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Theoretical Studies of Molecular Structure, Vibrational Spectra and Substitution Effect on the Electronic Structure of Indole

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ABSTRACT

Molecular geometry, vibrational frequencies, energy gaps, net charges, dipole moments and heats of indole formation at the ground state have been calculated by using the Molecular Mechanics, PM3, ab initio/HF and DFT/B3LYP methods. The optimized geometrical parameters are in good agreement with experimental values. Comparison of the obtained fundamental vibrational frequencies of Indole result by DFT/B3LYP (6-311G++(d,p)) method, are in a close agreement with the experimental data. Ab initio/HF with 6-31G basis set was used to investigate the effects of a variety of substituents (methyl, cyanide and dimethylamino) on the electronic properties of Indole derivatives.

Keywords: Indole, vibrational frequencies, substituent effect, frontier orbitals, ab initio, DFT.

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INTRODUCTION

Indole is an aromatic heterocyclic organic compound with a bicyclic structure; it consists of a six-membered benzene ring fused to five-membered nitrogen containing pyrrole ring. Indole is a model system in the study of the amino acid tryptophan (Trp), the fluorescence and absorption spectra of which are strongly sensitive to the environment [1]. It has been the object of numerous spectroscopic studies, motivated by the possibility of extracting useful structural and dynamical properties of proteins [2-3]. Indole is an important class of heterocycles, due to their biological and pharmacological activities; it also present in a wide variety of natural compounds, many of which have important physiological activities [4-7].

Accordingly, broad studies have been conducted on different solutions of indole and its derivatives, the results obtained have covered many other publications. In recent years, the theoretical study of geometry and electronic structures has proved to be very efficient to predict the physical-chemistry properties of large systems [8-12]. The theoretical calculation of vibrational properties is used to understand the spectra's of large number of donor-acceptor systems [13-14]. Consequently, these calculations can be performed at different accuracy levels depending on the aim of the theoretical study.

The substituents attached to the molecular framework can enhance or diminish the reactivity. The mechanistic conclusions based on the linear relationships with free energy have been extremely fruitful. The substituents were variable donating and withdrawing to study the effect of such change on the geometric, electronic and vibrational properties of the studied molecules. Accordingly, changes in reactivity in one reaction series caused by changes in substitution are related to changes in equilibrium or reactivity in another series caused by the same changes in substitution [15-16].

Accordingly, objective of the present research is to study the geometric, electronic and vibrational spectra will characterize and predict the molecular and spectroscopic properties of indole. Thus, in this work we have studied of the substituent groups effects at different positions in the indole ring. In this study, we have calculated the structure of indole and derivatives by using ab initio/HF and DFT/B3LYP methods [17-18].

COMPUTATIONAL DETAILS

Initial calculations were optimized using HyperChem 8.03 software [19]. The geometries of indole and its derivatives; were first fully optimized by molecular mechanics, with MM+ force-field (rms = 0.001 Kcal/Å). Further, geometries were fully re-optimized by using PM3 method [20]. In the next step, a parallel study has been made using Gaussian 09 program package [21], at various computational levels, HF/6-31G+, 6-31G++ (d,p), 6-311G++ (d,p), and B3LYP/6-31G+, 6-31G++ (d,p), 6-311G++ (d,p). The calculated results have been re-reported in the present work.

RESULTS AND DISCUSSION

Molecular geometry of indole

The molecular structure of indole is shown in (Figure 1). With this structural model, indole belongs to C_s point group symmetry. The optimized geometrical parameters of indole by ab initio/HF and DFT method have been depicted and compared with experimental parameters [22-23] obtained from the crystal structure analyses of indole in (Table 1).

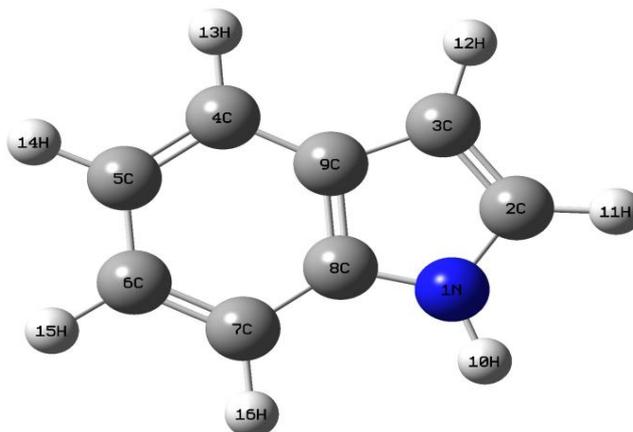


Fig 1: Conformation 3D of molecular structure and atom numbering adopted in this study for indole (GaussView 5.0.8)

The experimental data are in good agreement with the theoretical calculations for bond lengths and bond angles. The largest differences of the calculated geometries from the experimental parameters are 0.028\AA (C8–N) at ab initio/HF, 0.021\AA (C8–C9) at B3LYP/DFT for the bond lengths and 0.038° (C9–C4–C5) at ab initio/HF, 0.039° (C9–C4–C5) at B3LYP/DFT basis sets for the bond angles.

