Chapter 1
Introduction

1.1. Introduction:

The understanding of basic and applied scientific disciplines at a fundamental level is provided by the subject of chemistry and it is recognized as central science.[1] The process of interaction between atoms and molecules via chemical bonds to form new chemical compounds is explored in this area of science. The field of chemistry has been categorized in several branches, viz., inorganic chemistry, physical chemistry, organic chemistry, analytical chemistry, theoretical and computational chemistry, etc. Computational chemistry is one of the emerging areas of chemistry and deals with computer simulation to comfort in solving chemical problems. It is the study of chemistry through computers without the use of chemicals. Scientists have performed various experiments and have proposed different theories and mechanisms to explain various types of chemical interactions. Due to the development of different characterization techniques, it has become easy to understand the nature as well as mechanism of a chemical reaction. The development of theoretical and computational chemistry in the last few decades provides a great insight to explain almost all types of chemical interactions. The beauty of theoretical chemistry lies in the fact that it provides a mathematical proof to explain different types of chemical interactions. In other words, the theoretical chemistry gives perfection to the experimental chemistry. The applications of theoretical methods to different types of chemical reactions are based on the principles of quantum mechanics. Energetics and reactivity descriptors are two main theoretical tools which provide worthy information about different types of chemical interactions. Chemical energetic studies are based on the principle of energy minimization as well as on the activation energy studies. Thus, in the formation of products energetic studies provide the information of preferable reaction products. The reactivity descriptors are purely theoretical quantities that are useful to explain reactivity of a whole molecule (which is known as global reactivity) as well as site selectivity in a molecule (which is also known as local reactivity) or site of attack by a reactant to a substrate. Thus, chemical energetics and reactivity descriptors are associated with each other.

Initially, wave function theory based methods were used to carry out electronic-structure calculations on chemical systems. Hartree-Fock theory and its descendants such as Møller-Plesset (MP) perturbation theory,[2] Configuration interaction (CI) method,[3] the generalized valence bond (GVB) method,[4,5] coupled cluster (CC) methods[6] and multiconfigurational self-

consistent field (MCSCF) theory[7] are the commonly used wave function based methods to carry out electronic-structure calculations.

The aforementioned wave-function theory based methods are expensive from computational point of view which makes it difficult to perform electronic-structure calculations for larger systems. For critical understanding of chemical reactivity, various methodologies have been developed in past few decades. Frontier Molecular Orbital (FMO),[8,9] Molecular electrostatic Potential (MEP),[10-12] Electron Localization Function (ELF),[13,14] etc. treatments have been proposed and thoroughly explored on various types of reactions. The introduction of empirical principles such as the hard and soft acids and bases (HSAB) principle,[15,16] electronegativity equalization method (EEM),[17-20] etc. also provide significant contribution to rationalize chemical phenomena. The evolution of density functional theory (DFT)[21-23] since last three decades simplified the task of chemists in general and theoretical chemists in particular. DFT is a user-friendly computational method and employs electron density instead of wave-function for obtaining energies and properties. Consequently, the electron density functional incorporates electron correlation via the exchange-correlation functional.[24] The functional is defined as the function of a function. The electron density functional in DFT is a function of space and time. The fundamental property used in DFT is electron density unlike Hartree-Fock theory which deals directly with the many-body wave-function. The electron density is a function of cartesian coordinates x, y, z – only three variables, whereas the many-body electronic wave-function is a function of 3N variables (the coordinates of all N atoms in the system). So, the computational advantage of DFT is that it contracts 3N-degrees of freedom of N-body system to only three coordinate (x, y, z) system via its electron density. As a consequence of this contraction from 3N-degress of freedom to three spatial coordinates, reduces the computational expense by speeding up the calculation. Apart from providing computational advantage over wave-function based theory, DFT and its branch, most commonly known as Conceptual DFT[25] or Chemical Reactivity Theory (CRT) or Density Functional Reactivity Theory (DFRT), computes the reactivity of molecules in the form of the quantities – the reactivity descriptors. DFRT satisfactorily proposes a new quantitative principle, the principle of maximum hardness (PMH).[26-28] In addition to this DFRT based reactivity descriptors provide the information about the stability, chemical reactivity (from both thermodynamic and kinetic points of view) and selectivity of molecules.

On comparing the DFRT based energy decomposition with that of supermolecular approach, it is worthy to say that energy decomposition gives detailed account of the interaction, whereas, supermolecular approach provides only strength of the interaction. The present research focuses on: (i) DFRT based kinetic and thermodynamic studies on different types of chemical interactions and (ii) Correlation of experimentally reported parameters with kinetic and thermodynamic parameters derived from the DFRT.

1.2. Theoretical Background:

The theoretical background is discussed in the following sub-parts:

A. Fundamentals:

Two theorems given by Hohenberg and Kohn[29] are the fundamental theorems for the evolution of DFT. It is stated that energy, E is a functional of density (ρ) and can be represented as:

$$E = E[\rho] \tag{1.1}$$

The square bracket in the above relation represents a functional relation. The purpose of DFT is to calculate E and other ground state molecular properties from ground state electron density as follows:

$$E[\rho] = F[\rho] + \int v(\vec{r})\rho(\vec{r})\overrightarrow{dr} \tag{1.2}$$

Equation (1.2) is the full-form of Hohenberg-Kohn theorem. In this equation $F[\rho]$ is the sum of kinetic energy functional ($T[\rho]$) and the electron-electron interaction (i.e., electron repulsion energy) energy functional $V_{el}[\rho]$ and is known as the Hohenberg-Kohn functional.[30,31] In equation (1.2) $v(\vec{r})$ represents the external potential which represents the potential acting on an electron at position $\vec{r}$. $\rho(\vec{r})$ also determines N, the total number of electrons through its normalization which can be written as:

$$\int \rho(\vec{r})\overrightarrow{dr} = N \tag{1.3}$$

As stated above, Hohenberg-Kohn theorem form the basis of DFT but at the same time it is worthless to predict any hint for calculating density of a system. The second theorem proposed by Hohenberg and Kohn showed that the density obeys a variational principle. For the optimal $\rho(\vec{r})$, the energy E does not change upon variation of $\rho(\vec{r})$, provided that $\rho(\vec{r})$ integrates at all times to N [equation (1.3)]:

$$\delta\big(E - \mu\rho(\vec{r})\big) = 0 \tag{1.4}$$

where μ is the Lagrangian multiplier, and leads to the well-known Euler equation:

$$\mu = v(\vec{r}) + \frac{\delta F[\rho(\vec{r})]}{\delta \rho(\vec{r})} \tag{1.5}$$

Kohn and Sham efficiently turned equation (1.5) into an orbital equation as shown below:[32]

$$\left[-\frac{1}{2}\nabla^2 + v(\vec{r}) + v_{XC}(\vec{r}) + \int \frac{\rho(\vec{r}')}{|\vec{r}-\vec{r}'|} \overrightarrow{dr'} \right] \psi_i = \varepsilon_i \psi_i \tag{1.6}$$

The terms on the left side of equation (1.6) represent the kinetic energy of the non-interacting reference system, the external potential $v(\vec{r})$ and exchange-correlation potential $v_{XC}(\vec{r})$, respectively. ∇^2 represents Laplacian operator and ε_i is the energy of the Kohn-Sham orbital.

Where ψ_i represents Kohn-Sham orbital and the summation of their squares provide the electron density of the system as:

$$\rho(\vec{r}) = \sum_i |\psi_i^2| \tag{1.7}$$

The exchange-correlation potential $v_{XC}(\vec{r})$ is defined in terms of exchange-correlation energy $[E_{XC(\rho)}]$ and electron-density $[\rho(\vec{r})]$ as:

$$v_{XC}(\vec{r}) = \frac{\delta E_{XC(\rho)}}{\delta \rho(\vec{r})} \tag{1.8}$$

The Hartree-like equations are solved by Kohn-Sham (KS) method, the unexplored potential part of which is explored by scientists over years to find out preferable approximations of this unexplored part of the energy functional, i.e., the exchange-correlation energy.[33-35]

Local Density Approximation (LDA)[36] was the simplest approximation to compute exchange-correlation (E_{XC}) energy functional. The approximation exclusively proposes that exchange-correlation energy at any point in space depends upon the value of electron density at each point in space and can be given by the electron density of a homogeneous electron gas of the same density. Local Spin density Approximation (LSDA)[37-40] is used for open-shell systems or spin polarized systems. Despite the fact that LDA and LSDA approach are efficient for diverse problems, there are plentiful systems in quantum chemistry which requires non-local corrections to LDA. In order to overcome drawbacks of LDA and LSDA approaches, the efficient way is to make express E as a functional of not only on the local value of the density, but also on its gradient i.e., degree to which the density is locally varying. The gradient correction incorporation introduces 'generalized gradient approximation' (GGA) approach. The first and foremost GGA exchange functional was reported by Becke[40] (abbreviated as 'B') and

correlation functional by Lee, Yang and Parr[41] (abbreviated as LYP), together forming the BLYP functional.

Apart from GGA, Perdew-Wang (PW),[42] Perdew 86 (P),[43] Perdew-Burke-Ernzerhof (PBE),[44] etc. are some other matured exchange functionals and correlation functionals include Perdew 86,[45] Perdew-Wang 91 (PW91),[46] etc. The improvement of 'generalized gradient approximations' (GGA) is carried out by incorporating kinetic energy (or laplacian of the density). This approach is known as Meta-GGA approach and the corresponding functionals developed through this approach are known as Meta-GGA (MGGA) functionals.[47] MGGA functional is found to be more rigorous than the pure density functional (GGA).

Thus, it can be concluded that the hybrid density functional (H-GGA) methods i.e., combination of Hartree-Fock exchange and DFT correlation could be more suitable. In general, the hybrid density functional (H-GGA) is represented by E_{XC}^{hybrid} and is known as exchange-correlation energy. It is further decomposed into αE_X^{HF} (exchange functional) and E_c (correlation functional) as:

$$E_{XC}^{hybrid} = \alpha E_X^{HF} + E_c \qquad (1.9)$$

In equation (1.9), α is chosen to satisfy a particular criteria. The example is provided by one of the extensively used functional B3LYP[40,41] in which three adjustable parameters are used to fit computed values. B3PW91,[48,49] MPW1K,[50,51] mPW3LYP,[42,50] etc. are some more examples of hybrid density functionals. The development of range separated functionals (RSF) like PBE0,[52] CAM-B3LYP,[53] ωB97X-D,[54] etc. make it convenient to take care of both long range and short range corrections efficiently. The family of Minnesota density functionals[55,56] include M05, M05-2X, M06, M06-2X, M08-HX, M11, MN15, etc. were developed between the years 2005-2016 are well known to take care of dispersion interactions, non-covalent interactions and isomerization energies.

B. DFT based reactivity descriptors:

The well established theoretical quantities described by DFT provide valuable information about the reactivity as well as selectivity of a chemical system. These theoretical quantities are collectively known as reactivity descriptors which are broadly classified into two types: (i) global and (ii) local reactivity descriptors. Global reactivity descriptors are useful to understand global reactivity (i.e., intermolecular reactivity trends), whereas local reactivity descriptors implicitly provide information about site selectivity (i.e., intramolecular reactivity trends).

