Electronic Structure, Nonlinear Optical Properties, and Vibrational Analysis of Gemifloxacin by Density Functional Theory

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Abstract. The non-linear optical properties of gemifloxacin ($C_{18}H_{20}FN_5O_4$) have been examined using density functional theory (DFT). The molecular HOMO, LUMO composition, their respective energy gaps, MESP contours/surfaces have also been drawn to explain the activity of gemifloxacin. The equilibrium geometries and harmonic frequencies of title molecule was determined and analyzed at DFT/B3LYP level employing the 6-31G(d,p) basis set. The skeleton of both the optimized molecules is non-planar. In general, a good agreement between experimental and calculated normal modes of vibrations has been observed.

Keywords: Nonlinear optical properties, polarizability, first static hyperpolarizability, MESP, vibrational spectra

1. Introduction

Gemifloxacin (7-[(4E)-3-(aminomethyl)-4-methoxyiminopyrrolidin-1-yl]-1-cyclopropyl-6-fluoro-4-oxo-1,8-naphthyridine-3-carboxylic acid) is an oral broad-spectrum quinolone antibacterial agent widely used in the treatment of acute bacterial exacerbation of chronic bronchitis and mild-to-moderate pneumonia [1–3]. Gemifloxacin acts by inhibiting DNA synthesis through the inhibition of both DNA gyrase and topoisomerase IV enzymes, which are essential for bacterial growth. Notably this drug has about 100 times higher affinity for bacterial DNA gyrase than for mammalian ones. Gemifloxacin is a broad-spectrum antibiotic that is highly active against both Gram-positive and Gram-negative bacteria

Figure 1: Molecular structure and numbering scheme of gemifloxacin.

[4, 5]. Gemifloxacin is globally used for the treatment of bacterial infection caused by susceptible strains like *S. pneumoniae*, *H. influenzae*, *H. parainfluenzae*, or *M. catarrhalis*, *S. pneumoniae* (including multi-drug-resistant strains (MDRSP)), *M. pneumoniae*, *C. pneumoniae*; *K. pneumoniae*. Gemifloxacin rapidly absorbed from the gastrointestinal tract and the absolute bioavailability averages approximately 71%. Gemifloxacin is metabolized to a certain extent by the liver. All metabolites formed are minor (<10% of the administered oral dose); the principal ones are N-acetyl gemifloxacin, the E-isomer of gemifloxacin and the carbamyl glucuronide of gemifloxacin [6, 7].

The aim of the present communication is to investigate the molecular structure, vibrational spectra, and energetic data analysis of the molecule under study, in gas phase, due to biological and pharmaceutical importance of the title molecule. The structure and the ground-state energy of the drug under investigation have been analyzed employing density functional theory with B3LYP method. In order to obtain a more complete description of molecular vibration, vibrational frequency calculation has been carried out. The vibrational analysis also provides the detailed information about the intramolecular vibrations in the fingerprint region. The reported optimized geometries, molecular properties such as equilibrium energy, HOMO-LUMO gap, dipole moment, polarizability as well as first static hyperpolarizability components along with the electrostatic potential contours and surfaces have also been used to understand the activity of the molecules.

2. Experimental: Structure and Spectra

The fourier transform infrared spectrum was recorded with FT-IR Perkin Elmer spectrometer in KBr dispersion in the range of 400 to 4000 cm^{-1} . The optical properties of the gemifloxacin were examined using UV-visible spectrophotometer at room temperature. UV-visible spectrum was recorded in the range of 190–800 nm with Perkin Elmer-Lambda 950-UV-visible spectrometer. To measure the UV-visible absorption, the gemifloxacin particles were dispersed in distilled DI water and measured. The model molecular structure of gemifloxacin has been given in Figure 1. The experimental and calculated FT-IR spectra is given in Figure 2, and the experimental UV-visible spectrum is given in Figure 3.

Figure 2: Comparison of normalized IR spectra: (a) experimental (FTIR) and (b) scaled simulated spectrum obtained by using DFT (scaling factor $\times 0.96$) harmonic calculations for gemifloxacin.

Figure 3: UV-visible spectrum of gemifloxacin.

3. Computational Details

In the present communication the density functional theory (DFT) [8] has been employed using Becke's three-parameter hybrid exchange functionals [9] with the Lee-Yang-Parr correlation functionals [10, 11] to optimize the molecular structure and to calculate the electronic structure properties of the drug molecule. The Gaussian 03W program [12] was used to calculate the vibrational spectra, dipole moment (μ), polarizability (α), and the first static hyperpolarizability (β) of the title molecule, based on the finite field approach. The vibrational frequencies are calculated and scaled down by the appropriate factor [13, 14]. The vibrational wavenumber assignments and PED calculation have been carried out by combining the result of the GaussView 4.1 and the VEDA program [15, 16] with symmetry considerations.

Figure 4: PES scan for dihedral angle $N_9-O_3-C_{28}-H_{46}$ at B3LYP/6-31G(d,p).

The comparative experimental and calculated FTIR spectrum plotted using the pure Lorentzian band shape is shown in Figure 2.