Vibrational frequencies of indole

The vibrational spectroscopy of indole has, unsurprisingly, attracted a great deal of attention. Being an important model compound for the biologically significant molecule and also, at one time, close to the limits of size for conducting calculations, indole attracted considerable interest. Many papers were published both experimentally and theoretically [24-27]. The comparison of the frequencies calculated at ab initio/HF and DFT/B3LYP level of theories with experimental [28-30] values (Table 2) reveals the overestimation of the calculated vibrational modes due to neglect of anharmonicity in real systems. As can be seen, the predictions of the gradient-corrected of DFT/B3LYP (6-311G++(d,p)) method are in a close agreement with the experimental values within a wide spectral range. Inclusion of electron correlation in density functional theory to a certain extent makes the frequency values smaller in comparison with the HF frequency data.

A molecule composed of n -atoms has $3n$ degrees of freedom, six of them are translations and rotations of the molecule itself. This leaves $3n-6$ degrees of vibrational freedom. Vibrational modes are often given descriptive names, such as stretching, bending,

scissoring, rocking and twisting. The 42 normal vibrations are distributed as 29A' (in-plane modes) and 13A'' (out-of-the-plane modes).

C-H vibration

Table 1: Comparison of the experimental and calculated values of bond lengths and bond angles of indole

Parameters	Exp.		ab initio/HF			DFT/B3LYP		
	[22]	[32]	6-31G+	6-31G++(d,p)	6-311G++(d,p)	6-31G+	6-31G++ (d,p)	6-311G++ (d,p)
Bond length(Å)								
N-C2	1.43	1.38	1.38	1.37	1.37	1.40	1.38	1.38
C2-C3	1.36	1.34	1.36	1.35	1.35	1.38	1.37	1.37
C3-C9	1.44	1.45	1.45	1.44	1.44	1.44	1.44	1.44
C9-C4	1.37	1.40	1.40	1.40	1.40	1.41	1.41	1.41
C4-C5	1.38	1.39	1.38	1.38	1.38	1.40	1.39	1.39
C5-C6	1.37	1.39	1.41	1.41	1.41	1.42	1.41	1.41
C6-C7	1.39	1.40	1.38	1.38	1.38	1.40	1.39	1.39
C7-C8	-	1.38	1.40	1.40	1.39	1.40	1.40	1.40
C8-C9	1.45	1.39	1.41	1.40	1.40	1.43	1.42	1.42
C8-N	1.39	1.41	1.38	1.37	1.37	1.39	1.38	1.39
N-H10	1.00	-	0.99	0.99	0.99	1.01	1.01	1.01
Bond angle(°)								
N-C2-C3	111.50	111.50	109.57	110.00	110.02	109.26	109.51	109.52
C2-C3-C9	105.50	105.50	107.08	106.72	106.73	107.37	107.11	107.15
C4-C5-C6	124.80	124.80	120.87	120.86	120.85	121.10	121.11	121.12
C5-C6-C7	119.70	119.70	120.87	121.27	121.27	121.17	121.19	121.19
C6-C7-C8	116.40	116.40	117.60	117.50	117.52	117.54	117.48	117.52
C7-C8-C9	-	-	122.07	122.16	122.14	122.28	122.38	122.29
C3-C9-C8	-	-	106.83	106.70	106.71	106.99	106.89	106.89
C2-N-C8	107.40	-	109.13	109.01	108.97	109.33	109.31	109.29
N-C8-C9	-	-	107.39	107.57	107.57	107.05	107.17	107.15
C4-C9-C8	-	-	119.24	119.16	119.18	118.83	118.74	118.77
C3-C9-C4	-	-	119.24	134.14	134.11	134.17	134.37	134.34
C9-C4-C5	114.60	114.60	119.02	119.04	119.05	119.08	119.11	119.10
C7-C8-N	-	-	130.54	130.27	130.29	130.67	130.46	130.56

The aromatic moiety shows the presence of C-H stretching vibrations in the region 3100–3000 cm⁻¹ which is the characteristic region for the ready identification of C-H stretching vibrations [30]. There are six C-H stretching modes in indole, four from benzene ring and two from pyrrole ring. The absorption in the range 3000-3125 cm⁻¹ has been identified with that of C-H [32]. Hence the bands observed at 3255, 3235 cm⁻¹ and 3188, 3176, 3166, 3160 cm⁻¹ are assigned to C-H stretching in pyrrole ring and benzene, respectively. In general the experimental values are in good agreement with that obtained from B3LYP level theory using 6-311++G(d,p) basis set.

