleophilicity *N* indices in vacuo of molecules **1** − **20**.

Fig. 4. Plot of the M06-2X/6-311G(d,p) electrophilicity ω and nucleophilicity *N* indices in DMSO versus the standard B3LYP/6-31G(d) electrophilicity ω and nucleophilicity *N* indices in vacuo of molecules **1** − **20**.

Fig. 5. Plot of the ωB97X-D/6-311G(d,p) electrophilicity ω and nucleophilicity N indices in DMSO versus the standard B3LYP/6-31G(d) electrophilicity ω and nucleophilicity N indices in vacuo of molecules **1 – 20**.
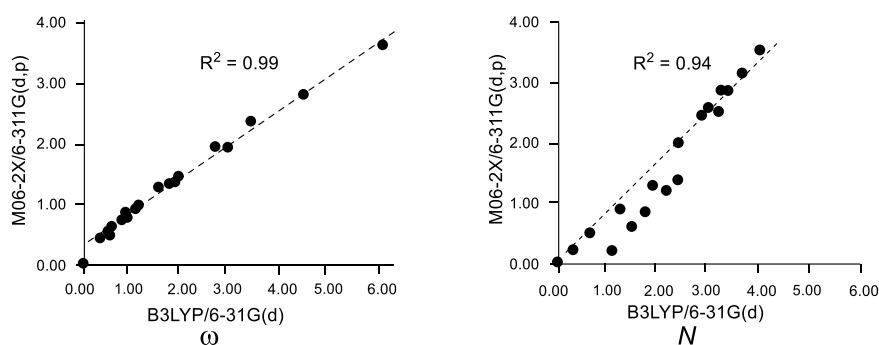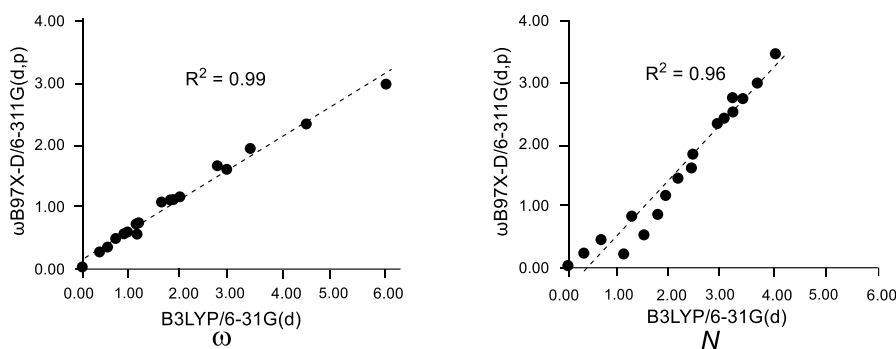
As can be seen, excellent linear regressions were obtained, with Pearson correlation coefficient R^2 values of 0.99 for the electrophilicity ω index, and ranging between 0.95 – 0.99 for the nucleophilicity N index (see Figures 1-3). These excellent Pearson correlation coefficients indicate a consistent linear relationship with the inclusion of DMSO solvent effects in the neutral molecules.

An exhaustive analysis of the linear regressions for the nucleophilic N indices given in Figures 2 – 5, with a R^2 ranging between 0.95 and 0.98, shows that the main deviations are associated with molecules with $N < 2.0$ eV, which are classified as marginal nucleophiles in the standard B3LYP/6-31G(d) scale. To improve these linear regressions, a set of twelve molecules with the best linear fits were analyzed (see molecules **2**, **4**, **7**, **11**, **12**, **13**, **14**, **15**, **17**, **18**, **19**, and **20** in Chart 1). The new linear regressions using the set of twelve selected neutral molecules show Pearson correlation coefficient R^2 values of 0.99 (see Figures S1-S4 in the in the Supporting Information).