4. Result and Discussion

4.1. Analysis of Conformers of Gemifloxacin

Theoretical calculations for conformers of gemifloxacin were carried out using the B3LYP/6-31G(d,p) method. The plots of the potential energy surface (PES) scans for this molecule are shown in Figures 4 and 5. The dihedral angles $N_9-O_3-C_{28}-H_{46}$ and $C_{18}-C_{23}-C_{27}-O_5$ are the relevant coordinates for conformational calculations within the molecule. In these calculations, all the geometrical parameters were simultaneously relaxed during the calculations while the dihedral angles were varied in steps of $10^\circ, 20^\circ, 30^\circ, \dots, 360^\circ$. The global minimum energy structure was obtained at -179.821° and -132.892° for the dihedral angles $N_9-O_3-C_{28}-H_{46}$ and $C_{18}-C_{23}-C_{27}-O_5$, respectively. The corresponding minimum energy for both PES scans was -1372.3884 Hartree, which implies that the obtained structure was a global minimum. This structure is shown in Figure 1 and was used for performing frequency calculations.

4.2. Molecular Geometry Optimization

The equilibrium geometry optimization of lowest energy conformer has been achieved by energy minimization. The optimized geometry of the molecule under study is confirmed to be located at the global minima on PES, as the calculated vibrational spectrum contains no imaginary wavenumber. The given molecule has three rings. Out of these two are six membered and one five membered. Ring R1 and R2 are in a plane while ring R3 deviates from the given plane due to two bulky groups, one attached at 6N of ring R1 and the other attached at 19C. The optimized bond length of C–C in six-membered pyridine ring R1 ranges between $1.367 \text{ \AA}$ and $1.475 \text{ \AA}$, while, for another pyridine ring R2, this ranges

Figure 5: PES scan for dihedral angle $C_{18}-C_{23}-C_{27}-O_5$ at B3LYP/6-31G(d,p).

between 1.366 Å and 1.401 Å. For five-membered pyrrole ring R3, C–C bond lengths are quite high and range between 1.510 Å and 1.536 Å. The optimized value of C23–C27 bond length adjacent to pyridine ring R1 is found to be 1.496 Å, which is also high in comparison to the C–C bond length in R1. The optimized value of C15–C22 bond length adjacent to pyrrole ring R3 is found to be 1.546 Å, which is also high in comparison to the C–C bond length in R3. Another important C–C bond length in cyclopropane attached to pyridine ring R1 is found in the range 1.501 Å–1.508 Å. The optimized C–N bond lengths in pyridine ring R1 are found to be 1.367 Å and 1.401 Å, while, in pyridine ring R2, the optimized C–N bond lengths are found to be 1.337 Å and 1.341 Å. On the other hand the optimized C–N bond lengths in pyrrole ring R3 are calculated as 1.473 Å and 1.469 Å, which is quite high in comparison to C–N bond length in both pyridine ring R1 and R2 because C–N bond in R2 is double bond while C–N bond in ring R1 has just double bond character due to delocalization of lone pair electrons of nitrogen in R1. C11–N6 bond length adjacent to ring R1 is found to be 1.451 Å, while C20–N7 bond length between ring R2 and R3 is calculated as 1.365 Å, which is quite small in comparison to C11–N6 bond length. The length of C19=N9 bond adjacent to ring R3 is found to be 1.276 Å, while C22–N10 bond length is found to be 1.465 Å. The length of C28–O3 bond adjacent to pyrrole ring R3 is found to be 1.425 Å. Values of all the bond angles are given in Table 1, and all are in accordance with previous experimental and theoretical studies on different biomolecules [17–19].

In five-membered ring, torsional strain also arises from the fact that, as the lateral distance between the bonds on two adjacent carbon atoms decreases, the repulsive interaction between the electrons of the bonds increases which cause decrease in bond angle. The double bond is sp^2 hybridized and forms bonds with bond angles of about 120° . In such cases the unsaturated double bond has two electron pairs, one of the sigma bond and the other of the pi bond. Repulsion by these two electron pairs, the other bond pair is greater than that between two single bond pairs. This leads to deviations from exact trigonal geometry. The same is the reason for R1 and R2 which shows lower bond angles as compared to true trigonal geometry.

Table 1: Optimized geometrical parameters of gemifloxacin, bond length (Å), and bond angle (°).