The C-H in-plane bending vibrations in benzene or aromatic are usually observed in the region between 1000-1300 cm^{-1} and are normally weak and the C-H out of plane vibrations occur between 700-900 cm^{-1} . With reference to this observation the band observed at 1266, 1220 and 1140 cm^{-1} are assigned to C-H in-plane bending while the band observed at 723, 749 and 851 cm^{-1} are assigned to C-H out of plane bending which is in agreement with the literature values [33-35].

N-H vibration

The N-H band of pyrrole is calculated at 3524 cm^{-1} in tryptamine [36]. The N-H stretch has been reported to occur at 3524 cm^{-1} experimentally [37], this value is in excellent agreement with the theoretical value of 3674 cm^{-1} (B3LYP/6-311++G(d,p)).

C=N, C-N vibration

The identification of C-N vibrations is a very difficult task, since the mixing of several bands is possible in the region. Silverstein et al. [38] assigned C-N stretching absorption in the region 1382–1266 cm^{-1} for aromatic amines. In benzamide the band observed at 1368 cm^{-1} is assigned to C-N stretching [39]. In the present work, the theoretically calculated values of C-N band observed at 1362 cm^{-1} and C=N band observed at 1442 cm^{-1} coincides with experimental data. The theoretical scale frequencies by (B3LYP/6-311++G(d,p)) method exactly correlates with experimental observation.

C=C vibration

Chithambarathanu et al. [40] have observed the bands C-C at 1574, 1498 and 1468 cm^{-1} in 1,3,5-triphenyl-4,5-dihydropyrazole. Based on these factors, in the present study the bands at 1362, 1380, 1442, 1477, 1522, 1546, 1614 and 1656 cm^{-1} for benzene and pyrrole.

Electronic properties of indole

Highest occupied molecular orbital (HOMO) and lowest unoccupied molecular orbital (LUMO) are very important parameters for quantum chemistry. We can determine the way the molecule interacts with other species; hence, they are called the frontier orbitals [41]. Energies of the HOMO and the LUMO are very popular quantum chemical descriptors. The HOMO represents the ability to donate an electron; their energy is directly related to the ionization potential and characterizes the susceptibility of the molecule to attack by electrophiles. On the other hand, the LUMO as an electron acceptor; their energy is directly related to the electron affinity and characterizes the susceptibility of the molecule to attack by nucleophiles [42]. HOMO and LUMO energies, energy gap ($\Delta E = E_{\text{HOMO}} - E_{\text{LUMO}}$) and dipole moments of indole calculated at ab initio/HF and B3LYP/DFT in 6-31G basis set is given in (Figure 2).

The value of energy gap (ΔE) between HOMO and LUMO energies is -0.19711 a.u. obtained at DFT/B3LYP (6-31G) whereas the (ΔE) is -0.41673 a.u. obtained at HF/ab initio (6-31G). Atomic charges of indole, which have been calculated by Mulliken method at the ab initio/HF (6-31G) and DFT/ B3LYP (6-31G) levels of calculation are shown in below (Figure 3).

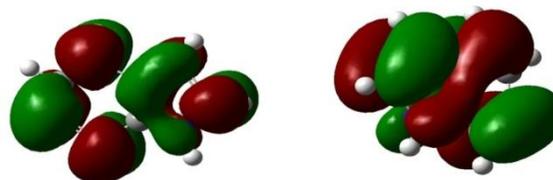


Table 2: Comparison of the experimental and calculated vibrational spectra of indole