(i) Global reactivity descriptors

The response functions describing the system's response to global perturbations are known as global reactivity descriptors. Global quantities consider the entire system as an entity and are independent on spatial position ($\vec{r}$) within the molecular framework. The paramount reactivity descriptors are electronegativity[57,58] and chemical hardness.[15] The definition of electronegativity was first provided by Pauling[59] as "the power of an atom in a molecule to attract electrons towards itself". It was concluded that the flow of electrons from one species to the another occurs only and only when there is a difference in the electronegativity values between the atoms.[60] Gyftopolous and Hatsopoulos[61] derived the quantum thermodynamic definition of electronegativity by considering the atom or molecule as a member of grand canonical ensemble where the energy (E) and the number of electrons (N) are continuous function and all other properties of the ensemble are written in terms of these two variables. The measurement of the escaping tendency of electron cloud is known as chemical potential (μ). So, it is closely related to the electronegativity. The definition of electronegativity was provided by Iczkowski and Margave[62] as:

$$\chi = - \left(\frac{\partial E}{\partial N}\right)_{v(\vec{r})} \tag{1.10}$$

Therefore, chemical potential of a molecule can be written as:

$$\mu = \left(\frac{\partial E}{\partial N}\right)_{v(\vec{r})} = - \chi \tag{1.11}$$

The theoretical proof of above equation was provided by Parr and collaborators.[63]

Mulliken defined electronegativity[57] as arithmetic mean of the two experimentally measurable quantities i.e., ionization potential (IP) and electron affinity (EA):

$$\chi = \frac{IP+EA}{2} \tag{1.12}$$

Equation (1.12) provides a systematic way to calculate electronegativity values for different chemical systems and hence, it is considered as a working equation for the calculation of electronegativity.

The above expression [i.e., equation (1.12)] is provided by the finite difference approximation[16] from Energy (E) vs. Number of electrons (N) plot (Figure 1.1) which is advantageous for the calculation of chemical potential and electronegativity quantitatively. Using this approximation, the first derivative $\left(\frac{\partial E}{\partial N}\right)$, i.e., μ is defined as the mean of IP and EA.
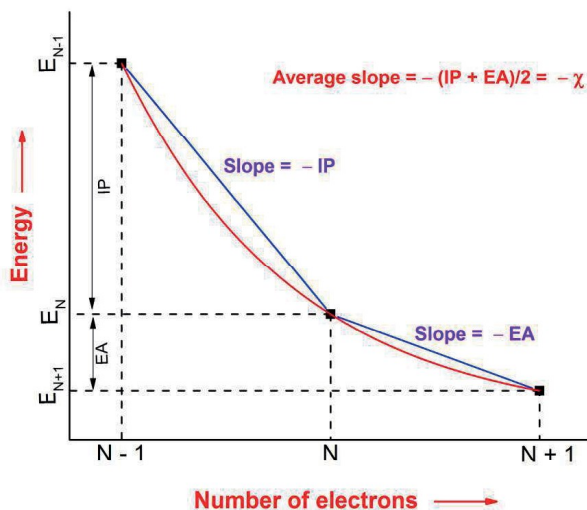
Figure 1.1. Energy of atom or molecule (E) versus number of electrons (N) at constant external potential (v).

The derivative representing the finite difference in energies of neutral species (N) and cationic species (N − 1) and is equal to negative of ionization potential (IP). The derivative representing the finite difference energies of neutral species (N) and anionic species (N + 1) and is equal to negative of EA. Hence, IP and EA are given by equations (1.13) and (1.14), respectively.

$$\mu^- = E_N - E_{N-1} = -IP \tag{1.13}$$

$$\mu^+ = E_{N+1} - E_N = -EA \tag{1.14}$$

$$\left(\frac{\partial E}{\partial N}\right)_{v(\vec{r})} = \mu = \frac{1}{2}\left(\mu^- + \mu^+\right) = -\frac{1}{2}(IP + EA) \tag{1.15}$$

The definition of χ derived from the finite difference approximation as stated above is similar to its Mulliken's definition [i.e., equation (1.12)].[57] Within the domains of molecular orbital theory, chemical potential (μ) can be related to Koopmans' approximation.[64] In this approximation, IP is replaced by negative of HOMO energy ($-E_{HOMO}$) and EA is replaced by LUMO energy ($-E_{LUMO}$). In conventional notation, HOMO denotes the highest occupied molecular orbital whereas, LUMO denotes the lowest unoccupied molecular orbital.[27,65,66] Therefore, IP and EA can also be represented as,

$$IP = -E_{HOMO} \tag{1.16}$$

$$EA = -E_{LUMO} \tag{1.17}$$

The chemical potential (μ) can be written using Koopmans' theorem,[64] as,

$$\mu = -\chi = \frac{E_{HOMO} + E_{LUMO}}{2} \tag{1.18}$$

The physical significance of HOMO lies in the fact that the gross equilibrium molecular geometry is controlled primarily by its behaviour.[67-69] Equation (1.18) represents the energy midpoint between HOMO and LUMO. Koopmans' approximation is feasible for the systems with larger number of atoms as it reduces the computational cost by using only neutral system calculation, whereas computations of global reactivity descriptors μ and χ through equation (1.15) requires three calculations (i.e., cationic, anionic and neutral systems at the optimized geometry of neutral system). In addition to this, equation (1.18)[70-72] is useful to tackle the situation of negative electron affinities which arises for metastable electron systems (i.e., N + 1 electron systems). The problem of negative electron affinities was also observed by Roy and Pal,[73] while calculating values of chemical potential and hardness[16] through equation (1.15), (which is popularly known as ΔSCF method) for open shell free radicals by wave function based approach.

The calculation of μ through equation (1.15) is computationally expensive as compared to Koopmans' method [equation (1.18)]. But the accuracy of μ calculated through equation (1.15) is found more than calculated through equation (1.18). It is because of the fact that the electron correlation and orbital relaxation are not taken into consideration in Koopmans' theorem.

Sanderson's principle of electronegativity equalization[17,74] (which states that when a molecule is formed, the electronegativities of the constituent atoms become equal, yielding a molecular electronegativity, which is the mean of the original electronegativities of the constituent atoms) is justified by equations (1.15) and (1.18).

Electronegativity equalization methods are used to a great extent for the calculation of atomic charges in a molecule.[75] The graphs between E and N do not show linear relation, however, E versus N plots, are normally convex upward. The global reactivity descriptor derived from these plots is the chemical hardness[16] and can be equated to second term in the Taylor series expansion of energy. The analytical form of chemical hardness is,

$$\eta = \frac{1}{2}\left(\frac{\partial^2 E}{\partial N^2}\right)_{v(\vec{r})} = \frac{1}{2}\left(\frac{\partial \mu}{\partial N}\right)_{v(\vec{r})} \tag{1.19a}$$

It has become a common practice for many researchers to drop the factor of $\frac{1}{2}$ in the equation (1.19a).[76,77] So, the analytical form of chemical hardness can also be represented as,

$$\eta = \left(\frac{\partial^2 E}{\partial N^2}\right)_{v(\vec{r})} = \left(\frac{\partial \mu}{\partial N}\right)_{v(\vec{r})} \qquad (1.19b)$$

The chemical hardness was critically explored to explain "hard-soft-acid-base" (HSAB) principle.[78-80] It is postulated that hard acids prefer to bind hard bases and soft acids prefer to bind soft bases. From Figure 1.1, the operational equation of chemical hardness is derived (using a finite difference approximation) and is given by,

$$\eta = \frac{IP - EA}{2} \qquad (1.20a)$$

Again for the operational equation of chemical hardness i.e., equation (1.20a), if 2 is dropped in the denominator,[76,77] then the equation (1.20a) takes the form:

$$\eta = IP - EA \qquad (1.20b)$$

Likewise, the definitions of chemical hardness by using Koopmans' theorem,[64] are given by,

$$\eta = \frac{E_{LUMO} - E_{HOMO}}{2} \qquad (1.21a)$$

and $\qquad\qquad \eta = E_{LUMO} - E_{HOMO} \qquad (1.21b)$

For an insulator or semiconductor, the band gap is calculated theoretically through equations (1.20a), (1.20b), (1.21a) or (1.21b) i.e., chemical hardness. If the value of chemical hardness is high (i.e., the band gap is large), then the material is having high stability and low reactivity. On the other hand, if the value of chemical hardness is low (i.e., band gap is smaller) then it is supposed to have low stability and high reactivity. Apart from this, the chemical hardness has been found a valuable parameter by chemists to study the concept of aromaticity and it has been critically examined that HOMO-LUMO energy gap is directly proportional to the extent of aromaticity.[76]

Another global reactivity descriptor which is inverse of the global hardness is global softness[77,81] which is considered as a measure of ease of charge transfer i.e., more the value of softness, more is the chance of deformation or reactivity in the system.

$$S = \frac{1}{\eta} = \left(\frac{\partial N}{\partial \mu}\right)_{v(\vec{r})} \qquad (1.22)$$

The softness parameter is correlated to the polarizability of system. It has been proved by various groups that the magnitude of softness is directly proportional to the polarizability of the chemical system.[82-85]

Another global reactivity descriptor proposed by Parr et al.[86] is known as global electrophilicity descriptor (w) which is given by,

$$w = \frac{\mu^2}{2\eta} \tag{1.23}$$

Global electrophilicity descriptor or electrophilicity index (w) may be considered as 'electrophilic power',[86] as it bears theoretical resemblance to power of classical electricity i.e., power $= V^2/R$, where V and R represent the potential difference and the resistance, respectively. A systematic study on thermodynamic and kinetic aspects of w was carried out by Elango *et al.*[87] by correlating it with the relative experimental rates of different types of reactions. Bagaria and Roy[88] carried out thorough studies on thermodynamic and kinetic aspects of electrophilicity index (w). Qualitatively the thermodynamic aspect of global electrophilicity index (w) assists to explain in the formation of favorable product.