S. no.	Optimized parameters	Bond length	Optimized parameters	Bond angle
1	F1–C25	1.3568	N9–O3–C28	108.7776
2	O2=C24	1.2292	C27–O4–H45	108.8845
3	O3–N9	1.4063	C11–N6–C14	119.7248
4	O3–C28	1.425	C11–N6–C18	120.7158
5	O4–C27	1.3734	C14–N6–C18	119.1417
6	O4–H45	0.9675	C16–N7–C17	112.2795
7	O5=C27	1.2025	C16–N7–C20	120.2429
8	N6–C11	1.4508	C17–N7–C20	125.3726
9	N6–C14	1.4014	C14–N8–C20	119.5509
10	N6–C18	1.3673	O3–N9–C19	111.185
11	N7–C16	1.4734	C22–N10–H43	109.9774
12	N7–C17	1.4695	C22–N10–H44	109.7683
13	N7–C20	1.3647	H43–N10–H44	106.2508
14	N8–C14	1.3369	N6–C11–C12	119.8908
15	N8–C20	1.3412	N6–C11–C13	119.6133
16	N9–C19	1.2761	N6–C11–H29	113.1169
17	N10–C22	1.4655	C12–C11–H29	116.832
18	N10–H43	1.0166	C13–C11–H29	117.5714
19	N10–H44	1.018	C11–C12–H30	117.0507
20	C11–C12	1.5012	C11–C12–H31	117.4329
21	C11–C13	1.5077	C13–C12–H30	117.2739
22	C11–H29	1.0867	C13–C12–H31	119.4588
23	C12–C13	1.5081	H30–C12–H31	114.7379
24	C12–H30	1.0845	C11–C13–H32	118.7106
25	C12–H31	1.0847	C11–C13–H33	117.2653
26	C13–H32	1.0853	C12–C13–H32	117.1928
27	C13–H33	1.0851	C12–C13–H33	119.3677
28	C14–C21	1.4051	H32–C13–H33	114.1386
29	C15–C16	1.5356	N6–C14–N8	116.6219
30	C15–C19	1.5101	N6–C14–C21	119.0267
31	C15–C22	1.546	N8–C14–C21	124.3514
32	C15–H34	1.095	C16–C15–C19	103.1176
33	C16–H35	1.0901	C16–C15–C22	112.5205
34	C16–H36	1.0988	C16–C15–H34	111.7457
35	C17–C19	1.5139	C19–C15–C22	111.514
36	C17–H37	1.093	C19–C15–H34	109.6012
37	C17–H38	1.0974	C22–C15–H34	108.2916
38	C18–C23	1.3673	N7–C16–C15	104.2976

Table 1: Continued.

S. no.	Optimized parameters	Bond length	Optimized parameters	Bond angle
39	C18–H39	1.084	N7–C16–H35	110.6862
40	C20–C25	1.428	N7–C16–H36	110.474
41	C21–C24	1.4753	C15–C16–H35	111.9643
42	C21–C26	1.4077	C15–C16–H36	111.7943
43	C22–H40	1.0995	H35–C16–H36	107.6519
44	C22–H41	1.0964	N7–C17–C19	102.8584
45	C23–C24	1.4728	N7–C17–H37	111.4483
46	C23–C27	1.4958	N7–C17–H38	112.38
47	C25–C26	1.3663	C19–C17–H37	111.6618
48	C26–H42	1.0846	C19–C17–H38	111.1651
49	C28–H46	1.0921	H37–C17–H38	107.3873
50	C28–H47	1.0954	N6–C18–C23	124.8211
51	C28–H48	1.0953	N6–C18–H39	114.179

Table 2: Calculated parameters using TDDFT/B3LYP/6-31G(d,p) for gemifloxacin.

Excitation	CI expansion coefficient	Wavelength (nm)		Oscillator strength (<i>f</i>)	Energy (eV)
		Calculated	Experimental		
Excited state 1		325.93	342	0.3149	3.8040
102 → 103	0.63798				
102 → 104	0.14530				
Excited state 2		309.18		0.0090	4.0101
99 → 103	0.65753				
100 → 103	−0.12556				
Excited state 3		295.49	270	0.0394	4.1959
100 → 103	−0.29490				
101 → 103	0.31447				
102 → 104	0.50647				

4.3. Electronic Spectra of Gemifloxacin

On the basis of fully optimized ground-state structure, TDDFT/B3LYP/6-31G(d,p) calculations have been used to determine the low-lying excited states of gemifloxacin. The calculated results involving the vertical excitation energies, oscillator strength (*f*), and wavelength are carried out using the *Gaussian 03W* program and compared with measured experimental wavelength. Electronic transitions determined from excited-state calculations are listed in Table 2 for the three lowest energy transitions of the molecule. TD-DFT calculation predicts two intense electronic transition at 3.8040 eV (325.93 nm) and 4.1959 eV (295.49) with oscillator strengths of 0.3149 and 0.0394, respectively, in good agreement with the measured experimental data (exp = 270 nm and 342 nm) as shown in Figure 3.

Table 3: Calculated values of polarizability and hyperpolarizability using DFT/6-31G(d,p) for gemifloxacin.

S. no	Polarizability parameters	Value (e.s.u)	Hyperpolarizability parameters	Value (e.s.u)
1	α_{xx}	155.517	β_{xxx}	588.2079
2	α_{xy}	7.2473627,	β_{xxy}	157.9636
3	α_{yy}	239.2203429	β_{xyy}	38.9723
4	α_{yz}	-13.711457	β_{yyy}	26.2387
5	α_{zz}	140.0071631	β_{zzz}	0.8472
6	α_{zx}	-4.3056718	β_{xxz}	-1.4496
7	A	122.9957	β_{xzz}	24.0212
8			β_{yzz}	7.9028
9			β_{yyz}	9.3606
10			β_{xyz}	8.7427
11			β_{total}	94.3118

4.4. Dipole Moment, Polarizability, and First Static Hyperpolarizability

According to Buckingham's definitions [20], DFT has also been used to calculate the dipole moment (μ), polarizability (α), and the first static hyperpolarizability (β). The total intrinsic hyperpolarizability β_{TOTAL} [21] and a component of the first hyperpolarizability along the direction of the dipole moment are represented by β [21, 22].