Electrophilicity ω and nucleophilicity N scales in DMSO

The threshold values of the electrophilicity ω scales at the five computational levels in DMSO (dependent variable y) were determined by substituting the reference B3LYP/6-31G(d) values in vacuo (independent variable x) into the corresponding linear regression equations given in Table 6. The thresholds of the nucleophilicity N scale at the B3LYP/6-31G(d) level in DMSO were obtained from the equation given in Table 6, as the corresponding linear regression has an $R^2 = 0.99$. On the other hand, the threshold values of nucleophilicity N scales at the other four computational levels were established using the equations given in Table 7, which were obtained from the linear regression given in Figure S1- S4.

The resulting values are presented in Table 7, which includes the moderate (lower), strong (upper) and, superior (super) indices. Note that the cationic species exhibit superelectrophilic character, while anionic species display supernucleophilic character.

Table 6. Linear regression equations from the plots of the electrophilicity ω and nucleophilicity N indices of the twenty selected neutral molecules **1 – 20** computed at the five selected computational levels in DMSO vs those obtained at the B3LYP/6-31G(d) level in vacuo.

	ω	R^2	N	R^2
B3LYP/6-31G(d)	y = 0.8658x + 0.1549	0.99	y = 0.8788x - 0.1514	0.99
B3LYP/6-311G(d,p)	y = 0.8833x + 0.3077	0.99	y = 0.8724x - 0.1682	0.98
MPWB1K/6-311G(d,p)	y = 0.6295x + 0.2486	0.99	y = 0.9137x − 0.2859	0.95
M06-2X/6-311G(d,p)	y = 0.5926x + 0.3071	0.99	y = 0.9022x - 0.2860	0.95
ωB97X-D/6-311G(d,p)	y = 0.4821x + 0.2381	0.99	y = 0.8884x - 0.2809	0.96

Table 7. Linear regression equations from the plots of the nucleophilicity N indices of the set of twelve neutral molecules computed at the four selected computational levels in DMSO vs those obtained at the B3LYP/6-31G(d) level in vacuo.

	N	R^2
B3LYP/6-311G(d,p)	y = 0.8742x - 0.1293	0.99
MPWB1K/6-311G(d,p)	y = 0.9022x - 0.1481	0.99
M06-2X/6-311G(d,p)	y = 0.8920x - 0.1469	0.99
ωB97X-D/6-311G(d,p)	y = 0.8842x - 0.1924	0.99

Table 8. Lower, upper and super limits of the electrophilicity ω and nucleophilicity N scales in DMSO, in eV. The limits of the nucleophilicity N scales were obtained using the linear regression equations given in Table 7.

	ω			N		
	Lower	Upper	Super	Lower	Upper	Super
B3LYP/6-31G(d)	0.85	1.45	3.62	1.61	2.49	3.36
B3LYP/6-311G(d,p)	1.01	1.63	3.84	1.62	2.49	3.37
MPWB1K/6-311G(d,p)	0.75	1.19	2.77	1.66	2.56	3.46
M06-2X/6-311G(d,p)	0.78	1.20	2.68	1.64	2.53	3.41
ωB97X-D/6-311G(d,p)	0.62	0.96	2.17	1.58	2.46	3.34

The new scales given in Table 8 emphasize that the electrophilicity ω index is more variable and dependent on the computational method than the nucleophilicity N index whose scale remains mostly unchanged. This behavior of the nucleophilicity N index is due to the fact that it is a relative index referenced to that of tetracyanoethylene (TCE) **1** (see Chart 1).[9]

Application of the proposed electrophilicity ω and nucleophilicity *N* scales in DMSO for cationic and anionic species.