Mode No.	Symmetry	Exp.IR	Exp.IR	ab-initio/HF			DFT/B3LYP			Assignment
		[28–29]	[30]	6-31G+	6-31G++(d,p)	6-311G++(d,p)	6-31G+	6-31G++(d,p)	6-311G++(d,p)	
1	A''	207	224	239.6063	229.6882	228.4514	221.0898	215.6334	212.0320	YCCN (Bz-Py)
2	A''	241	254	276.7307	263.9532	262.0191	255.1559	245.3052	242.805	YCNC (Bz-Py)
3	A''	387	-	439.0845	382.9186	364.6079	410.0881	395.4449	385.2516	YNH (Py)
4	A'	398	397	485.6642	430.5851	429.1088	443.0372	403.7544	404.1235	βCCC (Bz-Py)
5	A''	419	423	600.6206	470.0529	470.7175	542.3158	432.5648	430.3779	YCCC (Bz-Py)
6	A'	542	542	614.3093	586.0773	584.6603	561.5664	550.6917	551.1561	βCCN (Bz-Py)
7	A''	570	487	652.4777	629.8895	628.1462	594.8637	585.0772	583.3455	YCCC (Bz-Py)
8	A'	601	575	678.6055	659.9537	659.7233	623.7637	613.9898	613.9536	YCH-NH (Bz-Py)
9	A''	607	607	680.3237	661.3206	661.2355	630.5092	615.6582	617.6049	βCCC (Bz-Py)
10	A''	-	-	834.8967	804.4391	805.2259	745.2136	726.7603	723.3136	YCH (Py)
11	A'	714	608	840.8433	822.0861	819.1502	774.9007	753.4474	749.6970	YCH (Bz)
12	A''	738	725	870.1465	832.7144	830.8974	781.3303	773.6568	773.6997	β (Bz-Py)
13	A''	759	758	902.4800	853.6219	855.2805	810.2158	779.2829	777.6667	Y (Bz-Py)
14	A'	-	-	902.4800	945.2620	941.9491	886.3123	857.0529	851.9935	YCH (Bz-Py)
15	A''	840	767	997.9342	954.6229	950.5887	902.6501	867.7829	867.0972	YCH (Py)
16	A'	850	848	1006.0697	975.4497	973.6460	902.9206	884.0373	885.9064	βCCC (Bz-Py)
17	A''	876	873	1062.0478	1003.899	1001.5273	925.0158	907.5629	910.0774	βCCN (Py)
18	A''	899	895	1113.5079	1066.1012	1059.8261	969.1292	940.2346	936.8585	YCH (Bz)
19	A''	925	930	1116.621	1102.4494	1092.4930	1012.847	979.8852	975.2895	YCH (Bz)
20	A'	960	970	1165.6746	1104.0883	1096.8900	1043.1726	1034.6071	1031.8588	βCH (Bz)
21	A'	1013	1010	1175.329	1172.7636	1165.5814	1098.6516	1090.1285	1085.6739	βCH (Py)
22	A'	1067	1064	1211.7912	1188.2205	1180.9842	1126.6777	1111.089	1107.7682	βCH-CN (Py)
23	A'	1095	1092	1247.9085	1220.5957	1212.8331	1163.64	1143.6741	1140.6255	βCH (Bz-Py)
24	A'	1124	1119	1284.1643	1240.3793	1232.3401	1207.4215	1175.933	1174.1003	βCH (Bz)

25	A'	1150	1147	1332.6664	1310.9323	1303.5006	1245.2434	1224.6296	1220.4554	β CH (Bz-Py)
26	A'	1204	1191	1392.4971	1364.4870	1357.1872	1298.1770	1269.4226	1266.4988	β CH (Bz-Py)
27	A'	1244	1203	1403.7288	1385.0148	1370.5340	1310.4495	1299.8306	1293.9979	β CH (Bz-Py) and ν C=N (Py)
28	A'	-	-	1425.7865	1392.1279	1385.4825	1384.4215	1375.2498	1362.5734	ν CC (Bz-Py) and ν C-N (Py)
29	A'	1334	1276	1515.7223	1501.0736	1491.9232	1407.3519	1386.5387	1380.6993	ν CC (Bz-Py)
30	A'	1350	1343	1574.5054	1568.1642	1559.3069	1456.805	1451.0034	1442.0664	ν CC (Bz-Py) and ν C=N (Py)
31	A'	1414	1412	1622.1291	1612.5926	1603.5568	1494.7092	1486.2486	1477.8833	ν CC (Bz-Py)
32	A'	1458	1455	1663.9918	1652.4865	1644.2232	1539.8638	1527.6709	1522.2369	ν CC (Bz-Py)
33	A'	1491	1487	1695.5330	1691.5963	1681.6869	1559.7395	1555.4037	1546.1165	ν CC (Py)
34	A'	1577	1576	1770.7326	1768.5483	1760.9016	1627.2178	1622.4504	1614.7342	ν CC (Bz-Py)
35	A'	1625	1616	1808.9807	1804.7070	1796.8267	1669.0688	1664.2488	1656.2290	ν CC (Bz)
36	A'	3051	-	3348.3434	3337.7716	3314.9439	3185.8126	3176.4785	3160.1229	ν_{as} CH (Bz)
37	A'	3061	-	3356.6759	3346.1096	3323.7842	3192.6991	3182.5427	3166.4195	ν_s CH (Bz)
38	A'	3072	-	3369.7649	3358.1285	3335.6682	3204.7323	3193.2912	3176.9358	ν_{as} CH (Bz)
39	A'	3090	-	3384.0178	3370.1845	3347.4126	3218.4111	3204.8371	3188.4431	ν_s CH (Bz)
40	A'	3119	-	3433.0219	3410.6631	3385.1011	3272.7276	3253.4916	3235.3557	ν_{as} CH (Py)
41	A'	3140	-	3460.7085	3433.3471	3407.7894	3297.4526	3273.2020	3255.0110	ν_s CH (Py)
42	A'	3524	-	3942.9868	3934.4458	3918.1586	3695.6044	3686.2344	3674.4431	ν NH (Py)

ν : stretching; ν_s : sym. stretching; ν_{as} : asym. stretching; β : in-plane-bending; γ : out-of-plane bending.