The β components of the Gaussian output are reported in atomic units, where 1 a.u. = 8.3693×10^{-33} e.s.u..

Table 3 clearly shows that molecule has major component of polarizability along axial direction; however, perpendicular components of polarizability have negligible contribution. Thus the polarization ellipsoid nearly planar is stretched along Y axis and contracted along Z axis. Thus dipole formed along XYZ axis and less stretched along perpendicular direction. The plane contains XX and XY having major part of hyperpolarizability. It means ellipsoids flattered along this plane. This means that this molecule is optically reactive in X direction.

4.5. Electronic Properties

HOMOs and LUMOs determine the way the molecule interacts with other species. The frontier orbital gap helps characterize the chemical reactivity of molecule. A molecule which have more orbital gap is more less polarized and less chemically reactive [23]. According to the present DFT calculations, the frontier orbital gap in case of given molecule is 4.30 eV. The 3D and 2D plots of the HOMO, LUMO, and electrostatic potential for the molecule are shown in Figures (6–8). HOMO is located at ring R1 and R2, however, half R3 and F atom part of pentagon ring. If we see 2D plot of HOMO (Figure 6) a negative equipotential concentric line appears around N atom (ring R1) and F atom (adjacent to ring R2). However, a surface of positive line is closely concentrated around O atom adjacent to ring R1. It clearly

Figure 6: 3D and 2D plots of highest occupied molecular orbital.

Figure 7: 3D and 2D plots of lowest unoccupied molecular orbital.

indicates that delocalized electrons are confined at negative region of given molecule, however, shifted from positive part. This type of delocalized electron takes part in reaction and behaves as active part for binding to the receptor. LUMOs are located (Figure 7) at same place as HOMOs, except to those two carbon which are adjoint to ring R1 and R2. In the case of given molecule, the electronegative region (red) is towards the outer part and near the oxygen which is adjacent to ring R1, and moderate positive region (green) is located nearly over whole molecule.

The importance of MESP lies in the fact that it simultaneously displays size as well as shape and with the help of colour grading (shown in Figure 8) defined positive, negative, and neutral electrostatic potential regions, which are very useful in investigation of molecular structure with its physiochemical property relationship [24–28]. As we see from 2D molecular electrostatic potential plot (Figure 8), negative equipotential surface lines are passing near to O atom which is adjacent to ring R1, and other negative potential regions are found near to N atom of ring R2 (where negative lines closely form a concentric circle). Negative potential surface line near to O atom is passing through F atom. This indicates that it is suitable place for nucleophilic substitution reaction. The energy equal to the shielded

Figure 8: 3D and 2D plots of molecular electrostatic potential.

PES is required for any substitution reaction near the oxygen. The electronegative lines (between -0.08 u. and -0.04 u.) form a closed contour which clearly indicates that the total flux passing in between these curves is not equal to zero. It generates a negative electric field region near the oxygen atom which opposes the electrophilic substitution. The molecule acts as a dipole in which the area near the oxygen atom acts as the negative pole (better site for positive radicals in human bodies), however, the remaining part of the molecule is suitable for electrophilic substitution reaction. Out of these, all regions are surrounded by the positive potential surface line over whole molecule.

4.6. Vibrational Assignments

The molecule gemifloxacin contains 48 atoms, and it has 138 normal modes of vibration. All the 138 fundamental vibrations are IR active. The harmonic-vibrational frequencies calculated for gemifloxacin and experimental frequencies (FTIR) have been compared in Table 4. Vibrational assignments are based on the observation of the animated modes in *GaussView* and assignments reported in the literature.

In gemifloxacin, the C–H functional group is present at a number of positions. The stretching vibration, $\nu(\text{C–H})$, is expected to occur in the region $3010\text{--}3120\text{ cm}^{-1}$. The calculated values of the $\nu(\text{C–H})$ vibration lie within this spectral range. The other important stretching vibration corresponds to the C=O moieties at the C_{24} and C_{27} positions. The region $1650\text{--}1750\text{ cm}^{-1}$ is generally considered as the double bond stretching region for C=O, C=C, and C=N bonds [29–32]. The C=O stretching vibration, $\nu(\text{C=O})$ appears as a prominent mode in the FTIR spectra at 1716 cm^{-1} . Another important stretching vibration in gemifloxacin is the O–H stretching vibration. The O–H group vibrations are likely to be most sensitive to the environment, so they show pronounced shifts in the spectra of the hydrogen-bonded species. In the subject molecule, the $\nu(\text{O–H})$ vibration appears at 3439 cm^{-1} in the FTIR spectrum. The calculated (scaled) and experimental frequencies are deviated by large amount, which may be explained by the presence of hydrogen bondings in the solid sample.

