Original Research Article

Study of the Formation, Energetics, Specific Interaction, Charge Transfer and Nature of Hydrogen Bonds in Dimerization of the 2PY (C_5H_4X N (O) Derivatives (X= F, Cl, and Br): DFT, AIM and NBO analyses

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ABSTRACT

The hydrogen bonding interaction plays an important role in determining the shape, the structure and stability, physical properties and functions of molecules. In current research, two intermolecular interactions, i.e., (1) hydrogen bonds and (2) substituent effects, were analyzed and compared. For this purpose, the geometries of 2-pyridone and its substituted dimers (C_5H_4X N (O) X = F, Cl and Br) were optimized by means of $B_3LYP/6$-$311 + +G$ (d, p) method. The dependence between the strength of hydrogen bonding and the H···Y distance is discussed for the hydrogen bonds N-H…O (X=N; Y=O) system. The N-H…O angle is another geometrical characteristic of hydrogen bonding. To further investigation of nature and strength of hydrogen bond interactions in these systems the structural and electronic parameters were analyzed by using the quantum theory of atoms in molecule (QTAIM) and natural bond orbital (NBO) analyses. Natural bond orbital (NBO) analysis was performed to reveal the origin of the interaction.

Keywords: Density function theory, Hydrogen bond, Quantum Theory of atoms in molecule (QTAIM), NBO *analysis, Bond critical points, Interaction energy removal*

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Introduction

Hydrogen bond (H-bond) is one of the most important interactions in chemical and biochemical reactions which occurs generally in aqueous and polar environments [1, 2]. Due to the importance of hydrogen bond in natural science, many researchers have devoted their attention to study different aspects of this interaction [3, 8]. Hydrogen bonding has been a very interesting issue for chemists for a long time since it can account for characteristics of many chemical and biological phenomena [9]. There are several aspects of hydrogen bonding such as the nature of physical forces involved, various hydrogen bond donors-acceptors, distance and energy criteria, and spectroscopic characterization [10, 12]. However, this type of chemical attraction is weaker than other types of chemical bonds such as covalent and ionic bonds but is stronger than van der Waals interactions [10, 13].

The current research we evaluate structural parameters and stabilities of hydrogen bonded formed in the 2-pyridone. (2PY) dimers. We use topological parameters such as electron density $\rho(r)$ and Laplacian of electron density $\nabla^2\rho(r)$ from Bader's atoms in molecules theory (AIM) and natural bond orbital (NBO) analyses for interpretation of nature of intermolecular hydrogen bonds.

Theoretical method

The investigated monomers and dimers were geometrically optimized at the B3LYP/6-311++ G (d,p) levels using Gaussian 2003 program [14]. Energy minimizations followed by harmonic vibrational calculations were performed at this level of theory. Vibration frequencies are also calculated to confirm that all the stationary points correspond to true minima on the potential energy surface and these calculations were used to correct all the calculations to 298.15 K.

Quantum theory of atoms in molecule (QTAIM) was applied to investigate the electronic parameters and nature of hydrogen bonds in more details [15, 19]. The topological analysis was performed using the AIM2000 program [20]. QTAIM allows the calculation of certain physical properties per atom basis, by dividing space up into atomic volumes containing exactly one nucleus which acts as a local attractor of the electron density ($\rho_{(r)}$). In QTAIM, the values of electron density ($\rho_{(r)}$) and its Laplacian ($\nabla^2\rho_{(r)}$) in bond critical point (BCP) use to characterize the nature of the chemical interaction. The electron energy density at BCP has two components: the potential

electronic energy density $(V_{(r)})$ must be negative and the electronic kinetic energy density $(G_{(r)})$ which is always positive. There is a relation between these energetic characteristics, $H_{(r)} = V_{(r)} + G_{(r)}$. According to QTAIM theory, the interaction can be considered as partly covalent bonding when $\nabla^2 \rho_{(r)} > 0$ and $H_{(r)} < 0$ whereas for ionic, van der Waals and H-bond interactions are characterized by $\nabla^2 \rho_{(r)} > 0$ and $H_{(r)} > 0$. Popelier proposed the following criteria for strength of H-bonds: for weak H-bonds, $\nabla^2 \rho_{(r)} > 0$ and $H(r) > 0$; for H-bonds of medium strength, $\nabla^2 \rho_{(r)} > 0$ and $H(r) < 0$; for strong H-bonds, $\nabla^2 \rho_{(r)} < 0$ and $H(r) < 0$ [21, 28].

NBO analysis was introduced by Weinhold et al. transforms the delocalized molecular orbitals into localized ones that are closely related to chemical bond concepts. The stabilization energy $E^{(2)}$ associated with charge transfer between donor (i) and acceptor (j) can be evaluated by second-order perturbation theory analysis of the Fock matrix.

$$E(2) = \Delta E_{ij} = \Delta E_{CT} = -2 \frac{\langle i|\hat{F}|j\rangle^2}{\varepsilon j - \varepsilon i} \tag{1}$$

Where ε_i and ε_j are NBO's orbital energies, and $\hat{F}$ is the Fock operator. The quantities of transferred charge from a given donor orbital to a given acceptor orbital might be estimated again using the perturbation theory arguments, leading to the following approximate formula: [21, 29].

$$q_{donor-acceptor} \approx 2 \left[\frac{\langle i|\hat{F}|j\rangle^2}{\varepsilon j - \varepsilon i} \right] \tag{2}$$

Results and Discussion

Hydrogen bonding energies and geometrical parameters

The optimized structures of the monomer of pyridone, pyridone dimer and substituted dimers $(C_5H_4XNO, X= (F, Cl \text{ and } Br))$ obtained at DFT/B3LYP/6-311++G (d, p) are displayed in Figure 1. The frequency calculation results show no imaginary frequencies, which confirms that the obtained structures are local minima in the potential energy surfaces (PESs). All of above mentioned structures have *C1* symmetry point group. Generally, the energy will decrease when two molecules interact, which is called the interaction energy or binding energy. The stability of the complex is closely related to the interaction energy. The interaction energy (ΔE) is calculated

by evaluating the difference between the total energies of complex ($E_{complex}$) and individual monomers according to the following expression:

$$\Delta E = E \text{ (complex)} – E \text{ (monomer1)} – E \text{ (monomer 2)} \qquad (3)$$