(a)

(b)

Fig 2: 3D plots of (a) LUMO and (b) HOMO of the indole (DFT/B3LYP (6-31G)) (GaussView 5.0.8)

Figure 3 shows that the atoms C3, C4, C5, C6, C7 and N1 have negative Mulliken charges which leads to electrophilic substitution, whereas the atom C2 have positive Mulliken charge which lead to preferential site nucleophilic attack.

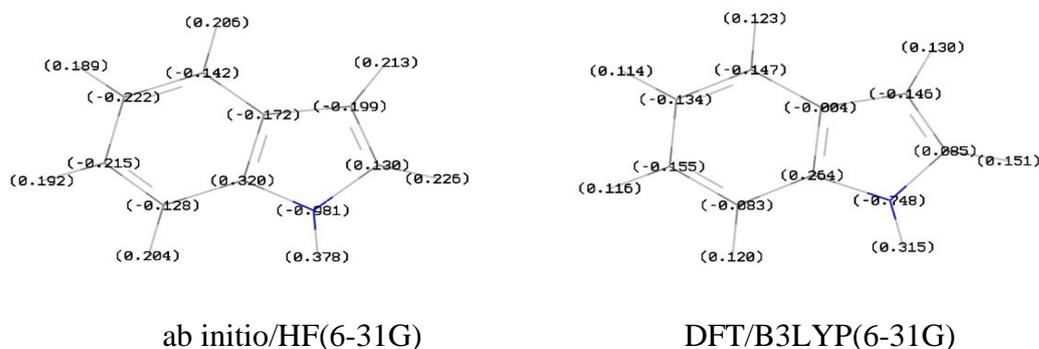


Fig 3: The Mulliken charges (Q_M) of indole (GaussView 5.0.8)

Substituent effects on the electronic structure in indole and derivatives

Substituent effects play a fundamental role in a variety of observed physical and chemical phenomena. For example, substituent effects influence the rates of nucleophilic substitutions and the molecule's reactivity, [43-46] vibrational specter, [47] acid-base properties, [48] the conformations of molecules, and so forth.

The calculated values of (methyl, cyanide and dimethylamino) substituted indole are given in Table 4, Table 5, Table 6, Table 7, Table 8 and Table 9. The chemical structures of the compounds studied of indole and derivatives are shown in (Figure 4)/ (Table 3). In (Table 4), Table 6 and Table 8, HOMO and LUMO energies, energy gaps ΔE , heat of formation and dipole moments are reported for indole and its derivatives. In Table 5, Table 7 and Table 9 net atomic charges are also reported.

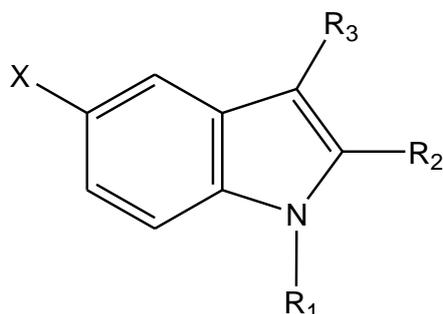


Fig 4: Structure of indole derivatives (ChemDraw Ultra 8.0)

Table 3: Series of indole and groups substituted indole

Compounds	R1	R2	R3	X
IND	H	H	H	H
Series 1				
A1	CH3	H	H	H
A2	H	CH3	H	H
A3	H	H	CH3	H
A4	CH3	CH3	H	H
A5	CH3	H	CH3	H
A6	H	CH3	CH3	H
A7	CH3	CH3	CH3	H
Series 2				
B1	CN	H	H	H
B2	H	CN	H	H
B3	H	H	CN	H
B4	CN	CN	H	H
B5	CN	H	CN	H
B6	H	CN	CN	H
B7	CN	CN	CN	H
Series 3				
C1	H	CH3	H	NMe2
C2	H	CN	H	NMe2
C3	CH3	CH3	H	NMe2
C4	CN	CN	H	NMe2
C5	CN	CN	CN	NMe2

Table 4: Energies of indole and derivatives (series 1)