The –NH_2 , and –CH_2 , functional groups are important constituents of gemifloxacin and vibrations corresponding to these groups are present in a number of modes. The stretching vibrations of these groups appear in a number of modes. The wagging vibrations $\omega(\text{CH}_2)$ and $\omega(\text{NH}_2)$ are also present in a number of modes. Mode 39 shows a pure $\omega(\text{CH}_2)$ vibration, and there is excellent correspondence between calculated (scaled) and experimental FTIR wavenumber as can be seen in Table 4.

Table 4: Vibrational assignments for gemifloxacin.

Mode no.	Experimental frequencies and intensities		Calculated frequencies and intensities using DFT/6-31G(d,p)		Vibrational assignment ^a
	FTIR (cm ⁻¹)	Intensity profile (% transmittance)	Unscaled (cm ⁻¹)	Scaled (cm ⁻¹)	
1	3439	48.64	3804	3652	$\nu(\text{O}_{39}-\text{H})$ (100)
2	3055	56.63	3578	3435	$\nu_{\text{as}}(\text{NH}_2)$ (98)
3			3491	3351	$\nu_{\text{s}}(\text{NH}_2)$ (98)
4			3249	3119	$\nu_{\text{as}}(\text{H}_2\text{C}-\text{CH}_2)$ (98)
5			3233	3104	$\nu_{\text{as}}(\text{H}_2\text{C}-\text{CH}_2)$ (97)
6			3229	3100	$\nu(\text{C}-\text{H})$ (100)
7			3219	3090	$\nu(\text{C}-\text{H})$ (97)
8			3165	3038	$\nu(\text{C}-\text{H})$ (91), $\nu_{\text{s}}(\text{H}_2\text{C}-\text{CH}_2)$
9			3158	3032	$\nu_{\text{s}}(\text{CH}_2)$ (89)
10			3151	3025	$\nu_{\text{s}}(\text{CH}_2)$ (94)
11	3005	55.67	3147	3021	$\nu_{\text{as}}(\text{CH}_3)$ (92)
12	2936	54.31	3144	3018	$\nu_{\text{as}}(\text{CH}_2)$ (97)
13			3106	2982	$\nu_{\text{as}}(\text{CH}_3)$ (100)
14			3101	2977	$\nu_{\text{as}}(\text{CH}_2)$ (91)
15			3086	2963	$\nu(\text{C}-\text{H})$ (91)
16			3069	2946	$\nu(\text{C}-\text{H})$ (89), $\nu_{\text{as}}(\text{CH}_2)$
17			3039	2917	$\nu_{\text{s}}(\text{CH}_2)$ (90)
18			3035	2914	$\nu_{\text{s}}(\text{CH}_3)$ (91)
19			3022	2901	$\nu_{\text{s}}(\text{CH}_2)$ (95)
20			3012	2892	$\nu_{\text{s}}(\text{CH}_2)$ (87)

Table 4: Continued.

Mode no.	Experimental frequencies and intensities		Calculated frequencies and intensities using DFT/6-31G(d,p)		Vibrational assignment ^a
	FTIR (cm ⁻¹)	Intensity profile (% transmittance)	Unscaled (cm ⁻¹)	Scaled (cm ⁻¹)	
21			1875	1800	$\nu(\text{C=O})$ (86), $\beta(\text{O-H})$
22			1747	1677	$\nu(\text{C=N})$ (84)
23	1716	47.92	1732	1663	$\nu(\text{C=O})$ (83)
24	1632	24.84	1674	1607	$\nu(\text{C-H})$ (40), $\beta(\text{C-H})$ (10), $\nu(\text{R1}), \nu(\text{R2})$
25			1667	1600	$\zeta(\text{NH}_2)$ (86)
26			1648	1582	$\beta(\text{C-H})$ (66)
27	1565	54.16	1592	1528	$\nu(\text{R2})$ (57), $\beta(\text{C-H})$
28	1548	53.99	1538	1476	$\zeta(\text{CH}_2)$ (52)
29	1505	45.15	1532	1471	$\zeta(\text{CH}_2)$ (21), $\nu(\text{C-C})$ (10), $\nu(\text{C-N})$ (13)
30	1463	22.92	1523	1462	$\zeta(\text{CH}_2)$ (81)
31			1521	1460	$\rho_i(\text{CH}_3)$ (89)
32			1519	1458	$\zeta(\text{H}_2\text{C-CH}_2)$ (80)
33			1514	1453	$\zeta(\text{CH}_2)$ (83)
34			1492	1432	$\beta(\text{R2})$ (55)
35			1489	1429	$\zeta(\text{CH}_3)$ (79)
36			1476	1417	$\zeta(\text{H}_2\text{C-CH}_2)$ (93)
37	1401	53.42	1473	1414	$\delta_s(\text{CH}_3)-$ Umbrella (84)
38	1380	56.21	1425	1368	$\beta(\text{C-H})$ (54)
39	1365	53.98	1422	1365	$\omega(\text{CH}_2)$ (76)
40			1411	1355	$\beta(\text{C-H})$ (20)

Table 4: Continued.