Quantum chemical calculations offer a direct estimation of Inter-molecular interaction energy as the energy lost by dimerization or complexation of molecules. This is what is known as super-molecular approach. ΔE must be corrected to account for basis set super-position errors (BSSE). ΔE^{CP} is positive because the energy calculated at complex basis set (A∪B) is lower than the energy calculated with the use of the monomer basis sets (A or B). There are also other approaches that lead to them reduction of the basis set superposition error. The other important correction often included in calculations is the so-called "zero point vibrational energy" (ZPVE). Thus, there are the following important effects that should be taken into account to estimate the binding energy, particularly H-bond energy: the deformation energy, a physical effect being the result of complexation; ZPVE, the physical effect connected with vibrations in the ground state; and BSSE, the effect connected with computational limitations because the frequently applied basis sets are not saturated. The uncorrected and corrected interaction energies including $(\Delta E)^{CP}$ and $(\Delta E)^{C, ZPE}$ of the complexes are defined by:

$$(\Delta E)^{CP} = (\Delta E) + BSSE \qquad (4)$$

$$(\Delta E)^{CP, ZPE} = (\Delta E)^{CP} + ZPE \qquad (5)$$

In order to take into account the basis set superposition error (BSSE), the values of interaction energy were corrected with the Boys and Bernardi procedure [30, 40], and to give the counterpoise corrected interaction energies (ΔE^{CP}). Table 1 presents the interaction energies (ΔE), basis-set superposition error (BSSE), interaction energies corrected for BSSE (ΔE^{CP}), $(\Delta E)^{CP, ZPE}$ and dipole moments (μ) obtained at the B3LYP/6-311++G (d, p) level.

Monomer   **H-bonded Dimer**
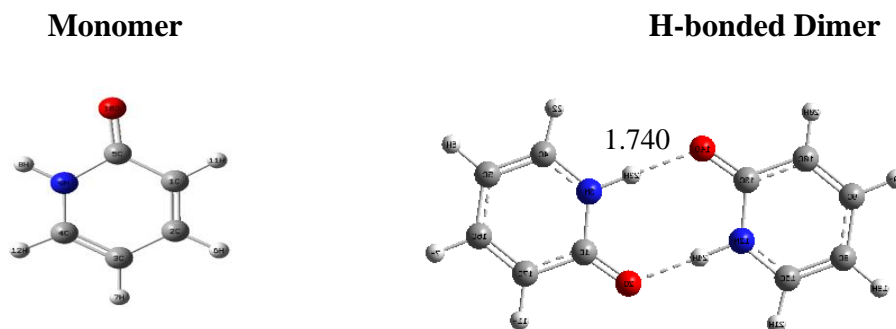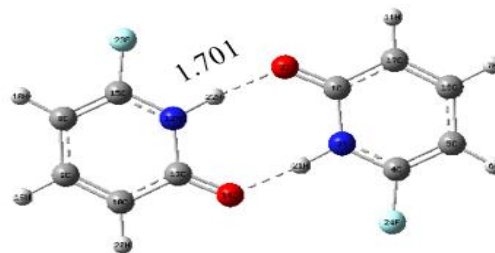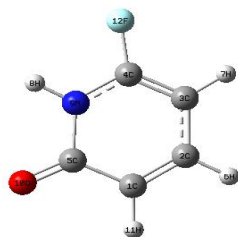
2-pyridone

6-Fluro-2-pyridone
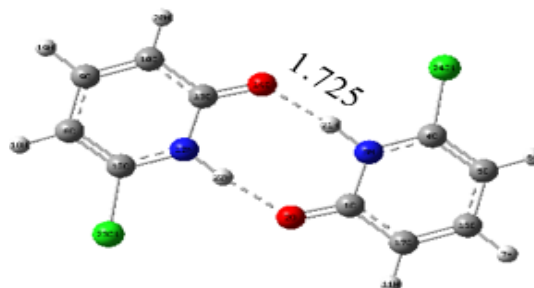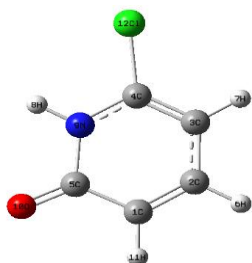
6-Choloro-2-pyridone

6-Bromo-2-pyridone

Figure 1. Optimized structures of monomer of 2-pyridone and its substituted dimers (C5H4XNO, X= (F, Cl and Br)) obtained at DFT/B3LYP/6-311++ G (d, p)
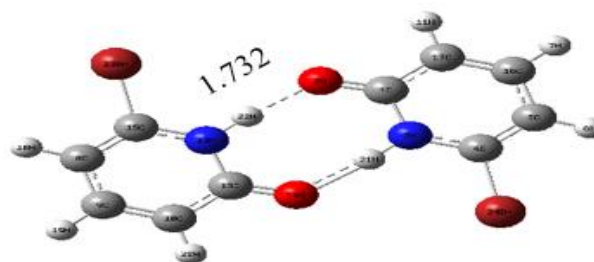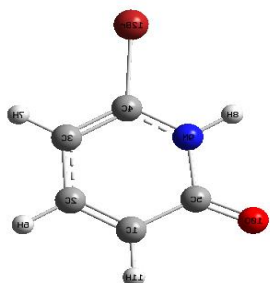
Table 1. The structures of monomer of pyridone molecules (X=F, Cl, and Br) were optimized at the DFT/B3LYP/6-311++ G (d, p) level of theory .The absolute energies of these molecules and dimer and its substituted dimers are listed in Table 1.