In terms of first vertical *IP* and first vertical *EA*, equation (1.23) can be expressed as,[86,89]

$$w = \frac{\mu^2}{2\eta} = \frac{[-(IP+EA)/2]^2}{2(IP-EA)/2} = \frac{(IP+EA)^2}{4(IP-EA)} \tag{1.24a}$$

[here $\eta = \frac{IP-EA}{2}$, equation (1.20a)]

or
$$w = \frac{\mu^2}{2\eta} = \frac{[-(IP+EA)/2]^2}{2(IP-EA)} = \frac{(IP+EA)^2}{8(IP-EA)} \tag{1.24b}$$

[here $\eta = IP - EA$, equation (1.20b)]

Equation (1.24b) is considered as well-known equation of electrophilicity index (w). From the above two equations, it is clear that the value of electrophilicity index (w) is dependent on both *IP* and *EA*. The value of w is directly related to *EA*. The higher the value of *EA*, the higher is the value of w. The chemical reaction in which substrate is having higher value of *EA* (i.e., acts an electron acceptor), the rate of reaction increases as compared to other reaction of the similar type having lower value of *EA* provided that other reaction conditions (i.e., reagent, temperature, pressure, etc.) remain same. This explains the kinetic aspect of global electrophilicity (w).[87]

Parr *et al.*[86] explained thermodynamic aspect of w by considering an electrophilic ligand immersed in an idealized zero-temperature free electron sea of zero chemical potential. If the ligand becomes saturated with electrons, its chemical potential rises and becomes equal to that of free-electron sea chemical potential (i.e., zero). Due to the electron transfer (ΔN) from sea of electrons to the ligand, the ligand gets saturated with electrons and results in energy change (ΔE) given by,

$$\Delta E = \mu\Delta N + \frac{1}{2}\eta\Delta N^2 \tag{1.25}$$

By minimizing the energy change (ΔE) associated with the electron transfer (ΔN) from the free electron sea of zero chemical potential to the electrophilic ligand i.e., $\left(\frac{\Delta E}{\Delta N}\right) = 0$, it is shown that,

$$\Delta E = -\frac{\mu^2}{2\eta} = -w \tag{1.26}$$

Equation (1.26) is achieved by approximating ΔE, due to the electron transfer ΔN, up to second order. In terms of IP and EA and on using $\eta = (IP - EA)/2$, ΔE is given by,

$$\Delta E = -\frac{[-(IP+EA)/2]^2}{2(IP-EA)/2} = -\frac{(IP+EA)^2}{4(IP-EA)} \tag{1.27a}$$

Using $\eta = IP - EA$, ΔE is given by,

$$\Delta E = -\frac{[-(IP+EA)/2]^2}{2(IP-EA)} = -\frac{(IP+EA)^2}{8(IP-EA)} \tag{1.27b}$$

Since hardness is always a positive quantity (i.e., $\eta > 0$), the energy change is a negative quantity (i.e., $\Delta E < 0$). Therefore, the charge transfer is an energetically favorable process.

In addition to the global reactivity descriptors discussed above, the recently evolved global reactivity descriptors related to w are nucleophilicity,[90] electrofugality and nucleofugality,[91] charge philicity and chargephobicity.[92]

(ii) Local reactivity descriptors

As already mentioned the global reactivity descriptors measures overall reactivity of a system. Analogous to the global reactivity descriptors, the local reactivity descriptors are helpful in prediciting local reactivity (or site selectivity) of a chemical species. The local quantities are one-point functions ($\vec{r}$) and may vary from point to point in a molecule. Fukui function,[93] local softness[94-96] and local hardness[97-101] are the fundamental local reactivity descriptors.

A. Fukui functions:

Fukui function or frontier function describes electron density in a frontier orbital as a result of small change in total number of electrons. Fukui function $[f(\vec{r})]$ is derived by considering the change in energy, E and the potential, $v(\vec{r})$ when a system goes from one state to another.

The ground state electron density $\rho(\vec{r})$ is regarded as the principal local reactivity descriptor[102-105] and is defined as:

$$\rho(\vec{r}) = \left(\frac{\partial E[\rho]}{\partial v(\vec{r})}\right)_N \tag{1.28}$$

The first order change of chemical potential,[93,106] reveals more information about the reactivity and is given by,

$$d\mu = \mu \, dN + \int f(\vec{r}) \, dv(\vec{r}) \, \overrightarrow{dr} \tag{1.29}$$

In equation (1.29), the second term comprises the Fukui function $[f(\vec{r})]$ which is defined as:[93,106]

$$f(\vec{r}) = \left[\frac{d\mu}{dv(\vec{r})}\right]_N \tag{1.30}$$

Assuming constant external potential, $v(\vec{r})$, the definition of Fukui function in terms of the electron density $\rho(\vec{r})$ with respect to number of electrons is given by,

$$f(\vec{r}) = \left[\frac{d\rho(\vec{r})}{dN}\right]_{v(\vec{r})} \tag{1.31}$$

Equation (1.31) is well-known expression of Fukui function and the name arises due to its theoretical resemblance with Fukui's molecular orbital theory.[8,9] The Fukui function[93,106] measures the propensity of a region in a molecule to accept or donate electrons. The concept of frontier orbitals (FMOs) is generalized by the concept of Fukui function by including corrections for orbital relaxation[107-109] and electron correlation.

It is formidable to evaluate the derivative of equation (1.31) as it is discontinuous for a chemical system. So, to evaluate this discontinuous function, finite differences are taken from right to the left side.[110] In the course of a reaction, a chemical species may act as an electrophile (electron acceptor), or a nucleophile (an electron donor), or an amphiphile. In this way, there occurs three different functions, $f^+(\vec{r})$ when the derivative is taken as N increases from N to $N + \delta$, $f^-(\vec{r})$ when the derivative is taken as N increases from $N - \delta$ to N, and $f^0(\vec{r})$ the average of above two, can be written as:

$$f^+(\vec{r}) = \left[\frac{d\rho(\vec{r})}{dN}\right]_{v(\vec{r})}^+ \quad \text{governing nucleophilic attack on the system} \tag{1.32a}$$

$$f^-(\vec{r}) = \left[\frac{d\rho(\vec{r})}{dN}\right]_{v(\vec{r})}^- \quad \text{governing electrophilic attack on the system} \tag{1.32b}$$

$$f^0(\vec{r}) = \left[\frac{d\rho(\vec{r})}{dN}\right]_{v(\vec{r})}^0 = \frac{1}{2}\left[f^+(\vec{r}) + f^-(\vec{r})\right] \quad \text{governing radical attack on the system} \tag{1.32c}$$

Using finite difference approximation,[16] these indices can be written as:

$$f^+(\vec{r}) = \rho_{N+1}(\vec{r}) - \rho_N(\vec{r}) \quad \text{: for nucleophilic attack on the system} \tag{1.33a}$$

$$f^-(\vec{r}) = \rho_N(\vec{r}) - \rho_{N-1}(\vec{r}) \quad \text{: for electrophilic attack on the system} \tag{1.33b}$$

$$f^0(\vec{r}) = \frac{\rho_{N+1}(\vec{r}) - \rho_{N-1}(\vec{r})}{2} \quad \text{: for radical attack on the system} \tag{1.33c}$$

The above functions are popularly known as Fukui functions and are associated with frontier molecular orbitals (FMOs). The function $f^+(\vec{r})$ computes reactivity towards a donor reagent and

is associated with unoccupied molecular orbital (LUMO), the function $f^-(\vec{r})$ computes reactivity towards an acceptor reagent and is associated highest occupied molecular orbital (HOMO). The average of both $f^+(\vec{r})$ and $f^-(\vec{r})$ is represented by $f^o(\vec{r})$ and it computes reactivity towards a radical. Under the frozen density approximation,[8,9,111-114] the Fukui functions can be expressed as:

$$f^+(\vec{r}) = \rho_{LUMO} \text{ : measures reactivity towards a nucleophilic reagent} \tag{1.34a}$$

$$f^-(\vec{r}) = \rho_{HOMO} \text{ : measures reactivity towards an electrophilic reagent} \tag{1.34b}$$

$$f^o(\vec{r}) = \frac{\rho_{LUMO} + \rho_{HOMO}}{2} \text{ : measures reactivity towards a radical reagent} \tag{1.34c}$$

The Fukui function $f(\vec{r})$ is a worthy local reactivity descriptor to study the molecular behavior of the species (neutral, mono-positive and mono-negative ions) and differentiates one portion of a molecule from another. It would be more advantageous for chemists to compute $f(\vec{r})$ indices of an atom in a molecule as they are more concerned with reactivities of atomic sites in reactions involving neutral systems and their corresponding monocationic and monoanionic species (i.e., when there is change in electron number by unity, instead of infinitesimally small amount, δ).

In order to compute $f(\vec{r})$ indices of an atom in a molecule, Yang and Mortier[113] developed condensed Fukui function (condensed to individual atoms in a molecule) which is wholly based on Mulliken population analysis[113,115,116] and a finite-difference approximation to equation (1.31). On the basis of this approach, Fukui function on an atom k [condensed Fukui function (f_k)] is defined as the change of the atomic charge (q_k) with respect to a change in the total number of electrons (N) in the molecule. It is given by,

$$f_k = -\left(\frac{\partial q_k}{\partial N}\right)_{v(\vec{r})} \tag{1.35}$$

The expressions of condensed Fukui functions of an atom k in a molecule can be expressed by:

$$f_k^+ = P_k(N+1) - P_k(N) \text{ : for nucleophilic attack} \tag{1.36a}$$

$$f_k^- = P_k(N) - P_k(N-1) \text{ : for electrophilic attack} \tag{1.36b}$$

$$f_k^o = \frac{P_k(N+1) - P_k(N-1)}{2} \text{ : for radical attack} \tag{1.36c}$$

where P_k represents the gross electronic population of atom k in the molecule. $N + 1$, N and $N - 1$ represent anionic, neutral and cationic systems, respectively. Condensed Fukui functions, f_k^+ and f_k^- determines the capability of an atom to accommodate an extra electron and to cope with the loss of an electron, respectively and f_k^o is then regarded as the parameter for measuring radical reactivity. Thus, the condensed Fukui function (f_k^α where $\alpha = +, -, 0$) is written by replacing the particular electron densities by the corresponding electron populations (P_k).

As proposed by Parr and Yang,[93] reactivity is directly proportional to the magnitude of Fukui function. Hence, it can be summed up that more the value of condensed Fukui function, the more reactive is the particular atomic center in the molecule. However, this computation process has various faults. The first one lies in the fact that while using finite difference approximation with $\Delta N = 1$ in equations (1.36a − 1.36c), which is considered as crude approximation for the calculation of the derivative. It is because of the fact that within the framework of DFT non-integral (fractional) number of electrons shall also be accounted. Another crude approximation is that optimized geometry of the neutral molecule is treated to be perfect structure for carrying out its cationic and anionic state calculations. Accuracy of optimization also depends on the DFT functional and basis sets for the neutral system (which is usually in a singlet state). However, the charged molecules are usually in doublet states.

The major and repeatedly pointed-out drawback of Fukui function is its negative values.[116-119] The addition of electron to the molecule reduces the electron density (i.e., for nucleophilic attack) in some spots, while as the removal of electron from the molecule enhances the electron density (i.e., electrophilic attack) in some spots. Both of the cases lead to negative values of Fukui functions, which is quite confusing and contradictory and is still under exploration. However, it is believed to some extent that if Fukui function values are taken positive, then these type of ambiguities should not occur. But it has also been asserted that the Fukui function should be normalized, i.e., they should sum to one,

$$\sum_{k=1}^{N} f_k = 1 \qquad (1.37)$$

Hirshfeld population analysis (HPA)[120] technique based on stockholders charge-partitioning technique solves the problem in regard to the negative Fukui function. It has been proposed and shown that HPA yields only positive Fukui functions.[117,118,120,121-125] It was authenticated further that electronic population derived on the basis of HPA generates precise intramolecular reactivity trends as compared to those generated from Mulliken population

analysis (MPA),[115] natural bond orbital (NBO) analysis,[126-129] and molecular electrostatic potential (MESP) based methods.[130] Roy *et al.* [117,118] precisely validated that HPA is superior to other charge-partitioning techniques even though it is very intricate to examine the excellence of one method to the others. Consequently, some considerable studies are carried out in this area,[119,124] affirm that HPA is excellent charge-partitioning technique as it suffers from minimum missing information when atoms form a molecule.[123,130-134]

B. Local softness:

The Fukui function is considered as an efficient local reactivity descriptor for regioselectivity. But it does not measure overall reactivity of a molecule. In order to measure overall reactivity of a molecule, a grand canonical ensemble is considered.[135] After replacing the derivatives with respect to the number of electrons (N) with derivatives with respect to electronic chemical potential (μ), reactivity descriptors in the grand canonical ensemble are obtained. The electronic chemical potential (μ) is considered as an efficient reactivity descriptor for measuring strength of Lewis acids and bases. Thus, the advantage of reactivity descriptors in the grand canonical ensemble lies in the fact that it computes how a molecule's reactivity changes with the change in its electron-withdrawing power or electronegativity.