Mode no.	Experimental frequencies and intensities		Calculated frequencies and intensities			Vibrational assignment ^a
	FTIR (cm ⁻¹)	Intensity profile (% transmittance)	Unscaled (cm ⁻¹)	Scaled (cm ⁻¹)	Intensity (km/mol)	
41			1399	1343	32.1298	$\beta(\text{C-H})$ (33)
42	1333	55.02	1387	1332	113.0278	$\omega(\text{CH}_2)$ (15), $\beta(\text{C-H})$
43			1378	1323	37.0029	$\omega(\text{CH}_2)$ (49), $\tau(\text{CH}_2)$, $\beta(\text{C-H})$
44			1360	1306	160.7416	$\omega(\text{CH}_2)$ (33), $\tau(\text{CH}_2)$ (15), $\beta(\text{C-H})$, $\beta(\text{O-H})$
45			1356	1302	5.7122	$\omega(\text{CH}_2)$ (42), $\tau(\text{CH}_2)$
46			1348	1294	177.0604	$\beta(\text{C-H})$ (23)
47			1345	1291	20.6199	$\tau(\text{NH}_2)$ (64), $\tau(\text{CH}_2)$, $\beta(\text{C-H})$
48	1277	64.25	1328	1275	7.0325	$\omega(\text{CH}_2)$ (40), $\beta(\text{C-H})$
49	1251	57.98	1286	1235	322.3537	$\beta(\text{O-H})$ (35), $\beta(\text{C-H})$
50	1200	32.68	1282	1231	5.9684	$\omega(\text{CH}_2)$ (22), $\beta(\text{C-H})$
51			1264	1213	72.3611	$\beta(\text{C-H})$ (24)
52			1259	1209	24.5975	$\beta(\text{O-H})$ (45), $\beta(\text{C-H})$, $\tau(\text{CH}_2)$, $\omega(\text{CH}_2)$
53			1242	1192	39.123	$\tau(\text{CH}_2)$ (36)
54			1230	1181	53.4191	$\beta(\text{O-H})$ (43), $\zeta(\text{H}_2\text{C-CH}_2)$

Table 4: Continued.

Mode no.	Experimental frequencies and intensities		Calculated frequencies and intensities using DFT/6-31G(d,p)		Vibrational assignment ^a
	FTIR (cm ⁻¹)	Intensity profile (% transmittance)	Unscaled (cm ⁻¹)	Scaled (cm ⁻¹)	
55			1214	1165	$\tau(\text{CH}_2)$ (45), $\rho_i(\text{CH}_3)$
56			1211	1163	$\tau(\text{CH}_2)$ (13), $\beta(\text{C-H})$, $\beta(\text{O-H})$
57			1208	1160	$\rho_i(\text{CH}_3)$ (62), $\tau(\text{CH}_2)$
58			1199	1151	$\tau(\text{H}_2\text{C-CH}_2)$ (56)
59			1190	1142	$\beta(\text{C-H})$ (30), $\tau(\text{NH}_2)$
60			1179	1132	$\rho_o(\text{CH}_3)$ (21)
61			1173	1126	$\tau(\text{CH}_2)$ (53), $\tau(\text{NH}_2)$
62			1167	1120	$\beta(\text{C-H})$ (20), $\beta(\text{O-H})$
63			1154	1108	$\beta(\text{C-H})$ (36)
64	1075	55.26	1126	1081	$\gamma(\text{C-H})$ (51)
65	1048	35.07	1101	1057	$\beta(\text{C-H})$ (13)
66			1093	1049	$\beta(\text{C-H})$ (61), $\omega(\text{NH}_2)$
67			1090	1046	$\omega(\text{H}_2\text{C-CH}_2)$ (88)
68			1087	1044	$\nu(\text{C-N})$ (65)
69			1084	1041	$\beta(\text{C-H})$, $\beta(\text{O-H})$
70			1070	1027	$\delta(\text{H}_2\text{C-CH}_2)$ -Umbrella (65)
71			1045	1003	$\delta(\text{H}_2\text{C-CH}_2)$ (11), $\beta(\text{C-H})$

Table 4: Continued.