Monomers of Compounds	Sum of Electronic and ZPE	Dimers of Compounds	Sum of Electronic and ZPE
pyridone	-323.520533	2-pyridone	-647.072782
1	-422.797258	6-Fluro-2-pyridone	-845.622557
2	-783.23451745	6-Choloro-2-pyridone	-1566.328843
3	-2897.071362	6-Bromo-2-pyridone	-5794.168525

Table 2. The different types of energy include Binding energy (ΔE), basis-set superposition error (BSSE), interaction energies corrected for BSSE (ΔE^{CP}) , $(\Delta E)^{CP, ZPE}$ (in kcal. Mol^{-1}), and dipole moments (μ, in Debye), of 2-pyridone dimer and its substituted dimers (complexes C_5H_4XN (O), X= (F (1), Cl (2) and Br (3)) obtained at B3LYP/6-311G++ (d, p) level.
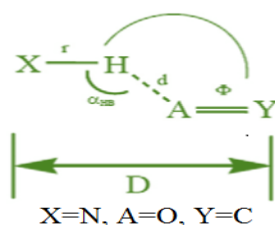
Structure				ΔE^{CP}	$(\Delta E)^{CP,ZPE}$	
	ZPE	ΔE	BSSE	ΔE + BSSE	ΔE + BSSE+ZPE	μ
2-pyridone dimer	0.1885	-19.45	0.707	-18.75	-18.55	0.0000
1	0.1710	-18.83	0.879	-17.95	-17.78	0.0005
2	0.1681	-18.20	0.974	-17.22	-16.05	0.0009
3	0.1668	-16.94	0.816	-16.12	-15.96	0.0017

The stability of the complex is closely related to the interaction energy. According to Table2, the results of B3LYP calculations show that the interaction energies ΔE^{CP} of hydrogen bonded complex decrease in the order **1 > 2 > 3**. This order for complex C_5H_4FNO is correlated to the electronegativity of the substituted -F atom. The corrected binding energy for its substituted -F atom, C_5H_4FN (O) complex (1), is -17.95 kcal.mol^{-1}, which is the largest among all substituted complexes. The binding energy for C_5H_4BrN (O) complex (1), -16.12 kcal/mol, is the smallest among all of substituted complexes. The BSSE of these substituted complexes are 0.879, 0.974 and 0.816 kcal/mol, respectively. The un-corrected interaction energies are -19.45 kcal/mol for 2- pyridone dimer and -18.83,-18.20 , and -16.94 kcal/mol for substituted *2PY* derivatives (C_5H_4XN (O), X=F (**1**), Cl (**2**) and Br (**3**)), respectively, and indicating that hydrogen bonding in

complex 2-pyridone dimer is almost as strong as in a substituted X dimer (X= F, Cl, Br atom). Binding energy could be caused by the change transient or permanent dipole intermolecular dipole. The direction of frequency shift in these complexes is governed by inter- and intramolecular hyperconjugation and re-hybridization factors. The X−H bond length changes and variation of frequency shifts in investigated complexes could cause by the formation of hydrogen bonds in dimers.

The strength of the hydrogen bond in X-H……A-Y hydrogen bond model, where the X-H group is called the donor and A-Y is called acceptor, is described by geometrical parameters such as d, D, Φ, r and α_{H-B} which are introduced in Table 3. These parameters for 2-pyridone and its substituted dimers (C_5H_4XN (O), X= (F (**1**), Cl (**2**) and Br (**3**)) have been collected and compared to reference parameters. Consequently, both the uncorrected and corrected binding energies indicate that the stability of the dimers order as **1**> **2** >**3**. This order is consistent with the proposed order based on the mean intermolecular distances.

Table 3. Calculated values of Hydrogen bond parameters, bond length (Å) and frequency (cm^{-1}) for 2-pyridone and C_5H_4XN (O) (X= F (**1**), Cl (**2**), and Br (**3**) dimers obtained at the B3LYP/6-311++G (d, p) level. All distances are in angstrom (Å).

X=N, A=O, Y=C

Structure	$r_{(N-H)}$	$\upsilon_{(N-H)}$	$r_{(N-H..O)2}$	$\upsilon_{(N-H..O)2}$	Δr	$\Delta \upsilon$	d	$\alpha°_{HB}$	D
	Monomer	Monomer	Dimer	Dimer	(Å)	(cm^{-1})	(H...O)		(Å)
2-pyridone	1.0120	730.95	1.0404	370.49	0.028	-360.5	1.74	178.57	3.63
1	1.0131	166.81	1.0474	448.89	0.034	-282.1	1.70	174.56	3.67
2	1.0125	564.55	1.0430	279.73	0.031	-284.2	1.72	174.57	3.66
3	1.0123	602.49	1.0413	237.42	0.029	-365.1	1.73	178.34	3.62

Generally, hydrogen bonding interactions are related with the number and strength of hydrogen bond, as well as structural parameters such as hydrogen bond lengths and angles. Shorter bonding distance usually means the strengthening of an interaction, and the interaction

energy ΔE shows the strength of the hydrogen bond, as well as the stability of the complexes. The N-H … B angle is another geometrical characteristic of hydrogen bonding. It was stated that for very strong hydrogen bonds, the N-H…O angle range is 175-180°, for strong it is 130-180°, while for weak it is 90-180°[1]. The bond angles ∠N−H···O for 2-pyridone and hydrogen bonded dimers are 178.57°, 174.56° (**1**), 174.57 (**2**) and 174.29 (**3**), respectively, which means the hydrogen bonds almost tend to be linear. This may be explained as a consequence of the maximal $n_O{\rightarrow}\sigma^*_{NH}$ overlap. This linear structure will lead to strong stability, which is the special electronic property of hydrogen bonds.

Subsequently, according to our results in Table 3 we note that complex 1 and 2 molecules have, respectively, the shortest and longest bond lengths in both hydrogen bonds. As can be seen in Table 3 there is an elongation of the H−N bond upon hydrogen-bonding formation in complexes. The corresponding harmonic vibrational frequencies in Table 3 (obtained at B3LYP/6-311++G (d, p) level) are also shown the red-shifting character of the N−H…O interaction. For the red-shifted hydrogen bonds, there is an additional bond lengthening due to orbital interactions that is not overcome by the modest bond compression resulting from the repulsive interactions. In agreement with the computed H−N bond elongation, the H−N stretching frequencies are decreased by -282.1, -284.2 and -365.1 cm^{-1} in **1**, **2** and **3**, hydrogen bonded complexes, respectively. The order of the N−H···O bond stretching vibration frequency is 1> **2** > **3**.