Local softness is one of the common local reactivity descriptor. It is represented by $s(r)$ and was defined by Yang and Parr[77] as,

$$s(\vec{r}) = \left(\frac{\partial \rho(\vec{r})}{\partial \mu}\right)_{v(\vec{r})} \tag{1.38}$$

In terms of Fukui function, $f(\vec{r})$, local softness, $s(\vec{r})$ can be written as:

$$s(\vec{r}) = \left(\frac{\partial \rho(\vec{r})}{\partial \mu}\right)_{v(\vec{r})} = \left(\frac{\partial \rho(\vec{r})}{\partial N}\right)_{v(\vec{r})} \left(\frac{\partial N}{\partial \mu}\right)_{v(\vec{r})} = f(\vec{r}) \, S \tag{1.39}$$

where S is the global softness defined by equation (1.22) i.e., $S = \frac{1}{\eta} = \left(\frac{\partial N}{\partial \mu}\right)_{v(\vec{r})}$. From equation (1.39) it can be argued that $f(\vec{r})$ redistributes the global softness among the distinct parts of the molecule and $s(\vec{r})$ integrates to S as,

$$\int s(\vec{r}) \, \overrightarrow{dr} = \int f(\vec{r}) \, S \, \overrightarrow{dr} = S \int f(\vec{r}) \, \overrightarrow{dr} = S \tag{1.40}$$

It is clear from equation (1.40) that local softness and Fukui function are closely related and play a significant role in the field of chemical reactivity. The already defined three types of Fukui functions (f_k^+, f_k^- and f_k^0) when multiplied by global softness (S) generates three types of local

softness functions. The condensed forms of these softness functions for a particular atom (k) are obtained on employing a finite difference approximation and are given as,[113]

$$s_k^+ = [P_k(N+1) - P_k(N)]S = f_k^+ S \quad : \text{for nucleophilic attack on the system} \qquad (1.41a)$$

$$s_k^- = [P_k(N) - P_k(N-1)]S = f_k^- S \quad : \text{for electrophilic attack on the system} \qquad (1.41b)$$

$$s_k^o = \left[\frac{P_k(N+1) - P_k(N-1)}{2}\right]S = f_k^0 S \quad : \text{for radical attack on the system} \qquad (1.41c)$$

In the above equations, $P_k(N)$, $P_k(N+1)$ and $P_k(N-1)$ denote the condensed electronic populations on atom (k) for neutral, anionic and cationic systems, respectively. It can be argued that for any atom (k) in a molecule having the highest value of s_k^+ is considered as the most preferred atom to be attacked by a nucleophile. Likewise, for any atom (k) in a molecule having the highest values of s_k^- and s_k^0 is considered as the most preferred atom to be attacked by an electrophile and radical, respectively. In general, equations $(1.41a - 1.41c)$ can be represented as,

$$s_k^\alpha = f_k^\alpha S \qquad (1.42)$$

where, $\alpha = +1, -1$ or 0.

It is clear from equation (1.42) that local softness and Fukui function are equivalent to each other and furnishes the same information with additional information about total molecular softness (S).

The basis set or correlation effects have a great impact on the values of s_k^+ and s_k^-. However, the basis set and correlation effects are expected to be less sensitive when the ratio of s_k^+ and s_k^- is taken. Keeping this into consideration two new reactivity descriptors, namely relative electrophilicity $\left(\frac{s_k^+}{s_k^-}\right)$ and relative nucleophilicity $\left(\frac{s_k^-}{s_k^+}\right)$, were proposed by Roy $et\ al.$[136] The relative nucleophilicity is defined as the nucleophilicity of any site as compared to its own electrophilicity and relative electrophilicity is the electrophilicity of any site as compared to its own nucleophilicity. For any particular atom (k), the descriptors $\frac{s_k^+}{s_k^-}$ and $\frac{s_k^-}{s_k^+}$ are helpful to identify the preferred sites for nucleophilic and electrophilic attack on it, respectively. However, the utility of this conjecture has been queried to some extent.[137] Clarification and explanation of imperfections in predicting intramolecular and intermolecular reactivity trends was further provided by Roy $et\ al.$,[138] thus till now no criticism is raised regarding the theoretical efficacy of $\frac{s_k^+}{s_k^-}$ and $\frac{s_k^-}{s_k^+}$.

C. Local hardness:

The exploration of local hardness $[\eta(\vec{r})]^{139}$ from its global analogue (η) is considered to be more intricate than the global-local softness relationship. Ghosh and Berkowitz[139] were the first who analytically proposed the definition of local hardness as the reciprocal of local softness as,

$$\eta(\vec{r}) = \left(\frac{\delta\mu}{\delta\rho(\vec{r})}\right)_{v(\vec{r})} \tag{1.43}$$

When the chain rule is applied to the global hardness (η), the quantity local hardness $\eta(\vec{r})$ appears as,

$$\eta = \frac{1}{2}\left(\frac{\partial^2 E}{\partial N^2}\right)_{v(\vec{r})} = \frac{1}{2}\left(\frac{\partial\mu}{\partial N}\right)_{v(\vec{r})} = \frac{1}{2}\int\left(\frac{\delta\mu}{\delta\rho(\vec{r})}\right)_{v(\vec{r})}\left(\frac{\delta\rho(\vec{r})}{\delta N}\right)_{v(\vec{r})}\overrightarrow{dr} = \frac{1}{2}\int\eta(\vec{r})\ f(\vec{r})\ \overrightarrow{dr} \tag{1.44}$$

From equation (1.44), it can be concluded that local hardness $\eta(\vec{r})$ and Fukui function $f(\vec{r})$ are related to each other. Also, a reciprocal relation is obtained with the local softness $s(\vec{r})$. Therefore, $\eta(\vec{r})$ and $s(\vec{r})$ are related to each other as,

$$\int\eta(\vec{r})\ s(\vec{r})\ \overrightarrow{dr} = 1 \tag{1.45}$$

1.3. Comprehensive Decomposition Analysis of Stabilization Energy (CDASE) Scheme:

The first theoretical proof for the Hard-Soft-Acid-Base (HSAB) Principle was formulated by Parr and Pearson[16] using Taylor series energy expansion in terms of number of electrons (N). The mathematical relation representing energy lowering due to electron transfer (ΔN) from a species B (i.e., electron donor) to another species A (i.e., electron acceptor) is given as,

$$\Delta E = \left(E_A - E_A^{\ 0}\right) + \left(E_B - E_B^{\ 0}\right) = \left(\mu_A^{\ 0} - \mu_B^{\ 0}\right)\Delta N + \frac{1}{2}\left(\eta_A + \eta_B\right)\Delta N^2 \tag{1.46}$$

where $\Delta N = N_A - N_A^{\ 0} = N_B^{\ 0} - N_B$ (implying that B is electron donor and A is electron acceptor). The symbols $E_A^{\ 0}$ and $E_B^{\ 0}$ represent the energies of systems A and B, respectively, before the electron transfer, whereas the symbols E_A and E_B represent the corresponding quantities after the electron transfer. The symbols $\mu_A^{\ 0}$ and $\mu_B^{\ 0}$ represent chemical potentials of acceptor and donor species, respectively. The symbols η_A and η_B represent hardness of the corresponding quantities. Equation (1.46) is the formalism for lowering of energy i.e., the stabilization energy as a result of electron transfer between the two chemical species A and B. In the formation of AB, the electron transfer occurs from B to A only when $\mu_B^{\ 0} > \mu_A^{\ 0}$ (i.e., electronegativity of A is more than B). Hence, the amount of charge (electron) transfer and the

corresponding energy expression can be expressed from the definitions of $\mu_B{}^0$, $\mu_A{}^0$, η_A and η_B as,

$$\Delta N = \frac{\mu_B{}^0 - \mu_A{}^0}{(\eta_A + \eta_B)} \tag{1.47}$$

$$\Delta E_{SE(AB)} = - \frac{(\mu_B{}^0 - \mu_A{}^0)^2}{2(\eta_A + \eta_B)} \tag{1.48}$$

Roy and collaborators[140] have claimed that besides ΔN, the components of $\Delta E_{SE(AB)}$ can furnish valuable information regarding the direction of electron flow when (i) two species, A and B, form a complex AB (i.e., $A + B \rightarrow AB$) and (ii) A and B react first and form AB which further breaks to give different products (i.e., $A + B \rightarrow [AB]^{\#} \rightarrow C + D$). From the energy components, it can also be envisioned whether a reaction is spontaneous or require any external assistance for case (ii). The energy components derived from equation (1.48), are represented as,

$$\Delta E_{B(A)} = \frac{\mu_B{}^0 - \mu_A{}^0}{\eta_A + \eta_B} \left[-\mu_B{}^0 + \frac{1}{2}\eta_B \left(\frac{\mu_B{}^0 - \mu_A{}^0}{\eta_A + \eta_B} \right) \right] \tag{1.49}$$

$$\Delta E_{A(B)} = \frac{\mu_B{}^0 - \mu_A{}^0}{\eta_A + \eta_B} \left[\mu_A{}^0 + \frac{1}{2}\eta_A \left(\frac{\mu_B{}^0 - \mu_A{}^0}{\eta_A + \eta_B} \right) \right] \tag{1.50}$$

$\Delta E_{B(A)}$ represents the change in energy of donor (B) in presence of acceptor (A) while as $\Delta E_{A(B)}$ represents the change in energy of acceptor in presence of donor (B). Analysis of equation (1.49) reveals that the value generated from the square-bracketed term will be positive if ΔN is a positive quantity (because $\mu_B{}^0$ is a negative quantity and η_B is a positive quantity). Positive value of ΔN is possible only if the flow of electrons occur from B to A (i.e., $\Delta N = N_B{}^0 - N_B$ = positive). Therefore, the positive value of ΔN when multiplied by positive value of square-bracketed term furnishes positive $\Delta E_{B(A)}$ value, which again implies that B is donor and A is acceptor. Correspondingly, $\Delta E_{A(B)}$ [equation (1.50)] will be negative quantity when B is donor and A is acceptor. If the values of ΔN and $\Delta E_{B(A)}$ are negative and the value of $\Delta E_{A(B)}$ is positive then, A acts as a donor and B acts as an acceptor.