Compound	System	Heat of formation (Kcal/mol)	HOMO (a.u.)	LUMO (a.u.)	ΔE (a.u.)	μ (D)
IND	Indole	42,38	-0,2824	0,1344	0,4167	2,45
A1	N-methyl indole	41,14	-0,2773	0,1355	0,4129	2,76
A2	2-methyl indole	32,12	-0,2753	0,1350	0,4103	2,38
A3	3-methyl indole	33,14	-0,2754	0,1381	0,4134	2,74
A4	N-2-dimethyl indole	31,29	-0,2641	0,1400	0,4040	2,47
A5	N-3-dimethyl indole	31,93	-0,2702	0,1360	0,4061	2,67
A6	2-3-dimethyl indole	22,60	-0,2688	0,1383	0,4071	2,21
A7	N-2-3-trimethyl indole	22,27	-0,2708	0,1399	0,4107	3,07

Heat of formation by PM3, HOMO, LUMO, ΔE and μ by ab initio/HF(6-31G)

Table 5: Mulliken charges of indole and derivatives (series 1)

Compound	IND	A1	A2	A3	A4	A5	A6	A7
N1	-0.9805	-0.9763	-1.0241	-0.9906	-1.0290	-0.9855	-1.0335	-1.0387
C2	0.1296	0.1404	0.3559	0.1081	0.3797	0.1204	0.3315	0.3584
C3	-0.1991	-0.2010	-0.2079	-0.0079	-0.2173	-0.0082	-0.0215	-0.0313
C4	-0.1417	-0.1404	-0.1465	-0.1314	-0.1449	-0.1300	-0.1358	-0.1340
C5	-0.2221	-0.2232	-0.2211	-0.2253	-0.2217	-0.2265	-0.2242	-0.2249
C6	-0.2149	-0.2148	-0.2160	-0.2129	-0.2163	-0.2125	-0.2138	-0.2140
C7	-0.1276	-0.1244	-0.1321	-0.1266	-0.1295	-0.1235	-0.1315	-0.1288
C8	0.3203	0.3637	0.3322	0.3277	0.3640	0.3711	0.3379	0.3686
C9	-0.1719	-0.1889	-0.1729	-0.1890	-0.1794	-0.2099	-0.1890	-0.1976
C-methyl-1	-	-0.1899	-	-	-0.1853	-0.4415	-	-0.4631
C-methyl-2	-	-	-0.4696	-	-0.1853	-	-0.4630	-0.4353
C-methyl-3	-	-	-	-0.4431	-	-0.1893	-0.4367	-0.1843

Net charge calculated by ab initio/HF (6-31G)

We note that the heat of formation decrease approximately 8 and 9 kcal/mol at each addition of methyl group. In the mono-substituted alkyl group category, the 2-methyl-indole (compound A2) showing maximum positive charge on 2th position carbon (0,3559) which leads to nucleophilic substitution (Table 5). This is further supported by the smaller HOMO-LUMO energy gap (0.4103) (Table 4) which depicts the chemical reactivity of the compound; higher is the HOMO-LUMO energy gap, lesser is the flow of electrons to the higher energy state, making the molecule hard and less reactive. On the other hand in smaller HOMO-LUMO gap, there is easy flow of electrons to the higher energy state making it softer and more reactive (HSAB principle: hard and soft acids and bases). Hard bases have highest-occupied molecular orbitals (HOMO) of low energy, and hard acids have lowest-unoccupied molecular orbitals (LUMO) of high energy [49].

In the case of dimethyl substituted of indole the C-2 position compound (A4) shows maximum charge (0, 3797), smaller HOMO-LUMO energy gap (0.4040) (Table 4) and (Table 5) which leads to preferential site of nucleophilic attack. We also note that the methyl substituent (donor effect) has the effect of increasing the energy of the HOMO, with little change in the LUMO (Table 4). The presence of a donor groups in the C2 and C3 positions causes the decrease in dipole moment (compound A6), the compound (A7) shows maximum dipole moment value (3,0691D) (Table 4).

In the present work, we have studied cyanide of substituted indole long the same line of methyl substituted indole for a comparative study.

Table 6: Energies of indole and derivatives (series 2)

Compound	System	Heat of formation (Kcal/mol)	HOMO (a.u.)	LUMO (a.u.)	ΔE (a.u.)	μ (D)
IND	Indole	42,38	-0,2824	0,1344	0,4167	2,45
B1	N-cyano indole	87,58	-0,3143	0,1042	0,4185	2,87
B2	2-cyano indole	77,41	-0,3079	0,0827	0,3906	3,99
B3	3-cyano indole	76,11	-0,3060	0,1039	0,4099	6,15
B4	N-2-dicyano indole	125,28	-0,3273	0,0488	0,3761	6,23
B5	N-3-dicyano indole	123,33	-0,3344	0,0715	0,4059	2,96
B6	2-3-dicyano indole	113,86	-0,3343	0,0547	0,3890	7,52
B7	N-2-3-tricyano indole	163,29	-0,3510	0,0203	0,3713	6,58