NBO and frequency analyses

The NBO analysis has been used to study the hydrogen bonds and explore the essence of frequency shift of the involved H−X bonds. Table 3 Results of the NBO analysis, bond length (Å) and frequency (cm^{-1}) for all hydrogen bonded dimers are given in Table 2. The large Δr(N−H) and Δv(N−H) values are closely related to the stronger intermolecular and smaller intramolecular interaction energies, respectively (Table 2). The intermolecular NBO interactions that reveal the origin of the intermolecular interactions between donor and acceptor belong to different sub-molecules in a system. The amount of partial transferred charge between a donor and an acceptor species ($q_{donor\rightarrow acceptor}$) was calculated by the occupation numbers from the NBO data for evaluating the orbital interaction energy ($\Delta E^{(2)}$) in donor-acceptor system. Therefore, to better understand the intermolecular interactions, NBO analysis has been carried out at the

B3LYP/6-311++ G (d, p) level. Table 3 summaries the NBO second-order perturbation stabilization energy between the donor and the acceptor (between 'filled' (donor) Lewis-type NBOs and 'empty' (acceptor) non-Lewis NBOs) in hydrogen bonded dimers (O…H-Y, Y=N). Based on these results the stabilization interaction between the lone pair (LP) orbital of O atom as donor and the anti-bonding sigma orbital of the N-H bond as acceptor in these complexes is directly related to the hydrogen-bond. Meaning while charge transfer from the oxygen lone pairs, n, of the electron donor to the proximate N-H anti-bond, $\sigma*$, of the electron acceptor was found to be of critical importance.

The NBO stabilization energies for 2-pyridone dimer associated with LP(1) $_{O2} \to \sigma*$ $_{N12-H24}$ and LP(2)$_{O2} \to \sigma*_{N12-H24}$ delocalization interactions are 7.41 and 18.16 kcal mol^{-1}, respectively. In substituted hydrogen bonded dimer the hydrogen bonds interaction energies, n$\to \sigma*$ interaction, are as follow (Table 4): LP2 (O$_2$)$\to$ N$_{12-}$ H$_{22}$ and LP2 (O$_{14}$) $\to\sigma*$(N3-H$_{21}$) with delocalization energy of 20.05 kcal/mol in C$_5$H$_4$FN (O), LP2 (O$_2$)$\to$ N$_{12-}$ H$_{22-}$ and LP2 (O$_{14}$) $\to\sigma*$ N$_3$-H$_{21}$ with delocalization energy of 17.70 kcal/mol in C$_5$H$_4$ClN (O), and LP2 (O$_2$) $\to$H$_{22-}$N$_{12}$ and LP2 (O$_{14}$) $\to\sigma*$ N$_3$-H$_{21}$ (E$^{(2)}$ = 16.68 kcal/mol in C$_5$H$_4$BrN (O). The natural hybrids (NHOs), occupancies and stabilization energies (E$^{(2)}$) for LP2 O$_2\to$H$_{22}$-N$_{12}$ and LP2$_{O14}$ $\to\sigma*$ N$_3$-H$_{21}$ interactions in 2-pyridone and C$_5$H$_4$XN structures dimers (X=F, Cl and Br) are given in Table 4. Generally, a certain amount of charge transfer occurs from the hydrogen bond acceptor to the hydrogen bond donor during the process of H-bond formation. This leads to a rearrangement of electron density within each part of molecule. The small value of E$^{(2)}$ is responsible for the weak orbital interaction of hydrogen bond and the larger E$^{(2)}$ value corresponds to strong charge transfer effect happened in hydrogen bond formation.

Table 4. The orbitals occupancy, orbital energy, the second-order perturbation energy (E$^{(2)}$) and the difference of energies between acceptor and donor NBOs ($\Delta\varepsilon$) for 2-pyridone and C$_5$H$_4$XNO (X= F (**1**), Cl (**2**) and Br (**3**)) Complexes.

Complex	Donor	Occupancy	Orbital energy	Acceptor	Occupancy	Orbital energy	E$^{(2)}$	F$_{ij}$
	LP(1)$_{O2}$	1.96161	-0.66291	BD* $_{N12-H24}$	0.06633	0.40705	7.41	0.080
2-PY	LP(2)$_{O2}$	1.86130	-0.28389	BD* $_{N12-H24}$	0.06633	0.40705	18.16	0.102
	LP(1)$_{O14}$	1.96162	-0.66293	BD* $_{N3-H23}$	0.06632	0.40705	7.41	0.080

	LP(2)O_{14}	1.86131	-0.28386	BD* $N3-H23$	0.06632	0.40705	18.15	0.102
	LP(1)$_{O2}$	1.95579	-0.66803	BD* $N12-H22$	0.07201	0.38021	9.83	0.091
1	LP(2)$_{O2}$	1.85650	-0.29980	BD* $N12-H22$	0.07201	0.38021	20.05	0.106
	LP(1)$_{O14}$	1.95579	-0.66803	BD* $N3-H21$	0.07201	0.38021	9.83	0.091
	LP(2)$_{O14}$	1.85650	-0.29980	BD* $N3-H21$	0.07201	0.38021	20.05	0.009
	LP(1)O_2	1.95628	-0.6716	BD* $N12-H22$	0.06923	0.38787	9.69	0.091
2	LP(2)O_2	1.85763	-0.2915	BD* $N12-H22$	0.06923	0.38787	17.70	0.100
	LP(1)O_{14}	1.95628	-0.6716	BD* $N3-H21$	0.06923	0.38787	9.69	0.091
	LP(2)O_{14}	1.85763	-0.2915	BD* $N3-H21$	0.06923	0.38787	17.70	0.100
	LP(1)O_2	1.95621	-0.67327	BD* $N12-H22$	0.06837	0.38959	9.71	0.091
3	LP(2)O_2	1.85707	-0.28895	BD* $N12-H22$	0.06837	0.38959	16.88	0.097
	LP(1)O_{14}	1.95621	-0.67327	BD* N_3-H_{21}	0.06837	0.38959	9.71	0.091
	LP(2)O_{14}	1.85707	-0.28895	BD* N_3-H_{21}	0.06837	0.38959	16.88	0.097

As shown in Table 4, the total stabilization energy for LP $_O \rightarrow \sigma^*$ delocalization decreases with increasing p character of oxygen lone pair. The present results illustrates that there is a logical relationship between the $\Sigma E^{(2)}$ in kcal/mol with p character of oxygen lone pair and hydrogen contact distance as well. Therefore, charge transfer changes occur in an inconsistent fashion with the interaction energy and is not the main factor causing the weak intermolecular interactions in these complexes. The data provided in Table 4 showed that the amount of charge transfer in these investigated complexes is very small. The NBO analysis showed that the increasing of total interaction energy between LP (O) and non-Lewis-type NBOs (σ^*) is consistent with the trend of binding energy obtained from geometry optimization and stabilization energies $E^{(2)}$ are proportional to the NBO interaction.