1.4. Efficiency of Parr and Pearson equation and its expansion:

Parr and Pearson equation [equation (1.46)] and its modification in terms of kinetic and thermodynamic components [CDASE scheme, equations (1.49) and (1.50)] have been found efficient to explain several types of chemical and biological interactions.[141-148] Equation (1.47) is

efficient enough to calculate the amount of charge transfer (ΔN) from the donor (B) to the acceptor (A) species. Energy change (ΔE) as a result of interaction between the two species as well as charge transfer (ΔN) from the electron rich to the electron deficient species are computed keeping in view chemical potential equalization principle.[149-151] At this stage, the energy change (ΔE) is maximum and is known as stabilization energy, $\Delta E_{SE(AB)}$ [equation (1.48)]. The charge transfer (ΔN) at this point is better known as equilibrium charge transfer ($\Delta N_{eqlm.}$). In order to prove that interaction (or stabilization energy [equation (1.48)] is optimum (most negative) at the equilibrium value of charge transfer ($\Delta N_{eqlm.}$), it seems to be an interesting task for researchers to calculate change in energy (ΔE) at different values of charge transfer other than from its equilibrium value (i.e., on moving higher and lower sides in small increments from the equilibrium value).

Since Parr and Pearson equation computes stabilization energy in terms of charge transfer component (ΔN) only. This equation ignores the role of electrostatic interaction, dispersion interaction and other non-bonding interactions. The same is true for its energy decomposition terms [i.e., CDASE scheme based equations i.e., equations (1.49) and (1.50)]. Nalewajski[152] was the first who expanded Parr and Pearson equation explicitly by including electrostatic effect in the stabilization energy and charge transfer expressions by applying the full second-order expansion of energy of an atom-in-a-molecule. Later on, Ayers[153] derived an elaborate expression of stabilization energy after inclusion of charge transfer, electrostatic, polarization and dispersion contribution in the original Parr and Pearson equation. Therefore, it seems to be an interesting problem for the researchers to highlight the role of non-bonding and electrostatic interactions in the kinetic [$\Delta E_{B(A)}$] and thermodynamic [$\Delta E_{A(B)}$] components of CDASE scheme as well as in the charge transfer (ΔN) expression.

1.5. Effect of solvent on DFRT based reactivity parameters:

Solvent plays a major role in the process of reaction as most of the chemical and biochemical reactions occur in solution. It has been found for a particular reaction that on changing the solvent and keeping the other reaction conditions fixed, there is a considerable change in its physical parameters (such as formation constants and binding energies).[154-158] The effect of solvent is typically included via two main models: (i) discrete solvent models[159-161] and (ii) continuum models.[162-164] The discrete model involves the specific interactions between solute

and the solvent molecules as it treats the solvent molecules explicitly. Due to the incorporation of solvent molecules, there is an adequate increase in the size of the system. With the increase in the size of system, the computational expense goes on increasing. However, in the continuum model (also known as implicit model), the solvent is specified as a continuum rather than using the solvent molecules explicitly. In this model the main criteria for defining the solvent is its dielectric constant (ε) which defines its power of polarizability. This model is found to be more significant and accessible (than explicit model) for specifying the solvent while carrying out electronic structure theory calculations. Implicit solvation models together form a set of methods which is popularly known as self-consistent reaction field (SCRF) methods. Onsager reaction field model[165] is considered as the simplest SCRF model. It is based on the assumption that solute is fixed in the spherical cavity of solvent whereas, the solvent is treated as homogeneous medium of constant dielectric constant (ε). The another model which is frequently used while carrying out electronic structure theory calculations is the polarized continuum model (PCM).[166-168] In this model, aggregation of set of interlocking atomic spheres defines a cavity. Further, the polarization effect of the continuum solvent induces the electric field. This model was further modified to isodensity PCM (IPCM) in which cavity is defined as an isodensity surface. Further modifications on IPCM gave rise to self-consistent isodensity PCM (SCI-PCM)[169,170] in which the role of solvent is taken into account self-consistently which further reinforces the substantial coupling of the cavity and electron density. The well established and most commonly used version of PCM is Integral Equation Formalism PCM (IEF-PCM).[171,172] It is modification of PCM in terms of the integral equation formalism. The criticism of PCM methods lies in the fact that they are all derived assuming that solute charge density is confined within the cavity which actually is not true always as the electron distributions generally spread beyond the cavity. IEF-PCM solvation model has been shown to cope well with this effect when compared to other PCM based methods.[173] Other less common continuum models used are SMD,[172,174] COSMO,[175] etc.

It was Safi *et al.*[176] who first carried out continuum solvent studies on different functional groups and it was concluded that electronegativity and hardness decrease with increase in dielectric constant of solvent. Further, the continuum model was used to investigate the influence of the solvent on the kinetic and thermodynamic aspects of the S_N2 reaction.[177]

The explicit solvation studies were carried out by Balawender *et al.*[178] to study the effect of adding number of H_2O molecules on several DFT-based reactivity descriptors of NH_3. From

their studies, it was concluded that the HOMO-LUMO gap and the electrophilic hardness increase with the addition of water molecules.

1.6. Formation constant (K) and its relation to DFRT based interaction energy:

A formation constant (also known as stability constant or binding constant) is defined as an equilibrium constant for the formation of a complex and is usually represented by K or K_f. Practically, it is the measure of the strength of interaction between the reactants that come together to form the complex. The formation constant provide valuable information required to calculate the concentration(s) of the complex(es) in solution. The utility of formation constant has been found in many areas of application in chemistry, biology and medicine.[179-182] Formation constants are the key parameters for the investigation of equilibria in solution. Bjrerrum was the first who determined stability constants for metal-ammine complexation.[183]

From thermodynamic view point, for a particular reaction, a formation constant (K) is related to the standard Gibbs free energy change ($\Delta G^\ominus$) as,

$$\Delta G^\ominus = -2.303\, RT \log_{10} K \qquad (1.51)$$

R is the ideal gas constant and T is the absolute temperature.
Several methods have been employed to measure the stability constants for the process of complexation. These include potentiometric titration,[184,185] conductometric[186,187] and spectrophotometric techniques.[184,187,188] Among these methods, spectrophotometric method is found to be more advantageous in terms of sensitivity and is convenient to determine stability constants in solution under different experimental conditions.

Dybal et al.[189] carried out DFT as well as experimental studies for the complexation of valinomycin with ammonium cation (NH_4^+). From the DFT calculations, the structural details of the valinomycin-NH_4^+ complex, authentication of stable complex formation and the interaction energy was determined (through supermolecular approach). Apart from this, the DFT studies were helpful to locate the position and the orientation of the NH_4^+ ion in the cavity of the valinomycin molecule and also to calculate the interatomic distances within the complex.

An extensive study on the complexation reactions of metal ions with different ligands has been carried out[190-192] among which Schiff base ligands received a considerable attention in different fields. These ligands are versatile in nature and are able to coordinate with different metals and stabilize them in various oxidation states.[193,194]

Esmaielzadeh and Mashhadiagha[195] carried out spectrophotometric and computational studies for the interaction of Schiff base ligand, methyl-2-{[1-methyl-2-(acetone)ethylidynenitrile] ethyl} amino-1-cyclopentenedithiocarboxylate (L) with four different metals in +2 oxidation state (viz., Co^{2+}, Cu^{2+}, Ni^{2+} and Zn^{2+}) and finally leads to four different 1:1 complexes (viz., CoL, CuL, NiL and ZnL). The formation constant (K) was calculated at different temperatures for all the complexes and was found to in the order as: CoL > CuL > NiL > ZnL under different temperatures. Also, the experimentally calculated $\Delta G^{\ominus}$ values reported for these complexes followed the similar trend as was followed formation constant (K) values. The calculated values of hardness $(\eta)^{15}$ and interaction energies (using supermolecular approach) of these complexes through DFT was found to be the highest for CoL and lowest for ZnL and follows the trend similar to that followed for K and $\Delta G^{\ominus}$ values for these four complexes.

1.7. Linear Free Energy Relationship (LFER) and DFRT:

The reactivity of the interacting species depends on the reaction variables like substrate structure, reagent structure and reaction medium. The clarification of the essential features of the fundamental reaction types has been explained through various relations among which the free energy relationship (also known as Gibbs energy relation) is considered worthy enough which describes the linear relation of the logarithm of a rate or equilibrium constant for one series of reactions with the logarithm of the rate or equilibrium constant for a related series of reactions. The relationship is given by,[196]

$$\log k = m \log k' + c \qquad (1.52)$$

The above equation may also be written in terms of equilibrium constants (K) as,[183]

$$\log K = m \log K' + c \qquad (1.53)$$

where k and are k' are the rate constants for a related series of reactions (say reaction 1 and reaction 2), respectively, K and K' are the equilibrium constants for reaction 1 and reaction 2, respectively, m is the slope and c the intercept of the straight line obtained.

For the structural changes in the substrate, the thermodynamic and kinetic requirements have been explored earlier to describe linear free-energy relationship.[197] Bronsted equation or Law of correlation[198] was the first experimental linear free energy relationship correlating acid strength and catalytic activity in general acid catalysis and is given by,

$$\log k = \alpha \log K_a + c \qquad (1.54)$$

where k is rate constant and K_a is ionization constant for a series of acids (e.g., substituted phenols or carboxylic acids), α (a proportionality constant) is slope of straight line and c is intercept. For reactions having low value of α are considered to have a transition state closely resembling the reactant with little proton transfer, whereas the reactions with a high value of α, proton transfer in the transition state is almost complete. However, after critical analysis, it was proved that this equation is not a fundamental equation for a linear correlation of free energy changes.[199] Hence, equation (1.54) is confined to only acid catalysis.

Hammett[200] introduced a linear free energy relationship (LFER) relating the reaction rates (k) and equilibrium constants (K) for many reactions involving benzoic acid derivatives with meta- and para-substituents to each other with just two parameters: a substituent constant (σ)[201,202] (determined by the substituent) and a reaction constant (ρ)[202] (determined by the reaction). Hammett equation[200] is considered as the oldest and most developed form of LFER.

Jaffe[203] reviewed Hammett equation in 1953 and considered it as fundamental equation among the free energy relationships. The simplest form of Hammett equation is given by,

$$\log\frac{k_X}{k_H} = \rho\sigma \tag{1.55}$$

or,

$$\log\frac{K_X}{K_H} = \rho\sigma \tag{1.56}$$

where k_H is the reference rate constants of the unsubstituted reactant and k_X is the rate constant of the substituted reactant. Similarly, K_H is the reference equilibrium constant of the unsubstituted reactant and K_X is the equilibrium constant of the substituted reactant. This equation has been authenticated great efficacy in physical-organic chemistry and has found application in other areas of chemistry as well.

Al-Ajlouni et al.[204] carried out experimental studies on adduct formation processes between: (i) methyltrioxorhenium (MTO) and a series of bidentate nitrogen donor ligands and (ii) dichloridodioxidomolybdenum (MoO_2Cl_2) and a series of bidentate nitrogen donor ligands and successfully verified the linear nature of Hammett equation. It was also verified that the stability of the adduct formed increases with the donating ability of the ligand.