 Heat of formation by PM3, HOMO, LUMO, ΔE and μ by ab initio/HF(6-31G)

Table 7: Mulliken charges of indole and derivatives (series 2)

Compound	IND	B1	B2	B3	B4	B5	B6	B7
N1	-0.9805	-1.0928	-1.0069	-0.9864	-1.1529	-1.1098	-1.0193	-1.1801
C2	0.1296	0.1782	0.3506	0.2279	0.4352	0.2784	0.4306	0.5238
C3	-0.1991	-0.1769	-0.0849	-0.0930	-0.0837	-0.0646	-0.0133	-0.0282
C4	-0.1417	-0.1429	-0.1209	-0.0999	-0.1237	-0.1002	-0.0772	-0.0773
C5	-0.2221	-0.2113	-0.2255	-0.2204	-0.2155	-0.2115	-0.2250	-0.2174
C6	-0.2149	-0.2146	-0.2047	-0.2114	-0.2043	-0.2102	-0.2017	-0.2002
C7	-0.1276	-0.1059	-0.1244	-0.1179	-0.1075	-0.0981	-0.1178	-0.1016
C8	0.3203	0.3877	0.3568	0.2935	0.4141	0.3651	0.3237	0.3828
C9	-0.1719	-0.1935	-0.2208	-0.0810	-0.2272	-0.1113	-0.1222	-0.1238
C-cyano-1	-	0.4069	-	-	0.4176	0.4110	-	0.0648
N-cyano-1	-	-0.2028	-	-	-0.1715	-0.1780	-	-0.1968
C-cyano-2	-	-	0.0436	-	0.0543	-	0.0583	0.1012
N-cyano-2	-	-	-0.2497	-	-0.2185	-	-0.2176	-0.1721
C-cyano-3	-	-	-	0.0371	-	0.0442	0.0832	0.4216
N-cyano-3	-	-	-	-0.2650	-	-0.2403	-0.2002	-0.1528

Net charge calculated by ab initio/HF(6-31G)

The heat of formation is increased approximately 38 Kcal/mol for each addition of cyanide group. In mono-substituted cyanide derivatives, 2-cyano-indole (compound B2) is predicted to be more chemically reactive on the basis of least HOMO-LUMO energy gap (0.3906) (Table 6) and shows maximum positive charge (0,3506) in carbon C-2 leading to favored site for nucleophilic attack (Table 7). In di-substituted cyanide derivatives, the carbon C-2 in N-2-dicyano-indole (compound B4) shows maximum positive charge (0,4352) leading to favored site for nucleophilic attack (Table 7). The compound N,2-dicyano-indole (B4) is more reactive than 2-3-dicyano-indole and N-3-dicyano-indole, this is due to smaller HOMO-LUMO energy gap (0.3761) which reflects a chemical stability (Table 6). The tri-substituted indole (compound B7) is predicted to be the most reactive with smaller HOMO-LUMO energy gap (0.37131) (Table 6) and maximum positive charge (0,5238) in carbon C-2 leading to favored site for nucleophilic attack (Table 6) of all indole systems. We note also that the cyanide substituent (attractor effect) lowers the energies of HOMO and LUMO, his influence on the

energy of the LUMO is more important. The compound B6 shows the maximum dipole moment value (7.5194), it would be originate from an attractor effect in positions C2-C3.

Table 8: Energies of indole and derivatives (series 3)

Compound	System	Heat of formation (Kcal/mol)	HOMO (a.u.)	LUMO (a.u.)	ΔE (a.u.)	μ (D)
IND	Indole	42,38	-0,2824	0,1344	0,4167	2,45
C1	2-metyl-5-NMe2 indole	29,04	-0,2462	0,1420	0,3882	1,01
C2	2-cyano-5-NMe2 indole	79,63	-0,2673	0,0878	0,3551	5,64
C3	N-2-dimethyl-5-NMe2 indole	33,95	-0,2428	0,1434	0,3862	1,31
C4	N-2-dicyano-5-NMe2 indole	121,65	-0,2891	0,0602	0,3493	8,23
C5	N-2-3-tricyano-5-NMe2 indole	163,92	-0,3015	0,0267	0,3282	9,07

Heat of formation by PM3, HOMO, LUMO, ΔE and μ by ab initio/HF (6-31G)

Table 9: Mulliken charges of indole and derivatives (series 3)