Table 5. Calculated natural hybrids (NHOs), occupancies resonance energies (in kcal mol^{-1}) of oxygen lone pair (using NBO analysis), binding energies and hydrogen contact distance (in Å) for -pyridone and three complexes $C_5H_4XN(O)$ (X= F (**1**), Cl (**2**) and Br (**3**)) obtained at the B3LYP/6- 311++G (d, p) level.

Structure	$\Delta q\ i \rightarrow j$/a.u	$\Sigma E^{(2)}$	Binding energy	NHOs	Hydrogen contact distance
2-PYdimer	1.7950	18.24	-19.45	$sp^{28.31}$	1.740
$C_5H_4FN(O)$	1.7845	20.12	-18.83	$sp^{24.90}$	1.701

C$_5$H$_4$ClN(O)	1.7884	17.78	-18.20	sp$^{31.36}$	1.725
C$_5$H$_4$BrN(O)	1.7887	16.96	-16.94	sp$^{34.65}$	1.732

Table 4 also shows that the total stabilization energies for investigated dimers are 20.12, 17.78 and 16.96 kcal/mol for C$_5$H$_4$FN (O), C$_5$H$_4$ClN (O) and C$_5$H$_4$BrN (O) dimers, respectively. Although the stability sequence does not simply depend on the largest or the main stabilization energy, it can be concluded that the order of the stabilization energies of dimers is **1** >**2** > **3** based on the total stabilization energies, which is in agreement with the sequence of the hydrogen bond lengths. It is worth to mention that the dipole moments for investigated hydrogen bonded dimers are zero due to its centrosymmetric structure.

Our results suggest that the increasing p character in hydrogen bonds at these compounds lead to the displacement of the bond angles from their idealized values (bond angles of 120° for sp^2 hybridized atoms) which tends system to be linear. This angle would make the molecule less stable .This might be explained as a consequence of the maximal n$_O$ →σ*$_{N-H}$ overlap. Hence, if hydrogen bonding is stronger, thus the X-H…Y angle is closer to 180°, It was stated that for very strong hydrogen bonds, the X-H…Y angle range is 175- 180°, for strong it is 130-180°, while for weak it is 90-180°.

Charge transfer changes occur in an inconsistent fashion with the interaction energy and is not the main factor causing the weak intermolecular interactions in these complexes. The order of the charge transfer changes ($\Delta q_{i\rightarrow j}$ /a.u) are **2PY** > **3** > **2** > **1** dimers. The molecular orbital (MO) theory is employed extensively to describe chemical behavior. The chemical properties of the molecules can be directly correlated to their electronic structures. The quantum chemical parameters in Table 5 provide information about the chemical reactivity of our studied molecules. The thermodynamic parameters and quantum molecular descriptors for investigated hydrogen-bonded dimers such as values of the highest occupied molecular orbital (E$_{HOMO}$), the lowest unoccupied molecular orbital (E$_{LUMO}$), the gap (ΔE), ionization potential (IP), electron affinity (EA), global hardness (η), electronegativity (χ), chemical potential (*μ*), global softness (σ), electrophilicity (*ω*), and dipole moments (μ) are listed in Table 5.

Table 5. Thermodynamics parameters and quantum molecular descriptors for C_5H_4XN (O) (X= F, Cl and Br) systems.

Molecular Descriptors	2PY-dimer	C5H4FN (O)	C5H4ClN (O)	C5H4BrN (O)
H (a.u.)	-647.059975	-845.608107	-1566.313536	-5794.152654
G (a.u.)	-647.112693	-845.664940	-1566.373115	-5794.215137
HOMO (eV)	-0.22889	-0.23718	-0.23539	-0.23451
LUMO (eV)	-0.05434	-0.05992	-0.06406	-0.06445
ΔE_{Gap} (eV)	0.1746	0.1773	0.1713	0.1701
IP = $-E_{HOMO}$ (eV)	0.22889	0.23718	0.23539	0.23451
EA = $-E_{LUMO}$ (eV)	0.05434	0.05992	0.06406	0.06445
(I-A)/2 (eV) = η	0.0872	0.0886	0.08566	0.08503
(I+A)/2 (eV) = χ	0.1416	0.14855	0.149725	0.14948
$\mu = -\chi$ (eV)	-0.1416	-0.14855	-0.149725	-0.14948
$\sigma = 1/\eta$ (eV^{-1})	11.4679	11.2867	11.6741	11.7605
$\omega = \chi^2/2\eta$ (eV)	0.00087	0.00097	0.00096	0.00095
Dipole moment (μ)	0.0054	0.0005	0.0009	0.0017

The energy of HOMO implies the ability of a molecule to donate electrons and the energy of LUMO describes the electron accepting ability of a molecule [41-42]. As shown in Table 5 the

complexes of F and Br have the lowest and the highest values of E_{HOMO} and E_{LUMO}, respectively. As the HOMO-LUMO gap and the global hardness are the index of chemical reactivity and the chemical potential the electron-escaping tendency from a molecule could measure by these parameters. It is well-known that molecules with large HOMO–LUMO gaps are generally stable and unreactive; while those with small gaps are generally reactive. Ionization potential (IP) is a basic description of the chemical reactivity of atoms and molecules. High IP pertains to strong stability; therefore, Br-substituted dimer has lower IP energy than other substituted dimers (Table 5). The ability of the molecules to accept electrons may be described by the electrophilicity (ω) index. Therefore, F-substituted dimer is more electrophilic than Cl-substituted dimer and later one is more electrophilic than Br-substituted dimer. The results of NBO analysis are in a good agreement with geometric, energetic, and structural properties which confirms that the trend of reactivity for C_5H_4XN (O) (X= F, Cl and Br) dimers.