Akhani et al.[205] used Hammett equation and critically examined the effect of substituent on para-substituted triphenylsilyl chlorides on silylation-based kinetic resolutions. In this study, the reactions were carried out between para-substituted triphenylsilyl chlorides and 1,2,3,4-

tetrahydronaphthalen-1-ol and Hammett's LFER was successfully validated with highly adjusted R^2 (square of the correlation coefficient) values.

In the context of DFRT, Elango et al.[87] performed theoretical studies on para-substituted benzoicacid derivatives and computed their global electophilicity indices (w). A linear correlation between the already known Hammett substituent constants (σ) and electophilicity indices (w) was obtained with highly adjusted R^2 values.

Further studies were carried out by Ayouchia et al.[206] on [3+2] cycloaddition reaction. Computation of global electrophilicity indices (w) of para-substituted phenylazides and para-substituted phenylalkynes was carried out. A linear correlation was found between the global electrophilicity indices (w) and Hammett substituent constants (σ). The logarithm ratios of global electrophilicity indices (w) of substituted molecules with that of unsubstituted molecule [i.e., $\log\left(\frac{w}{w_H}\right)$] were also computed. A linear nature of plot between $\log\left(\frac{w}{w_H}\right)$] vs. σ with a good correlation coefficient ($R^2 > 0.9$) was obtained hence validating Hammett's LFER. It was further proved that the reactivity of both azide and alkyne derivatives depends on the substituents (electronic withdrawing and electron releasing) leading to their stabilization or destabilization.

1.8. Applications of Density Functional Reactivity Theory (DFRT): Motivation behind the present thesis:

The previously conducted studies on the applicability of CDASE scheme[140] was performed by Saha et. al[142] and Sarmah et. al[143-148] to explain kinetic and thermodynamic parameters of different types of chemical and biological interactions. Various mechanisms have been proposed to explain different types of chemical interactions. The most important types of reactions often experienced in chemistry are substitution, addition (including pericyclic reactions), elimination and rearrangements.

DFRT has been found useful to explore different types of mechanisms involved in different chemical and biological interactions at a reasonably low computational cost. From the theoretical chemistry view point, kinetic and thermodynamic data is advantageous to analyze all these types of reactions. The kinetic aspect significantly depicts the rate of reaction while the thermodynamic aspect measures the overall stability of products. The global reactivity descriptors are well known in analyzing the reactivity and stability of chemical and biological systems. The customary DFT based techniques have some drawbacks over DFRT while dealing

with bigger systems (i.e., biomolecules, polymers, etc.). In this thesis, the full profiles of the energy components of the DFRT based CDASE scheme as well as the net stabilization energy with respect to charge transfer (ΔN) are explored. Apart from this some modifications are made in the already known equations [i.e., equations (1.47) – (1.50)] of CDASE scheme by performing external potential perturbation in the expressions of CDASE scheme and testing the effect of variation of solvent on stabilization energy as well as correlation of stabilization energy with experimental formation constant (K) is carried out in this thesis. Further, a correlation of formation constant (K) with the stabilization energy is also carried out. Finally, DFRT based Hammett equation is proposed for the first time and tested and correlated with experimental data for some reactions.

The model reactions chosen in this thesis include: (i) Diels-Alder reactions, (ii) charge-transfer complexes formed by NH_3 and BH_3 and their derivatives, (iii) Huisgen [3+2] cycloaddition reaction,[207] (iv) methyltrioxorhenium (MTO)-ligand adduct formation reactions,[154,208] (v) semicarbazone formation from semicarbazide and different ortho- and para-substituted benzaldehydes,[209] (vi) reaction of para-substituted acetophenones with hydroxylamine,[210] (vii) reaction of para-substituted cumenes with dimethyldioxirane,[211] (viii) reaction of para-substituted benzylbromides with diphenylamine,[212] (ix) reaction of 2,2,2-trifluroaceticacid with β-substituted ethanol,[213] (x) reaction of norbornene with meta-substituted arylazide[214] and (vi) reaction of norbornene with para-substituted arylazide.[214]

1.9. Organization of the thesis:

This thesis focuses on the applications and modifications of DFRT based CDASE scheme and finding the correlation between experimental data and DFRT based reactivity descriptors. The thesis is organized in the following chapters:

Chapter 1: Theoretical background and advantages of the DFRT based global and local reactivity descriptors along with the related principles are thoroughly discussed in this chapter. Apart from that the present chapter provides an overview of the research work carried-out in this thesis. Thus it describes in brief: (i) the efficacy of Parr and Pearson equation and its modification (ii) the solvent effect on the DFRT based reactivity parameters (iii) an overview of formation or equilibrium constant (K) and its utility (iv) an overview of linear free energy relationship (LFER) and its utility. Hence, this chapter is dedicated to the general introduction and literature review.

Chapter 2: The first and foremost work is carried out in this chapter which involves generating and analyzing full profiles of the components of the DFRT based stabilization energy and modification of the already proposed equations of CDASE scheme [equations (1.49) and (1.50)] after incorporating perturbation on the external potential.

Apart from that the modified equation of stabilization energy highlights the role of solvent in the adduct formation process. This modified form stress the importance of electrostatic and other non-bonding interactions in evaluating the charge transfer and stabilization energy values in the process of adduct formation.

Chapter 3: Whatever conjectured from the modified equations of stabilization energy in Chapter 2 is tested on some reactions and correlated with the experimental formation constant (K) values. Therefore, Chapter 3 focuses on the development of new formalism and its validation on some model reactions. The developed computational method takes care of the effect of solvation on stabilization energy in the adduct (or product) formation process.

Chapter 4: Chapter 3 correlates the formation constant values of a particular reaction in different solvents with DFRT based stabilization energy. The corresponding analytical relation between formation constant (or equilibrium constant, K) and DFRT based stabilization energy is developed in this chapter using a combined approach based on chemical thermodynamics, statistical thermodynamics and DFRT. Further, correlation of experimental formation constant (K) with DFRT based stabilization energy is tested on several sets of reactions.

Chapter 5: The Chapter 5 tries to validate Hammett's linear free energy relationship (LFER) through DFRT based approach. Kinetic energy component $[\Delta E_{B(A)}]$, which is based on DFRT (CDASE scheme, to be more particular) is used to verify the linear nature of Hammett's $\log\left(\frac{k_X}{k_H}\right)$ vs. σ plot. The study shows that $\log\frac{[\Delta E_{B(A)}]_X}{[\Delta E_{B(A)}]_H}$ vs. σ plot (where -X is the atom or group substituted in place of –H) is linear in nature (with reasonably high correlation coefficient values) for different series of reactions.

Chapter 6: Chapter 6 summarizes the work presented in this thesis. Areas that require further exploration are identified and accordingly future scope of work is presented.

References:

1. T. L. Brown, H. E. Lemay. Bruce Edward Bursten, H. Lemay. Chemistry: The Central Science. Prentice Hall, 8 edition, **1999**, 3.

2. C. Møller, M. S. Plesset, *Phys. Rev.* **1934**, *46*, 618.

3. A. Szabo, N. S. Ostlund, Modern Quantum Chemistry: Introduction to Advanced Electronic Structure Theory, Courier Corporation, **2012.**

4. W. J. Hunt, P. Hay, W. A. Goddard III, *J. Chem. Phys.* **1972**, *57*, 738.

5. F. W. Bobrowicz, W. A. Goddard III, Methods of Electronic Structure Theory, **1977**, 3, 79.

6. R. J. Bartlett, *J. Phys. Chem.* **1989**, *93*, 1697.

7. R. Shepard, Advances in chemical physics: Ab Initio Methods in Quantum Chemistry. Part 2, **1987**, 69, 63.

8. K. Fukui, T. Yonezawa, H. Shingu, *J. Chem. Phys.* **1952**, *20*, 722.

9. K. Fukui, T. Yonezawa, C. Nagata, H. Shingu, *J. Chem. Phys.* **1954**, *22*, 1433.

10. R. Bonaccorsi, E. Scrocco, J. Tomasi, *J. Chem. Phys.* **1970**, *52*, 5270.

11. P. Politzer, *J. Chem. Phys.* **1980**, *72*, 3027.

12. P. Politzer, *J. Chem. Phys.* **1980**, *73*, 3264.

13. A. D. Becke, K. E. Edgecombe, *J. Chem. Phys.* **1990**, *92*, 5397.

14. A. Savin, O. Jepsen, J. Flad, O. K. Andersen, H. Preuss, H. G. v. Schnering, *Angew.Chem. Int. Ed. Engl.* **1992**, *31*, 187.

15. R. G. Pearson, *J. Am. Chem. Soc.* **1963**, *85*, 3533.

16. R. G. Parr, R. G. Pearson, *J. Am. Chem. Soc.* **1983**, *105*, 7512.

17. R. T. Sanderson, *Science.* **1951**, *114*, 670.

18. G. J. Klopman, *Chem. Phys.* **1965**, *43*, S124.

19. N. C. Baird, J. M. Sichel, M. A. Whitehead, *Theor. Chim. Acta.* **1968**, *11*, 38.

20. N. K. Ray, L. Samuels, R. G. Parr, *J. Chem. Phys.* **1979**, *70*, 3680.

21. T. Ziegler, *Chem. Rev.* **1991**, *91*, 651.

22. P. Geerlings, F. De Proft, W. Langenaeker, *Chem. Rev.* **2003**, *103*, 1793.

23. H. Chermette, *J. Comput. Chem.* **1999**, *20*, 129.

24. Y. Zhao, N. E. Schultz, D. G. Truhlar, *J. Chem. Phys.* **2005**, *123*, 161103.

25. R. G. Parr, W. Yang, *Annu. Rev. Phys. Chem.* **1995**, *46*, 701.

26. R. G. Pearson, *J. Chem. Educ.* **1987**, *64*, 561.

27. R. G. Pearson, *Acc. Chem. Res.* **1990**, *23*, 1.

28. R. G. Parr, P. K. Chattaraj, *J. Am. Chem. Soc.* **1991**, *113*, 1854.

29. W. J. Kohn, L. J. Sham, *Phys. Rev.* **1965**, *140*, A1133.

30. P. Hohenberg, W. Kohn, *Phys. Rev.* **1964**, *136*, B864.

31. L. J. Sham, W. Kohn, *Phys. Rev.* **1966**, *145*, 561.

32. P. C. Hohenberg, W. Kohn, L. J. Sham, *Advances in Quantum Chemistry*. P.-O. Löwdin, Ed. Academic Press, **1990**, p 7-26.