In order to evaluate the applicability of the proposed electrophilicity ω and nucleophilicity *N* scales in DMSO for cationic and anionic species, the ω and *N* indices for cationic species **21** - **25**, and anionic species **26** - **30** as shown in Chart 2, were computed at the B3LYP/6-31G(d) and B3LYP/6-311++G(d,p) levels in vacuo, as well as at the B3LYP/6-31G(d) and B3LYP/6-311G(d,p) levels in DMSO. The corresponding electrophilicity ω and nucleophilicity *N* values are given in Table 9, while the total electronic energies E, the ε_H and ε_L energies, the electronic chemical potentials μ, and the chemical hardnesses η are gathered in Tables S6-S11 in the Supporting Information.
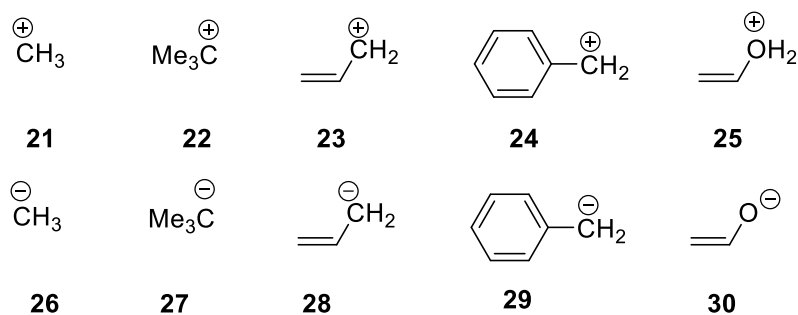
Chart 2. Structures of the cationic species **21** – **25** and the anionic species **26** – **30**.

The maximum values (MV) of the electrophilicity ω indices for the cationic species **21** – **25** and the nucleophilicity *N* indices for the anionic species **26** – **30** as presented in Table 9 demonstrate the strong impact of including solvent effects of DMSO in the calculations of the indices for these ionic species. Note that the inclusion of diffuse functions at the high B3LYP/6-311++G(d,p) level does not significantly alter the values computed at the standard B3LYP/6-31G(d) level (see Table 9).

As shown in Table 9, the in vacuo B3LYP/6-31G(d) electrophilicity ω index of the cationic species **21** – **25**, range between 6 and 18 eV, indicating very high values. The inclusion of diffuse functions at the B3LYP/6-311++G(d,p) level yields similar results with electrophilicity ω indices ranging from 7 to 18 eV. However, when solvent effects of DMSO are included, these values are considerably reduced, falling between 5 and 11 eV. In DMSO, while the protonated enol **25** is classified in the borderline of strong electrophiles, the carbocations **21** – **24**, retain their classification as superelectrophiles at both computational levels (see Table 9). Note that tricyanoethylene **2** is also classified as superelectrophile at two computational levels in DMSO (see Tables 4 and 9).

Table 9. B3LYP/6-31G(d) and B3LYP/6-311++G(d,p) in vacuo, and B3LYP/6-31G(d) and B3LYP/6-311G(d,p) in DMSO electrophilicity ω and nucleophilicity *N* indices, in eV, of the cationic species **21 –25** and the anionic species **26 – 30**.

	B3LYP/6-31G(d)		B3LYP/6-311++G(d,p)		B3LYP/6-31G(d)		B3LYP/6-311G(d,p)	
	in vacuo				in DMSO			
	ω	*N*	ω	*N*	ω	*N*	ω	*N*
21	18.22	-12.33	18.42	-11.93	7.41	-6.54	7.51	-6.29
22	16.21	-6.49	10.73	-6.54	4.15	-2.64	4.20	-2.50
23	15.61	-3.38	16.59	-6.25	6.10	-1.88	6.31	-1.79
24	10.68	-6.85	16.17	-3.20	5.80	0.33	6.10	0.38
25	6.30	-4.65	7.07	-4.50	1.44	-0.04	1.58	0.03
26	3.76	12.85	1.93	11.27	0.08	6.30	0.02	5.74
27	2.82	11.92	1.31	10.76	0.03	6.74	0.03	6.33
28	2.79	11.91	1.56	10.98	0.03	6.50	0.01	6.18
29	1.74	10.85	0.86	10.35	0.06	6.15	0.17	5.94
30	1.87	10.76	0.60	9.85	0.00	5.14	0.05	4.91
MV	18.22	12.85	18.42	11.27	7.41	6.74	7.51	6.33