Quantum Theory of Atoms-In-Molecules Analysis

The electron density of distribution of QTAIM analysis is mainly affected by interactions between nuclei. The maxima of electron density are attributed to these nuclei (approximately to the atomic positions), and each atom may be described by its boundaries dependent on the balance of forces of the considered system. To more investigate the nature and essence of hydrogen bonds in investigated dimers, QTAIM topological parameters of 2-pyridone dimer and its hydrogen-bonded dimers obtained at the B3LYP/6- 311++G (d, p) level are given in with the results listed in Table 6.

The character of the A···B interaction in bond critical point could be classified as a function of the Laplacian of the electron density $\nabla^2\rho$ (r) and the total electron energy density at the associated critical points. QTAIM molecular graph of the 2-pyridone dimer is shown in Figure 2. There is an intermolecular bond critical point in the line O···H and two bond paths appear between the hydrogen bond critical point (BCP). According to AIM analysis, for 2-pyridone dimer, the electron density $\rho(r)$ at the BCP of N-H…O hydrogen bond is $\rho(r)$) is very small (< 0.1 a.u, indicating that the charge is dispersed around the nucleus with positive Laplacian $\nabla^2\rho$ (r) (0.1598 a. u.). Weak interaction of the electron density $\rho(r)$ at the BCP is a measure of an important indicator of the interaction strength that related to bond order and the. Hydrogen bonds with weak and medium in strength show both positive $\nabla^2\rho$ (r) and H(r) values. For very strong hydrogen bonds, $\nabla^2\rho$ (r) and consequently H(r) values are negative. If H(r) is negative, then the

local potential electron energy dominates and the localization of electron density at BCP has a stabilizing impact on the species; when H(r) is positive, then the electron localization has a destabilizing impact on the system. Meaning while $H(r) < 0$ reflects a prevalence of the potential energy, which is a consequence of the stabilization of the accumulated electron charge, a typical feature of covalent interactions. Hence, a partial covalent character is attributed to the H-bonds exhibiting $H(r) < 0$.

Table 6. Topological properties of the BCPs for intermolecular hydrogen bonds of 2-pyridone dimer and its substituted complexes (in a.u.) and E $_{H...X}$ (hydrogen bond energy, in kcal/mol).

Structure	N−H⋯O	d (Å)	ρ(r), e/a.u³	∇²ρ(r), e/a.u⁵	G(r)	H(r)	V(r)	E $_{H...X}$
								$\Delta E = \frac{1}{2} V(r)$
2PY dimer	N3-H23…O2	1.740	0.0486	0.1598	0.0412	-0.0013	0.0425	-13.35
	N12-H24…O14		0.0486	0.1598	0.0412	-0.0013	0.0425	-13.35
C₅H₄FN (O)	N3-H21…O2	1.047	0.0513	0.1716	0.0441	-0.0012	0.0453	-14.23
	N12-H22…O14		0.0513	0.1716	0.0441	-0.0012	0.0453	-14.23
C₅H₄ClN (O)	N3-H21…O2	1.725	0.0421	0.1291	0.0350	-0.0027	0.0377	-11.83
	N12-H22…O14		0.0421	0.1291	0.0350	-0.0027	0.0377	-11.83
C₅H₄BrN (O)	N3-H21…O2	1.732	0.0414	0.1282	0.0344	-0.0024	0.0368	-11.50
	N12-H22…O14		0.0414	0.1282	0.0344	-0.0024	0.0368	-11.50

The results obtained of Table 6 demonstrated that from the positive value of $\nabla^2 \rho(r)$ and negative value of H(r) for in N3…H-O2 and N12-H…O14 hydrogen bonds in 2-pyridone dimer and its complexes must be considered as partially covalent interactions. The three types of H-bond are characterized on the basis of topological parameters. According to Rozas et al. [17], the characterization demands at BCP (i) $\nabla^2 \rho(r) < 0$ and $H < 0$ for strong H-bond of covalent nature (ii) $\nabla^2 \rho(r) > 0$ and $H < 0$ for medium H-bond of partially covalent nature (iii) $\nabla^2 \rho(r) > 0$ and $H > 0$ for weak H-bond of electrostatic character. According to Espinosa et al. [22] the interaction energy of A…B contact is defined as, $\Delta E = \frac{1}{2} V$ at BCP

$$\text{BCP} \begin{cases} \nabla^2\rho(r) > 0 \\ H(r) < 0 \end{cases} \rightarrow \quad \text{partially covalent H-bond interactions}$$
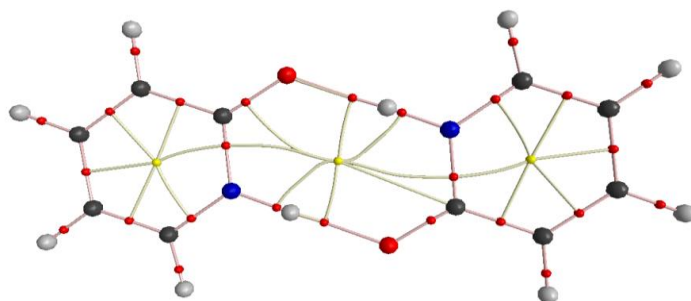

Figure 2. QTAIM molecular graph of the 2-pyridone dimer. All critical points are shown, as are attractors by greater circles: BCPs, small red circles; RCPs, yellow ones. Carbon atoms, black; hydrogen atoms, gray; oxygen atoms, red; nitrogen atoms, blue. The bond paths are also shown.