33. B. I. Dunlap, J. W. D. Connolly, J. R. Sabin, *J. Chem. Phys.* **1979**, *71*, 3396.

34. P. M. Boerrigter, G. T. Velde, J. E. Baerends, *Int. J. Quantum Chem.* **1988**, *33*, 87.

35. J. Andzelm, E. Wimmer, *J. Chem. Phys.* **1992**, *96*, 1280.

36. U. v. Barth, L. Hedin, *J. Phys.C: Solid State Phys*. **1972**, *5*, 1629.

37. M. M. Pant, A. K. Rajagopal, *Solid State Commun.* **1972**, *10*, 1157.

38. O. Gunnarsson, B. I. Lundqvist, *Phys. Rev. B.* **1976**, *13*, 4274.

39. J. C. Slater, *Phys. Rev.* **1951**, *81*, 385.

40. A. D. Becke, *J. Chem. Phys.* **1993**, *98*, 5648.

41. C. Lee, W, Yang, R. G. Parr, *Phys. Rev. B.* **1988**, *37*, 785.

42. J. P. Perdew, W. Yue, *Phys. Rev. B.* **1986**, *33*, 8800.

43. J. P. Perdew, *Phys. Rev. B.* **1986**, *33*, 8822.

44. J. P. Perdew, K. Burke, M. Ernzerhof, *Phys. Rev. Lett.* **1996**, *77*, 3865.

45. J. P. Perdew, Y. Wang, *Phys. Rev. B.* **1992**, *45*, 13244.

46. J. Tao, J. P. Perdew, V. N. Staroverov, G. E. Scuseria, *Phys. Rev. Lett.* **2003**, *91*, 146401.

47. A. D. Becke, *J. Chem. Phys.* **1996**, *104*, 1040.

48. A. D. Becke, *Phys. Rev. A.* **1988**, *38*, 3098.

49. C. Adamo, V. J. Barone, *Chem. Phys.* **1998**, *108*, 664.

50. B. J. Lynch, P. L. Fast, M. Harris, D. G. Truhlar, *J. Phys. Chem. A.* **2000**, *104*, 4811.

51. B. J. Lynch, Y. Zhao, D. G. Truhlar, *J. Phys. Chem. A.* **2003**, *107*, 1384.

52. C. Adamo, V. Barone, *J. Chem. Phys.* **1999**, *110*, 6158.

53. T. Yanai, D. P. Tew, N. C. Handy, *Chem. Phys. Lett.* **2004**, *393*, 51.

54. J.-D. Chai, M. Head-Gordon, *Phys. Chem. Chem. Phys.* **2008**, *10*, 6615.

55. N. Mardirossian, M. Head-Gordon, *J. Chem. Theory Comput.* **2016**, 12, 4303.

56.   M. Walker, A. J. A. Harvey, A. Sen, C. E. H. Dessent, *J. Phys. Chem. A.* **2013,** *117,* 12590.

57.   R. S. Mulliken, *J. Chem. Phys.* **1934,** *2,* 782.

58.   R. G. Pearson, *Science.* **1966,** *151,* 172.

59.   L. Pauling, *J. Am. Chem. Soc.* **1932,** *54,* 3570.

60.   J. Cioslowski, B. B. Stefanov, *J. Chem. Phys.* **1993,** *99,* 5151.

61.   E. P. Gyftopoulos, G. N. Hatsopoulos, *PNAS. USA.* **1968,** *60,* 786.

62.   R. P. Iczkowski, J. L. Margrave, *J. Am. Chem. Soc.* **1961,** *83,* 3547.

63.   R. G. Parr, R. A. Donnelly, M. Levy, W. E. Palke, *Chem. Phys.* **1978,** *68,* 3801.

64.   T. Koopmans, *Physica.* **1934,** *1,* 104.

65.   R. G. Pearson, *PNAS. USA.* **1986,** *83,* 8440.

66.   R. G. Pearson, *J. Chem. Educ.* **1999,** *76,* 267.

67.   B. M. Deb, *J. Am. Chem. Soc.* **1974,** *96,* 2030.

68.   B. M. Deb, P. N. Sen, S. K. Bose, *J. Am. Chem. Soc.* **1974,** *96,* 2044.

69.   B. M. Deb, *J. Chem. Educ.* **1975,** *52,* 314.

70.   J. Simons, K. D. Jordan, *Chem. Rev.* **1987,** *87,* 535.

71.   A. Z. Szarka, L. A. Curtiss, J. R. Miller, *Chem. Phys.* **1999,** *246,* 147.

72.   A. Dreuw, L. S. Cederbaum, *Chem. Rev.* **2002,** *102,* 181.

73.   R. K. Roy, S. Pal, *J. Phys.Chem.* **1995,** *99,* 17822.

74.   R. T. Sanderson, *Science.* **1955,** *121,* 207.

75.   W. J. Mortier, S. K. Ghosh, S. Shankar, *J. Am. Chem. Soc.* **1986,** *108,* 4315.

76.   F. De Proft, P. Geerlings, *Chem. Phys.* **2001,** *101,* 1451.

77.   W. Yang, R. G. Parr, *PNAS. USA.* **1985,** *82,* 6723.

78.   R. G. Pearson, *Coord. Chem. Rev.* **1990,** *100,* 403.

79.   S. Pal, K. R. S. Chandrakumar, *J. Am. Chem. Soc.* **2000,** *122,* 4145.

80.   K. R. S. Chandrakumar, S. Pal, *J. Phys. Chem. A.* **2002,** *106,* 5737.

81.   M. Berkowitz, R. G. Parr, *J. Chem. Phys.* **1988,** *88,* 2554.

82.   T. K. Ghanty, S. K. Ghosh, *J. Phys.Chem.* **1993,** *97,* 4951.

83.   S. Hati, D. Datta, *J. Phys.Chem.* **1994,** *98,* 10451.

84.   R. K. Roy, A. K. Chandra, S. Pal, *J. Phys.Chem.* **1994,** *98,* 10447.

85.   K. R. S. Chandrakumar, T. K. Ghanty, S. K. Ghosh, *J. Phys. Chem. A.* **2004,** *108,* 6661.

86.   R. G. Parr, L. v. Szentpály, S. Liu, *J. Am. Chem. Soc.* **1999**, *121*, 1922.

87.   M. Elango, R. Parthasarathi, G. K. Narayanan, A. M. Sabeelullah, U. Sarkar, N. S. Venkatasubramaniyan, V. Subramanian, P. K. Chattaraj, *J. Chem.Sci.* **2005**, *117*, 61.

88.   P. Bagaria, R. K. Roy, *J. Phys. Chem. A.* **2008**, *112*, 97.

89.   A. T. Maynard, M. Huang, W. G. Rice, D. G. Covell, *PNAS. USA.* **1998**, *95*, 11578.

90.   F. D. Vleeschouwer, V. V. Speybroeck, M. Waroquier, P. Geerlings, F. De Proft, *Org. Lett.* **2007,** *9,* 2721.

91.   P.W. Ayers, J. S. M. Anderson, J. I. Rodriguez, Z. Jawed, *Phys. Chem. Chem. Phys.* **2005,** *7,* 1918.

92.   P. W. Ayers, S. Liu, T. Li, *Chem. Phys. Lett.* **2009**, *480*, 318.

93.   R. G. Parr, W. Yang, *J. Am. Chem. Soc.* **1984**, *106*, 4049.

94.   A. K. Chandra, P. Geerlings, M. T. Nguyen, *J. Org. Chem.* **1997,** *62,* 6417.

95.   Y. Simón-Manso, P. Fuentealba, *J. Phys. Chem. A.* **1998**, *102*, 2029.

96.   L. T. Nguyen, F. De Proft, M. C. Amat, V. L. Gregory, P. W. Fowler, P. Geerlings, *J. Phys. Chem. A.* **2003,** *107,* 6837.

97.   M. Berkowitz, S. K. Ghosh, R. G. Parr, *J. Am. Chem. Soc.* **1985,** *107,* 6811.

98.   R. G. Parr, W. Yang, *Annu. Rev. Phys. Chem.* **1985,** *46,* 107.

99.   S. Saha, R. K. Roy, *J. Phys. Chem. B.* **2007,** *111,* 9664.

100.   S. Saha, R. K. Roy, *J. Phys. Chem. B.* **2008,** *112,* 1884.

101.   S. Saha, R. K. Roy. *Phys. Chem. Chem. Phys.* **2008,** *10,* 5591.

102.   T. Akama, M. Kobayashi, H. Nakai, *J. Comput. Chem.* **2007**, *28*, 2003.

103.   R. F. W. Bader, *Acc. Chem. Res.* **1975**, *8*, 34.

104.   V. H. S. Jr, I. Absar, *Israel J. Chem.* **1977**, *16*, 87.

105.   R. F. W. Bader, T. T. Nguyen-Dang, *Adv. Quantum Chem.* **1981**, *14*, 63.

106.   T. Fievez, N. Sablon, F. De Proft, P. W. Ayers, P. Geerlings, *J. Chem. Theory Comput.* **2008,** *4,* 1065.

107.   W. Langenaeker, K. Demel, P. Geerlings, *J. Mol Struct. (THEOCHEM).* **1991**, *80*, 329.

108.   M. H. Cohen, M. V. Ganduglia-Pirovano, *J. Chem. Phys.* **1994,** *101*, 8988.

109.   L. J. Bartolotti, P. W. Ayers, *J. Phys. Chem. A.* **2005**, *109*, 1146.

110.   J. P. Perdew, R. G. Parr, M. Levy, J. L. Balduz Jr., *Phys. Rev. Lett.* **1982**, *49*, 1691.

111. S. Nagakura, J. Tanaka, *J. Chem. Soc. Japan. Pure Chem. Sec.***1954**, *75*, 993.

112. K. Fukui, In Molecular Orbitals in Chemistry, Physics and Biology; Lowdin, P. O., Pullman, B., Eds., Academic Press: New York, **1964**.