Compound	IND	C1	C2	C3	C4	C5
N1	-0.9805	-1.0290	-1.0119	-1.0322	-1.1554	-1.1801
C2	0.1296	0.3647	0.3596	0.3884	0.4428	0.5280
C3	-0.1991	-0.2206	-0.1013	-0.2309	-0.0968	-0.0467
C4	-0.1417	-0.2070	-0.1847	-0.2057	-0.1834	-0.1362
C5	-0.2221	0.4315	0.4285	0.4322	0.4403	0.4431
C6	-0.2149	-0.2651	-0.2479	-0.2662	-0.2500	-0.2451
C7	-0.1276	-0.1154	-0.1083	-0.1114	-0.0884	-0.0819
C8	0.3203	0.3174	0.3404	0.3484	0.3982	0.3594
C9	-0.1719	-0.1571	-0.2024	-0.1625	-0.2122	-0.1021
C-methyl-1	-	-	-	-0.1836	-	-
C-methyl-2	-	-0.4701	-	-0.4701	-	-
C-cyano-1	-	-	-	-	0.4125	0.0636
N-cyano-1	-	-	-	-	-0.1794	-0.2034
C-cyano-2	-	-	0.0428	-	0.0541	0.1012
N-cyano-2	-	-	-0.2534	-	-0.2219	-0.1760
C-cyano-3	-	-	-	-	-	0.4172
N-cyano-3	-	-	-	-	-	-0.1601
N-dimethylamino	-	-0.9331	-0.9335	-0.9333	-0.9360	-0.9387
C1-dimethylamino	-	-0.1859	-0.1909	-0.1855	-0.1950	-0.1999
C2-dimethylamino	-	-0.1856	-0.1902	-0.1851	-0.1951	-0.1978

Net charge calculated by ab initio/HF(6-31G)

The heat of formation is decreased for each addition of methyl group and increased for each addition of cyanide group. In the mono-substituted methyl group, the 2-methyl-5-NMe2-indole (compound C1) showing positive charge on 2th position carbon (0,3647) and in the mono-substituted cyanide group, the 2-cyano-5-NMe2-indole (compound C2) showing positive charge on 2th position carbon (0,3596) which leads to nucleophilic substitution (Table 9). In mono-substituted cyanide derivatives the compound (C2) are predicted to be more chemically reactive on the basis of least HOMO-LUMO energy gap (0,3551) (Table 8).

The di-substituted indole (compound C4) is predicted to be the most reactive with smaller HOMO-LUMO energy gap (0,3493) (Table 8) and maximum positive charge (0,4428) in carbon C-2 leading to favored site for nucleophilic attack (Table 9).

The carbon C-2 in N-2-3-tricyano-5-NMe₂-indole (compound C5) shows maximum positive charge (0,5280) leading to favored site for nucleophilic attack and the maximum dipole moment value (9,0689), (Table 9). In tri-substituted cyanide derivatives, the compound N-2-3-tricyano-5-NMe₂-indole (C5) is more reactive due to smaller HOMO-LUMO energy gap (0,3282) which reflects a chemical stability of all indole systems (Table 8). The negative atomic charge on nitrogen atoms increases considerably for methyl derivatives (Table 8). We note also that the dimethylamide substituent (donor effect) in the C5 position causes the decrease in energy gaps, which reflects a chemical stability. For example, the compound N-2-3-tricyano-5-NMe₂-indole (C5) shows maximum positive charge on C-2 (0,3282), the maximum dipole moment value (9,0689) and smaller HOMO-LUMO energy gap (0,32382) (Table 8) and (Table 9) relative N-2-3-tricyano-indole (compound B7) with energy gap (0.37131) (Table 6), positive charge (0,5238) in carbon C-2 and dipole moment (6,5776) (Table 6) and (Table 7).

CONCLUSIONS

In this study, we are trying to clarify the characterization of indole, through computational methods. Bond lengths and angles have been calculated by using HF/6-31(G+), 6-31G++(d,p) and 6-311G++(d,p) and B3LYP/6-31(G+), 6-31G++(d,p) and 6-311G++(d,p) methods and compared with experimental values. All compared data have been shown to have a good agreement with each other. We have carried out ab initio and density functional theory calculation on the vibrational spectrum of indole. The vibrational frequencies of infrared intensities calculated by DFT/B3LYP (6-311++G(d,p)) method agree satisfactorily with experimental results. On the basis of agreement between the calculated and experimental results, assignments of all the fundamental vibrational modes of indole were examined and proposed in this investigation. This study demonstrates that scaled DFT/B3LYP calculations are a powerful approach for understanding the vibrational spectra of medium sized organic compounds. In the substituted methyl group, N-2-dimethyl-indole is predicted to be the most reactive with least HOMO-LUMO energy gap of all methyl-indole derivatives. The tri-cyano-indole is predicted to be the most reactive with all-cyano-indole derivatives. The presence of donor group (dimethylamine) in the C5 position causes the decrease in energy gaps, which reflects a chemical stability and show the maximum dipole moment value in tri-substituted cyanide derivatives.

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