The stabilization energy related to intermolecular H-bonds $\Delta E = \frac{1}{2} V(r)$ at BCP (given in Table 6) has been estimated using the local potential energy density proposed by Espinosa [18]. According to Table 6, the trend for H-bond strength interaction energies in substituted molecules are consistent with the decreasing order of N-H…O distance these complexes (**1** > **2** > **3** hydrogen bonded dimer). The H-bond strength for these dimers are -14.23 (C_5H_4FN (O)),-11.83 (C_5H_4ClN (O)) and -11.55 kcal/mol (C_5H_4BrN (O)), respectively. The ellipticity of the electron density at the bond critical points is a parameter computed in the framework of QTAIM. This parameter provides a quantitative measurement of the anisotropy of the electron density at the BCP. The ellipticity has been originally associated to the π character of bonds, and therefore, it has been also employed as a measurement of delocalization and ultimately, aromaticity. The number of applications of this parameter, however, has increased significantly in recent years and studies on the description of unusual bonds in charge transfer interactions, steric contacts, organometallic complexes, etc. include the ellipticity as a useful chemical index. QTAIM ellipticity analysis confirms the presence of resonance-assisted hydrogen bonding in dimer. The ellipticity of C_5H_4XN (O) (X= F (**1**), Cl (**2**) and Br (**3**)) hydrogen bonded dimers at the B3LYP/6- 311++G (d, p) level are 0.025, 0.0333, and 0.0334, respectively. It is worth to mention that larger the ellipticity ε indicates the more p character the chemical bond.

2PY dimer C_5H_4FN (O)

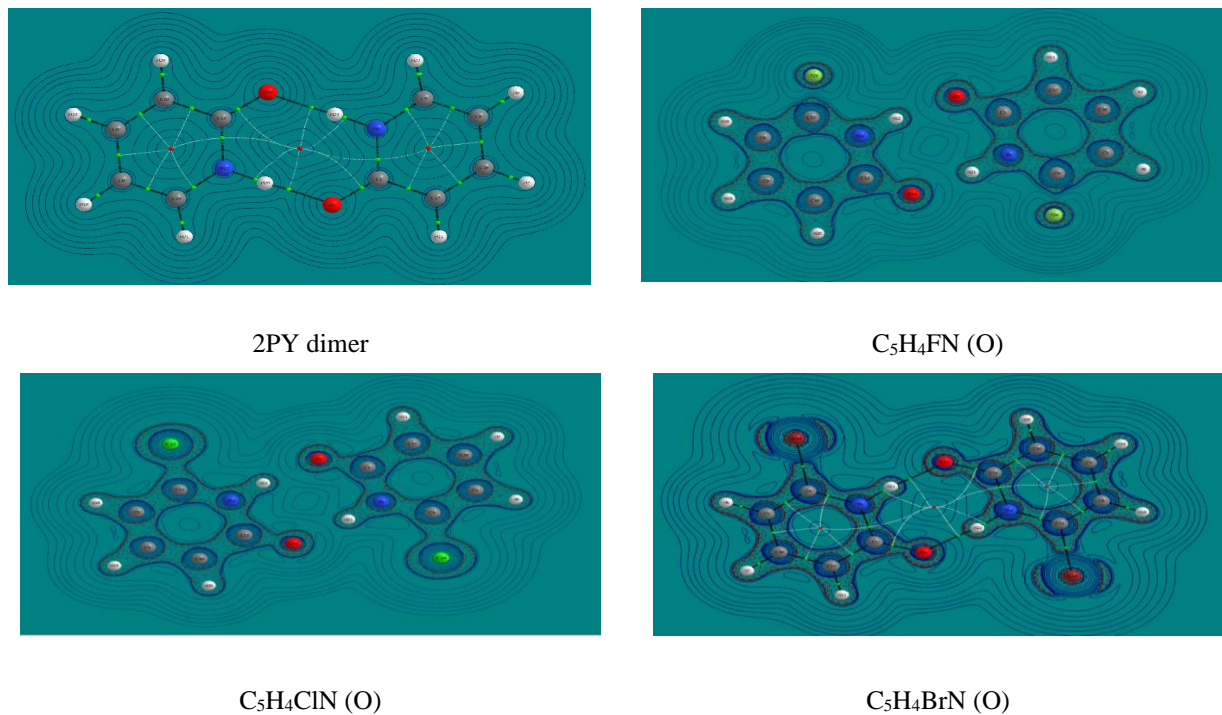C_5H_4ClN (O) C_5H_4BrN (O)

Figure 3. Electron density contour map for 2-pyridone and its substituted dimers (C5H4XN (O), X=F, Cl and Br) obtained at the B3LYP/6- 311++G (d,p) level attractors are designated by blue circles, BCPs by small red circles, and RCPs by yellow ones, and the gradient paths are also presented by violet lines.

The electron density contour map for the 2-pyridone and its substituted dimers (C_5H_4XN (O), X=F, Cl and Br) dimers are shown in Figure 3. This contour map were obtained for planar geometry of 2-pyridone and C_5H_4XN (O) dimers (X=F, Cl and Br) dimers to visualize the pictures with visible gradient paths' lines. There is only a slight energy difference between the fully optimized geometry of the dimer and the planar configuration (less than 0.05 kcal/mol at B3LYP/6-311++G (d, p) level).

Molecular Electrostatic Potential (MEP) surface of C5H4XN (O) dimers (X=F, Cl and Br) dimers

The molecular electrostatic potential MESP surface which is a plot of electrostatic potential mapped onto the iso-electron density surface [43-44], the importance of the MESP lies in the fact that it simultaneously displays the molecular size and shape as well as positive, negative and neutral electrostatic potential regions in terms of the electrostatic surface, which explain the investigation of the molecular structure with its physiochemical property relationships [45- 46]. The MESP surface map and QTAIM molecular graph of C5H4XN (O) dimers (X=F, Cl and Br)