113. W. Yang, W. J. Mortier, *J. Am. Chem. Soc.* **1986**, *108*, 5708.

114. W. T. Yang, R. G. Parr, R. Pucci, *J. Chem. Phys.* **1984**, *81*, 2862.

115. R. S. Mulliken, *J. Chem. Phys.* **1955**, *23*, 1833.

116. Z. Demircioglu, C. A. Kastas, O. Buyukgungor, *J. Mol. Struct.* **2015**, *1091*, 183.

117. R. K. Roy, S. Pal, K. Hirao, *J. Chem. Phys.* **1999**, *110*, 8236.

118. R. K. Roy, K. Hirao, S. Pal, *J. Chem. Phys.* **2000**, *113*, 1372.

119. P. Fuentealba, P. Perez, R. Contreras, *J. Chem. Phys.* **2000**, *113*, 2544.

120. R. K. Roy, K. Hirao, S. Krishnamurty, S. Pal, *J. Chem. Phys.* **2001**, *115*, 2901.

121. F. L. Hirshfeld, *Theor. Chim. Acta.* **1977**, *44*, 129.

122. P. W. Ayers, R. G. Parr, *J. Am. Chem. Soc.* **2000**, *122*, 2010.

123. P. W. Ayers, R. G. Parr, *J. Am. Chem. Soc.* **2001**, *123*, 2007.

124. P. W. Ayers, R. C. Morrison, R. K. Roy, *J. Chem. Phys.* **2002**, *116*, 8731.

125. J. Olah, C. V. Alsenoy, A. B. Sannigrahi, *J. Phys. Chem. A.* **2002**, *106*, 3885.

126. J. P. Foster, F. Weinhold, *J. Am. Chem. Soc.* **1980**, *102*, 7211.

127. A. B. Rives, F. Weinhold, *Int. J. Quantum Chem. Symp.* **1980**, *14*, 201.

128. A. E. Reed, F. Weinhold, *J. Chem. Phys.* **1983**, *78*, 4066.

129. A. E. Reed, R. B. Weinstock, F. Weinhold, *J. Chem. Phys.* **1985**, *83*, 735.

130. R. Bonaccorsi, E. Scrocco, J. Tomasi, *J. Chem. Phys.* **1970**, *52*, 5270.

131. R. G. Parr, R. F. Nalewajski, *PNAS. USA.* **2000**, *97*, 8879.

132. R. F. Nalewajski, *Phys. Chem. Chem. Phys.* **2002**, *4*, 1710.

133. P. W. Ayers, *J. Chem. Phys.* **2000**, *113*, 10886.

134. P. W. Ayers, *PNAS. USA.* **2000**, *97*, 1959.

135. P. W. Ayers, C. Morell, F. De Proft, P. Geerlings, *Chem. Eur. J.* **2007**, *13*, 8240.

136. R. K. Roy, S. Krishnamurti, P. Geerlings, S. Pal, *J. Phys. Chem. A.* **1998**, *102*, 3746.

137. O. Tishchenko, N. Pham-Tran, E. S. Kryachko, M. T. Nguyen, *J. Phys. Chem. A.* **2001**, *105*, 8709.

138. R. K. Roy, V. Usha, J. Paulovic, K. Hirao, *J. Phys. Chem. A.* **2005**, *109*, 4601.

139. S. K. Ghosh, M. Berkowitz, *J. Chem. Phys.* **1985**, *83*, 2976.

140. P. Bagaria, S. Saha, S. Murru, V. Kavala, B. Patel, R. K. Roy, *Phys. Chem. Chem. Phys.* **2009,** *11*, 8306.

141. K. R. S. Chandrakumar, S. Pal. *Int. J. Mol. Sci.* **2002**, *3*, 324.

142. S. Saha, R. K. Roy, S. Pal, *Phys. Chem. Chem. Phys.* **2010,** *12,* 9328.

143. A. Sarmah, S. Saha, P. Bagaria, R. K. Roy, *Chem. Phys.* **2012,** *394,* 29.

144. A. Sarmah, R. K. Roy, *RSC Adv.* **2013,** *3,* 2822.

145. A. Sarmah, R. K. Roy, *J. Phys. Chem. C.* **2013,** *117,* 21539.

146. A. Sarmah, R. K. Roy, *J. Comp. Aid. Mol. Des.* **2014,** *28,* 1153.

147. A. Sarmah, R. K. Roy, *J. Phys. Chem. C.* **2015,** *119,* 7940.

148. A. Sarmah, R. K. Roy, *Chem. Phys.* **2016,** *472,* 218.

149. R. T. Sanderson, *Science.* **1951,** *114,* 670.

150. R. T. Sanderson, *Science.* **1952,** *116,* 41.

151. R. G. Parr, R. A. Donnely, M. Levy, W. E. Palke, *J. Chem. Phys.* **1978,** *68,* 3801.

152. R. F. Nalewajski, *J. Am. Chem. Soc.* **1984,** *106,* 944.

153. P. W. Ayers, *Faraday Discuss.* **2007,** *135,* 161.

154. S. M. Nabavizadeh, A. Akbari, M. Rashidi, *Dalton Trans.* **2005,** 2423.

155. L. Miyan, Zulkarnain, A. Ahmad, *J. Mol. Struct.* **2017,** *1133,* 144.

156. M. Sánchez-Lozano, N. Otero, J. M. Hermida-Ramón, C. M. Estévez, M. Mandado, *J. Phys. Chem. A.* **2011,** *115,* 2016.

157. M. Cossi, C. Adamo, V. Barone, *Chem. Phys. Lett.* **1998,** *297,* 1.

158. M. Souri, A. K. Mohammadi, *J. Mol. Liq.* **2017,** *230,* 169.

159. U. C. Singh, P. A. Kollman, *J. Comput. Chem.* **1984**, *5*, 129.

160. G. King, A. Warshel, *J. Chem. Phys.* **1989**, *91*, 3647.

161. F. Maseras, K. Morokuma, *J. Comput. Chem.* **1995**, *16*, 1170.

162. M. Szafran, M. M. Karelson, A. R. Katritzky, J. Koput, M. C. Zerner, *J. Comput. Chem.* **1993**, *14*, 371.

163. D. J. Giesen, C. J. Cramer, D. G. Truhlar, *J. Phys. Chem.* **1995**, *99*, 7137.

164. D. J. Giesen, J. W. Storer, C. J. Cramer, D. G. Truhlar, *J. Am. Chem. Soc.* **1995**, *117*, 1057.

165. L. Onsager, *J. Am. Chem. Soc.* **1936**, *58*, 1486.

166. J. Tomasi, M. Perisco, *Chem. Rev.* **1994**, *94*, 2027.

167. S. Miertus, E. Scrocco, J. Tomasi, *J. Chem. Phys.* **1981**, *55*, 117.

168. J. Tomasi, R. Bonaccorsi, F. Cammi, F. O. Valle, *J. Mol. Struct. THEOCHEM.* **1991**, *234*, 401.

169. K. B. Wiberg, T. A. Keith, M. J. Frisch, M. Murcko, *J. Phys. Chem.* **1995**, *99*, 9072.

170. J. B. Foresman, T. A. Keith, K. B. Wiberg, J. Snoonian, M. J. Frisch, *J. Phys. Chem.* **1996**, *100*, 16096.

171. B. Mennucci, E. Cancès, J. Tomasi, *J. Phys. Chem. B.* **1997**, *101*, 10506.

172. A. V. Marenich, C. J. Cramer, D. G. Truhlar, *J. Phys. Chem. B.* **2009**, *113*, 6378.

173. J. Tomasi, B. Mennucci, R. Cammi, *Chem. Rev.* **2005**, *105*, 2999.

174. E. L. M. Miguel, C. I. L. Santos, C. M. Silva, J. R. P. Jr, *J. Braz. Chem. Soc.* **2016**, *27*, 2055.

175. A. Klamt, G. Schuurmann, *Chem. Soc. Perkin Trans 2.* **1993**, 799.

176. B. Safi, K. Choho, F. De Proft, P. Geerlings, *J. Phys. Chem. A.* **1998**, *102*, 5253.

177. B. Safi, K. Choho, P. Geerlings, *J. Phys. Chem. A.* **2001**, *105*, 591.

178. R. Balawender, B. Safi, P. Geerlings, *J. Phys. Chem. A.* **2001**, *105*, 6703.

179. R. Golbedaghi, F. Khajavi, *Bull. Chem. Soc. Ethiop.* **2014**, *28*, 1.

180. S. O. Mohod, D. T. Tayade, *Indo Am. J. Pharm. Sci.* **2017**, *4*, 245.

181. R. Thanavelan, G. Ramalingam, G. Manikandan, V. Thanikachalam, *J. Saudi Chem. Soc.* **2014**, *18*, 227.

182. M. Wacker, A. Seubert, *J. Anal. At. Spectrom.* **2014**, *29*, 707.

183. J. Bjerrum, Metal ammine formation in aqueous solution, theory of the reversible step reactions, Copenhagen, Denmark: P. Haase and Son, **1941**, 296.

184. L. Zekany, I. Nagypal, Plenum Press, New York, **1985**, 291.

185. P. Gans, A. Sabatinib, A. Vaccab, *Talanta.* **1996**, *43*, 1739.

186. H. D. Inerowicz, J. Chojnacki, *J. Incl. Phenom. Macro.* **2000**, *38*, 123.

187. M. Payehghadr, F. Nourifard, M. Kalhor, Ch. Shahoei, *J. Phys. Theor. Chem.* **2015**, *11*, 165.

188. E. Ohyoshi, *Polyhedron.* **1986**, *5*, 2101.

189. J. Dybal, S. Ehala, V. Kasicka, E. Makrlik, *Biopolymers.* **2008**, *89*, 1055.

190. M. Shiotsuka, Y. Ueno, D. Asano, T. Matsuoka, K. Sako, *Trans. Met. Chem.* **2015**, *40*, 673.

191. S. Iravani, G. Rounaghi, M. Ebrahimi, *Russ. J. Electrochem*. **2016**, *52*, 1015.

192. Y. Jia, J. Li, *Chem. Rev*. **2015**, *115*, 1597.

193. M. Y. Udugala-Ganehenege, N. M. Dissanayake, A. M. K. S. P. Adhikari, *J. Inorg. Organomet. Polym. Mat*. **2015**, *25*, 964.

194. M. Amina, M. Tariq, M. R. Elsegood, G.W. Weaver, *J. Nucl. Med. Radiat. Ther*. **2016**, *7*, 1.

195. S. Esmaielzadeh, G. Mashhadiagha, *Bull. Chem. Soc. Ethiop*. **2017**, *31*, 159.

196. P. R. Wells, *Chem. Rev*.**1963**, *63*, 171.

197. R. W. Taft Jr, John Wiley and Sons, Inc., New York, NY., **1956,** Chapter 13.

198. J. N. Brønsted, K. J. Pedersen, Zeitschrift für Phys. Chemie, Stöchiometrie und Verwandtschaftslehre, **1924,** *108*, 185.

199. R. P. Bell, Clarendon Press, Oxford, Eng., 1941 (a) Chapter X, (b) 158.

200. L. P. Hammett, *J. Am. Chem. Soc*.**1937**, *59*, 96.

201. C. Hansch, A. Leo, R. W. Taft, *Chem. Rev*. **1991**, *91*, 165.

202. S. L. Keenan, K. P. Peterson, K. Peterson, K. Jacobson, *J. Chem. Educ*. **2008,** *85*, 558.

203. H. H. Jaffe, *Chem. Rev*. **1953**, *53*, 191.

204. A. M. Al-Ajlouni, A.Günyar, M-D. Zhou, P. N. W. Baxter, Fritz E. Kühn, *Eur. J. Inorg. Chem*. **2009**, 1019.

205. R. K. Akhani, M. I. Moore, J. G. Pribyl, S. L. Wiskur, *J. Org. Chem*. **2014,** *79*, 2384.

206. H. B. E. Ayouchia, H. Anane, M. L. E. I. Moubtassim, L. R. Domingo, M. Julve, S-E. Stiriba, *Molecules*. **2016**, *21*, 1434.

207. S. K. Yousuf, D. Mukherjee, B. Singh, S. Maity, S. C. Taneja, *Green Chem*. **2010,** *12*, 1568.

208. S. M. Nabavizadeh, *Inorg. Chem*. **2003,** *42*, 4204.

209. R. Wolfenden, W. P. Jencks, *J. Am. Chem. Soc*. **1961,** *83*, 2763.

210. R. J. Mullins, A. Vedernikov, R. Viswanathan, *J. Chem. Educ*. **2004,** *81*, 1357.

211. R. W. Murray, G, Hong, *J. Org. Chem*. **1995,** *60*, 5673.

212. S. R. Reddy, P. Manikyamba, *J. Chem. Sci*. **2006,** *118*, 257.

213. J. B. Smith, H. Byrd, S. E. O'Donnell, W. Davis, *J. Chem. Educ*. **2010,** *87*, 845.

214. P. Scheiner, J. H. Schomaker, S. Deming, W. J. Libbey, G.P. Nowack, *J. Am. Chem. Soc*. **1964,** *87*, 307.