Mode no.	Experimental frequencies and intensities		Calculated frequencies and intensities using DFT/6-31G(d,p)			Vibrational assignment ^a
	FTIR (cm ⁻¹)	Intensity profile (% transmittance)	Unscaled (cm ⁻¹)	Scaled (cm ⁻¹)	Intensity (km/mol)	
72			1044	1002	7.029	$\rho(\text{CH}_2)$, $\tau(\text{NH}_2)$
73			1005	965	14.8417	$\rho(\text{CH}_2)$ (60)
74	995	62.23	996	956	7.3192	$\beta(\text{C-H})$, $\omega(\text{CH}_2)$
75	966	65.78	975	936	3.9291	$\delta(\text{H}_2\text{C-CH}_2)$
76			949	911	16.5036	$\rho(\text{CH}_2)$, $\rho(\text{NH}_2)$
77			948	910	1.6637	$\gamma(\text{C-H})$
78			944	906	18.9177	$\gamma(\text{C-H})$
79			936	899	79.4214	$\omega(\text{CH}_2)$, $\nu(\text{O-N})$
80			914	877	21.479	$\beta(\text{C-H})$, $\delta(\text{H}_2\text{C-CH}_2)$
81	899	63.39	899	863	9.4454	$\tau(\text{CH}_2)$, $\beta(\text{C-H})$
82	846	69.37	883	848	18.0586	$\omega(\text{NH}_2)$, $\rho(\text{CH}_2)$
83	808	61.76	851	817	45.6951	$\delta(\text{H}_2\text{C-CH}_2)$
84	790	67.54	837	804	5.8479	$\gamma(\text{C-H})$, $\delta(\text{H}_2\text{C-CH}_2)$
85	780	67.77	826	793	37.0415	$\omega(\text{NH}_2)$, $\rho(\text{H}_2\text{C-CH}_2)$
86			819	786	74.1025	$\omega(\text{NH}_2)$, $\rho(\text{CH}_2)$
87			805	773	29.7494	$\rho(\text{CH}_2)$, $\gamma(\text{C=O})$, $\gamma(\text{C-H})$
88	744	71.20	784	753	5.5338	$\rho(\text{H}_2\text{C-CH}_2)$
89	730	69.94	774	743	2.3155	$\rho(\text{H}_2\text{C-CH}_2)$

Table 4: Continued.

Mode no.	Experimental frequencies and intensities		Calculated frequencies and intensities using DFT/6-31G(d,p)		Vibrational assignment ^a
	FTIR (cm ⁻¹)	Intensity profile (% transmittance)	Unscaled (cm ⁻¹)	Scaled (cm ⁻¹)	
90	649	70.04	770	739	ν (Ring)-breathing (39), ρ (H ₂ C-CH ₂)
91	633	69.26	733	704	γ (Ring), τ (H ₂ C-CH ₂)
92	565	65.32	724	695	δ (R3), ρ (CH ₂)
93			709	681	τ (CH ₂), δ (H ₂ C-CH ₂)
94			687	660	β (C-H), δ (H ₂ C-CH ₂), δ (R2)
95			678	651	β (O-H), γ (R2), β (C-H)
96			644	618	β (O-H), β (C-H)
97			632	607	ω (CH ₂), β (O-H), δ (R2)
98	556	64.01	583	560	τ (CH ₂), γ (R3)
99	537	65.90	563	540	γ (O-H)
100			546	524	γ (O-H), δ (H ₂ C-CH ₂)
101			532	511	γ (O-H), ω (CH ₂)

Table 4: Continued.

Mode no.	Experimental frequencies and intensities		Calculated frequencies and intensities using DFT/6-31G(d,p)			Vibrational assignment ^a
	FTIR (cm ⁻¹)	Intensity profile (% transmittance)	Unscaled (cm ⁻¹)	Scaled (cm ⁻¹)	Intensity (km/mol)	
102			524	503	38.0854	$\gamma(\text{O-H})$
103	491	70.38	510	490	36.598	$\gamma(\text{O-H}), \gamma(\text{C-H})$
104			488	468	18.4656	$\delta(\text{H}_2\text{C-CH}_2),$
105			462	444	0.6491	$\gamma(\text{O-H}), \gamma(\text{C-H})$
106			456	438	0.4181	$\gamma(\text{C-H}), \gamma(\text{O-H})$
107	411	75.35	442	424	9.799	$\beta(\text{C=O}), \beta(\text{O-H}),$ $\rho(\text{CH}_2)$
108			378	363	3.8598	$\delta(\text{H}_2\text{C-CH}_2),$ $\nu(\text{C-F})$
109			374	359	2.5382	$\gamma(\text{C-H}), \gamma(\text{O-H})$
110			364	349	3.7118	$\beta(\text{O-CH}_3)$
111			357	343	10.0529	$\beta(\text{O-H}), \nu(\text{C-N}),$ $\rho_i(\text{CH}_3)$
112			332	319	4.4483	$\beta(\text{C-F}), \delta(\text{CH}_2),$ $\delta(\text{NH}_2)$
113			318	305	2.6928	$\rho(\text{CH}_2),$ $\nu(\text{C-COOH})$
114			307	295	4.629	$\rho(\text{CH}_2), \rho_o(\text{CH}_3)$
115			282	271	6.6786	$\rho(\text{CH}_2)$
116			270	259	5.1601	$\beta(\text{C-F}), \beta(\text{C=O}),$ $\rho(\text{H}_2\text{C-CH}_2),$ $\rho(\text{CH}_2), \rho(\text{NH}_2)$

Table 4: Continued.