dimers (Figure 4) show one region characterized by red color (negative electrostatic potential)) which explain the ability for an electrophilic attack on this position, also by blue color (positive electrostatic potential which explain that these regions are susceptible for a nucleophilic attack. All the results of the QTAIM calculations correspond to their structural mappings.
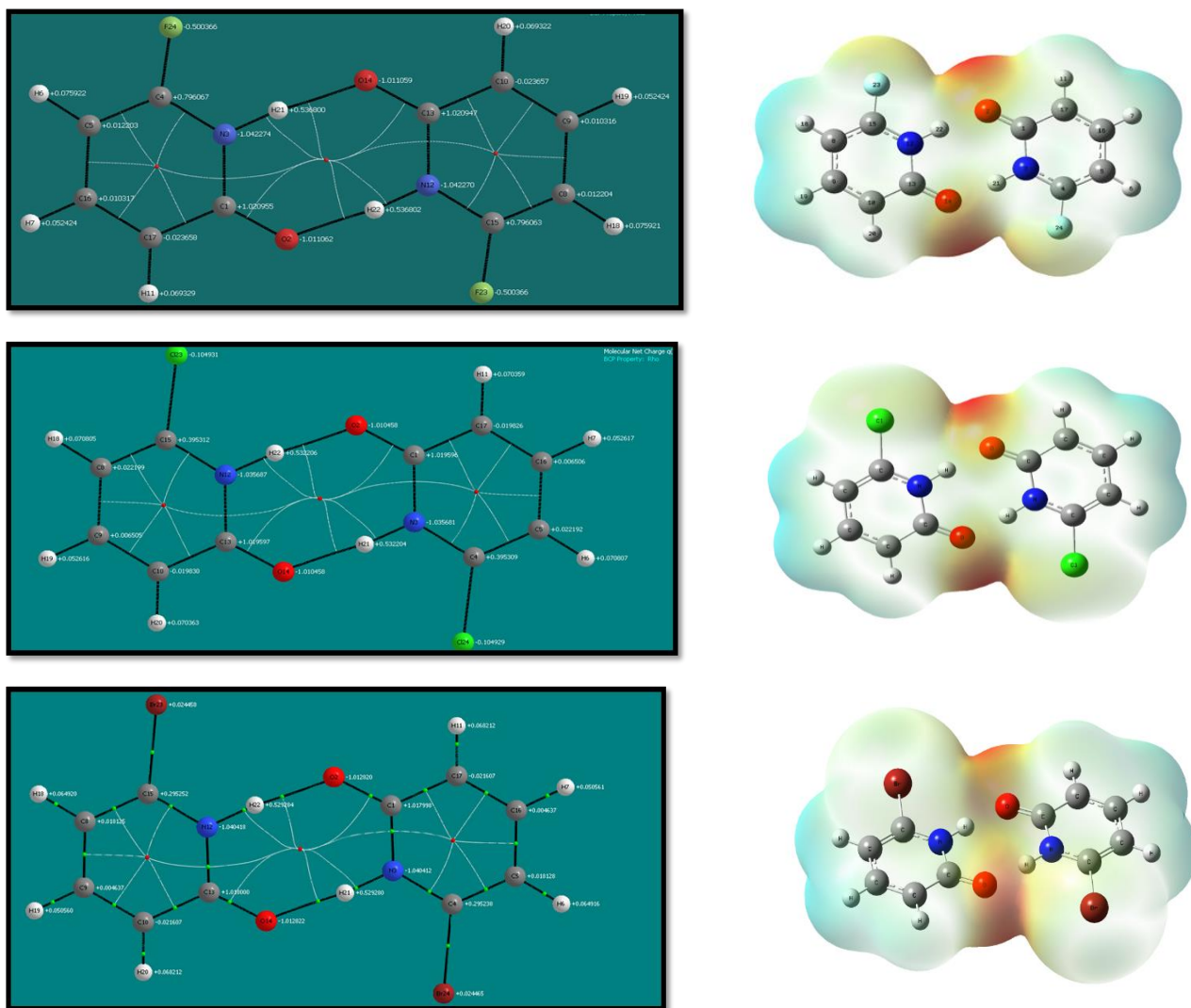

Figure 4: 3D MESP surface map and QTAIM molecular graph of C5H4XN (O) dimers (X=F, Cl, and Br) dimers

4. Conclusions

The hydrogen bond plays a crucial role in chemistry and biology which normally characterized as a relatively weak interaction involving an electronegative proton donor X,

hydrogen atom and an electronegative proton acceptor Y. The interaction is believed to be predominantly electrostatic in nature; although charge-transfer interactions are also important factors in the formation of a hydrogen bond. The main aim of this research was to study inter-molecular hydrogen bonding interaction in some dimers using AIM and NBO quantum theory approaches. It has been proved, that the AIM-based analysis of electron density can provide valuable information on many physical and chemical properties of the molecular systems. DFT calculations have been employed to optimize the geometries of 2-pyridone dimer and its substituted dimers C5H4XNO (X=F, Cl, Br). The binding energy is calculated with the basis set superposition error (BSSE) correction and zero-point energy (ZPE) correction. The results show that hydrogen bonds leads to bond length elongation and stretches the frequency red-shift of N−H···Y. The extent of the red-shift has been correlated with the strength of the hydrogen bond, the proton donor-acceptor distance. The results obtained allowed us to show that substituents F atoms in the position-6 of the 2-pyridone dimer with respect to interaction energy value in H-bonded system stability more strongly than the other two Cl and Br-complexes.

The calculated interaction energies show that the greatest corrected intermolecular interaction energy among three investigated dimers is -17.95 kcal/mol for C5H4FN (O) dimmer. It can be seen that the change in bond length (Δr) for C5H4FN (O) dimer is slightly greater than the complexes C5H4ClN (O) and C5H4BrN (O) dimmers.

The obtained results demonstrated that the positive value of $\nabla 2\ \rho(r)$ and negative value of H(r) for N3…H-O2 and N12-H…O14 hydrogen bonds in 2-pyridone dimer and its complexes could be considered as partially covalent interactions. The NBO results revealed that intermolecular charge-transfer interactions from one of the oxygen lone pairs, n, as the electron donor to the proximate N-H anti-bonding orbital, $\sigma*$, as the electron acceptor play important role in stabilization of dimers. Meaning while charge redistribution mainly occurs on the adjacent N–H...O atoms of the submolecular.

We can elicit the following conclusions from obtained results at DFT/B3LYP/6-311++G (d,p) level:

1. The greatest corrected binding energy among the three dimers is -17.95 kcal mol^{-1}. Therefore, complex C_5H_4FNO is the most stable of the three complexes. The stability of the complex is closely related to the interaction energy.

2. Both the binding energies and the mean intermolecular distances indicate that the stability of the dimers is in the order $C_5H_4FNO > C_5H_4ClNO > C_5H_4BrNO$.

3. The H-bonding lengths usually determine the binding energies when the intermolecular contacts are similar.

4. The bond lengths, NBO and QTAIM analyses support the results obtained from binding energy values.

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