On the other hand, the in vacuo B3LYP/6-31G(d) nucleophilicity *N* indices of the anionic species **26** - **30** also show very high values between 11 and 13 eV (B3LYP/6-31G(d)). The inclusion of diffuse functions at the B3LYP/6-311++G(d,p) level does not improve these results significantly, with nucleophilicity *N* indices ranging from 10 to 11 eV. In DMSO these values are significantly reduced ranging between 5 and 7 eV. The five nucleophilic anionic species **26 – 30**, with a *N* > 4.92 eV, are classified as supernucleophiles (see Table 9). Note that vinyl amine **20**, *N* = 3.50 eV, is also classified as supernucleophile at two computational levels in DMSO (see Tables 5 and 9).

Computational and theoretical details

DFT calculations were performed using the DFT B3LYP,[18,19] MPWB1K [20] M06-2X [21] and ωB97X-D,[22] functionals, and the 6-31G(d) and 6-311G(d,p) and 6-311++G(d,p) basis sets,[23] including different degrees of polarization functions. This selection was based on the most commonly used DFT methods recently used in theoretical organic chemistry studies. Optimizations were carried out by using the Berny analytical gradient optimization method [24,25] within the Gaussian 16 suite of programs.[26] Solvent effects of DMSO were studied using the polarizable continuum model [27,28] (PCM) within the framework of the self-consistent reaction field [29-31] (SCRF).

The electrophilicity ω index,[8] is given by the following expression, $\omega = \frac{\mu^2}{2\eta}$, in terms of the electronic chemical potential μ and chemical hardness η, which are in turn obtained from the electron affinities and ionization potentials. Using Koopmans' theorem [32] and

Kohn-Sham formalism,[33] both electron affinities and ionization potentials may be approached in terms of the one-electron energies of the frontier molecular orbitals HOMO and LUMO, ε_H and ε_L, thus leading to $\mu = \frac{(\varepsilon_H + \varepsilon_L)}{2}$ and $\eta = \varepsilon_L - \varepsilon_H$, respectively.[5] The empirical nucleophilicity N index,[9] based on the HOMO energies obtained within the Kohn-Sham scheme,[33] is defined as $N = \varepsilon_H(Nu) - \varepsilon_H(TCE)$, where TCE **1** is the reference as it presents the most negative ε_H that enables to obtain positive values of N.

Conclusions

New electrophilicity ω and nucleophilicity N scales for neutral, cationic and anionic species at the B3LYP/6-31G(d), B3LYP/6-311G(d,p), MPWB1K/6-311G(d,p), M06-2X/6-311G(d,p) and ωB97x-D/6-311G(d,p) levels in DMSO have been established. Excellent linear correlations with Pearson correlation coefficient R^2 values of 0.99, for a series of twenty neutral species with increasing electrophilic, and for a series of twelve neutral species with increasing nucleophilic character, were obtained. The corresponding linear regression equations allow for the establishment of the new lower, upper and superior limits of the electrophilicity ω and nucleophilicity N scales, which enable the direct classification and quantification of the electrophilic and nucleophilic character of cationic and anionic species.

The inclusion of diffuse functions at the B3LYP/6-311++G(d,p) level does not significantly improve the very high electrophilicity ω and nucleophilicity N indices found for cationic and anionic species at the standard B3LYP/6-31G(d) level in vacuo.

While for neutral species the DFT-based reactivity indices at the B3LYP/6-31G(d) reference scales are slightly modified in DMSO, the corresponding values in DMSO for ionic species are strongly reduced, remaining as superelectrophilic and supernucleophilic species in the proposed scales. The new electrophilicity ω and nucleophilicity N scales facilitate the direct prediction of corresponding properties for cationic and anionic species without reliance on the B3LYP/6-31G(d) reference scales originally established in 2002 [12] and 2008 [13] by Domingo et al.

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