Mode no.	Experimental frequencies and intensities		Calculated frequencies and intensities using DFT/6-31G(d,p)		Vibrational assignment ^a
	FTIR (cm ⁻¹)	Intensity profile (% transmittance)	Unscaled (cm ⁻¹)	Scaled (cm ⁻¹)	
117			266	255	$\rho(\text{CH}_2)$, $\delta(\text{H}_2\text{C}-\text{CH}_2)$
118			257	247	$\rho(\text{NH}_2)$
119			212	204	$\delta(\text{H}_2\text{C}-\text{CH}_2)$, $\beta(\text{C}=\text{O})$, $\beta(\text{O}-\text{H})$, $\omega(\text{CH}_2)$
120			206	198	$\rho(\text{NH}_2)$, $\rho(\text{CH}_2)$
121			199	191	$\beta(\text{R}1)$, $\beta(\text{R}3)$, $\delta(\text{H}_2\text{C}-\text{CH}_2)$
122			178	171	$\rho(\text{CH}_2)$, $\omega(\text{CH}_2)$, $\gamma(\text{R}1)$, $\gamma(\text{R}2)$
123			170	163	$\rho_i(\text{CH}_3)$
124			160	154	$\rho_i(\text{CH}_3)$, $\rho(\text{CH}_2)$
125			147	141	$\rho(\text{CH}_2)$, $\tau(\text{NH}_2)$, $\rho_i(\text{CH}_3)$, $\delta(\text{H}_2\text{C}-\text{CH}_2)$
126			136	131	$\rho(\text{CH}_2)$, $\beta(\text{O}-\text{CH}_3)$, $\delta(\text{H}_2\text{C}-\text{CH}_2)$
127			129	124	$\beta(\text{C}-\text{COOH})$, $\rho(\text{H}_2\text{C}-\text{CH}_2)$
128			111	107	$\beta(\text{O}-\text{CH}_3)$, $\rho(\text{CH}_2)$
129			87	84	$\rho_i(\text{CH}_3)$
130			85	82	$\rho_i(\text{CH}_3)$, $\omega(\text{NH}_2)$, $\delta(\text{H}_2\text{C}-\text{CH}_2)$, $\gamma(\text{C}=\text{O})$

Table 4: Continued.

Mode no.	Experimental frequencies and intensities		Calculated frequencies and intensities using DFT/6-31G(d,p)		Vibrational assignment ^a
	FTIR (cm ⁻¹)	Intensity profile (% transmittance)	Unscaled (cm ⁻¹)	Scaled (cm ⁻¹)	
131			69	66	0.8606
132			63	60	2.5986
133			61	59	0.327
134			56	54	1.5885
135			50	48	0.9022
136			44	42	0.4721
137			25	24	0.8119
138			15	14	0.0919

^a Abbreviations: ν , stretching; ν_s , symmetric stretching; ν_{as} , asymmetric stretching; β , in-plane bending; γ , out-of-plane bending; δ_s , symmetrical deformation; δ_{as} , asymmetrical deformation; ζ , scissoring; ρ , rocking; ρ_i , in-plane rocking; ρ_o , out-of-plane rocking; ω , wagging; τ , twisting.

The twisting (τ) and rocking (ρ) vibrations for both the functional groups are present mixed with other vibrations.

The other important functional group in gemifloxacin is the $-\text{CH}_3$ group. There are nine modes of vibration of methyl group, which are distributed as follows: one symmetric stretching (ν_s), two anti-symmetric stretching (ν_{as}), one symmetrical deformation (δ_s), two asymmetrical deformation (δ_{as}), one in-plane rocking (ρ_i), one out-of-plane rocking (ρ_o), and one twisting (τ) vibration modes [30]. The $\nu_s(\text{CH}_3)$ and $\nu_{as}(\text{CH}_3)$ vibrations, are present in higher frequency modes as pure vibrations, and the other vibrations are mixed with other vibrations. The $\text{H}_2\text{C}-\text{CH}_2$ functional group which is attached to the C_{11} atom in gemifloxacin has unique vibrational fingerprints. It shows a number of vibrations, and these are distributed throughout the spectrum.

In gemifloxacin, a very important vibration corresponds to the modes involving the vibrations of the ring atoms. For the purpose of easing the analysis, we have classified the structure of gemifloxacin into three rings R1, R2, and R3 as shown in Figure 1. The ring stretching vibrations $\nu(\text{Ring})$ are complicated combinations of stretchings of C–N, C=C, and C–C bonds. The most important ring stretching vibration is the ring breathing vibration at mode 90. In this mode, all bonds of the rings appear to stretch and contract in-phase with each other [33]. In the experimental infrared spectrum of gemifloxacin, this mode appears at 649 cm^{-1} . Other ring vibration modes present a mixed profile.

5. Conclusion

In the present work we have calculated the geometric parameters, vibrational frequencies, frontier molecular orbitals, molecular electrostatic potential contours, and surfaces and the nonlinear optical properties of gemifloxacin using DFT/B3LYP method. Optimized geometry clearly shows that the skeleton of the title molecule is nonplanar. The higher frontier orbital gap of 4.30 eV shows that gemifloxacin has high kinetic stability and can be termed as hard molecule. However, the higher value of dipole moment shows that gemifloxacin molecule is highly polar. Nonlinear optical behavior of title molecule was investigated by the determination of the dipole moment, the polarizability, and the first static hyperpolarizability using density functional B3LYP method. In general, a good agreement between experimental and calculated normal modes of vibrations has been observed. The molecular electrostatic potential contours and surfaces have also been drawn to explain the activity of gemifloxacin molecule. The present quantum chemical study may further play an important role in understanding of the structure, activity, and dynamics of the molecule.

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