Structural and Vibrational studies (FT-IR, FT-Raman) of Voglibose using DFT calculation

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Keywords: FT-IR; FT-Raman; NBO; UV-Vis; NMR; TED.

ABSTRACT. In the present study, we report on the Molecular structure and infrared (IR) and FT-Raman studies of Voglibose (VGB) as well as by calculations based on the density functional theory (DFT) approach; utilizing B3LYP/6-31G(d,p) basis set. The targeted interpretation of the vibrational spectra intended to the basis of calculated potential energy distribution matrix (PED) utilizing VEDA4 program. Stability of the molecule arising from hyperconjugative interactions and charge delocalization was studied using natural bond orbital (NBO) analysis. The results show that change in electron density in the σ and π antibonding orbitals and E2 energies confirm the occurrence of intramolecular charge transfer within the molecule. The UV-Visible and NMR spectral analysis were reported by using TD-DFT and gauge GIAO approach respectively and their chemical shifts related to TMS were compared. The lowering of HOMO and LUMO energy gap appears to be the cause for its enhanced charge transfer interactions. Besides, molecular electrostatic potential (MEP) analysis was reported. Due to different potent biological properties, the molecular docking results are also reported.

1. INTRODUCTION

Voglibose is a new and potent in-hibitor of α-glucosidases and is used for the treatment of diabetes mellitus. Voglibose is chemically known as 3,4-Dideoxy-4-[2-hydroxy-1-(hydroxymethyl)ethyl]amino-2-c-(hydroxymethyl)-D-epinositol has attracted considerable interests due to its wide range of therapeutic and pharma-cological properties, including its excellent inhibitory activity against α-glucosidase and its action against hyperglycemia and various disorders caused by hyper-glycemia [1]. Voglibose obtained from organic synthesis processes is similar to structurally related carbohydrates found naturally [2, 3] and has the empirical formula C10H23NO5. For the treatment of diabetes. It is specifically used for lowering postprandial blood glucose levels thereby reducing the risk of macrovascular complications.

Recently, Iwamoto et al reported [4] Efficacy and safety of vildagliptin and voglibose in Japanese patients with type 2 diabetes: a 12-week, randomized, double-blind, active-controlled study. Mallikarjuna Rao et al [1] presented RP-HPLC method development and validation for estimation of Voglibose in bulk and tablet dosage forms. Determination of voglibose in pharmaceutical formulations by high performance liquid chromatography using refractive index detection given by Karunanidhi Lakshmi et al [5]. Hong Zhang et al [2] reported 1H and 13C NMR analysis of Voglibose and its derivatives. A Comparative Study of Acarbose and Voglibose on Postprandial Hyperglycemia and serum lipids in Type 2 Diabetic patients reported by P. Revathi et al [6].

With the guide of above seen written works, it is clear that there is no quantum mechanical study on this VGB molecule which has propelled to do a definite quantum mechanical investigation for comprehension the vibrational modes, UV-Visible, chemical shifts, HOMO-LUMO, MEP. In this commitment, the structural and vibrational investigations of a basic VGB molecule was introduced and talked about. In the present work we want to focus on vibrational spectrum of the title compound inclusive its interpretation based on the theoretical spectrum calculated by means of...
density functional theory (DFT). The redistribution of electron density (ED) in various bonding, antibonding orbitals and \( E^{(2)} \) energies have been calculated by natural bond orbital (NBO) analysis to give clear evidence of stabilization originating from the hyperconjugation of various intramolecular interactions.

2. MATERIALS AND METHODS

2.1. FT-IR, FT-Raman and UV–Vis analysis

The compound Voglibose was purchased from Aldrich chemicals, USA and used as such to record the FT-IR and FT-Raman, UV spectra. Bruker IFS 66 V spectrometer was used to record the FT-IR spectrum by KBr pellet method on a equipped with a Globar source, Ge/KBr beam splitter, and a TGS detector in the range of 4000–400 cm\(^{-1}\). The spectral resolution was 2 cm\(^{-1}\). The FT-Raman spectrum was obtained on a Bruker RFS 100/s, Germany and the excitation of the spectrum is with the emission of Nd:YAG laser with a wavelength of 1064 nm, maximal power 150 mW. Cary 500 UV-VIS-NIR spectrometer was used to record the UV absorption spectra associated with Voglibose were examined with the range 200-800 nm. The UV pattern is usually acknowledged from the \( 10^{-5} \) molar solution connected with VGB, dissolved with ethanol solvent.

3. COMPUTATIONAL DETAILS

Calculations of the title compound were carried out with the Gaussian 03W program [7] using B3LYP/6-31G(d,p) basis set to predict the molecular structure and vibrational wave numbers and a scaling factor of 0.9608 is used for obtaining a considerably better agreement with experimental data [8,9]. The assignments of the calculated wave numbers are aided by the animation option of the VEDA4 [10] program. The atomic charges, distribution of electron density (ED) in various bonding and antibonding orbitals and stabilization energies, \( E^{(2)} \) have been calculated by natural bond orbital (NBO) analysis were performed using NBO 3.1 program [11] as implemented in the Gaussian 03W [7] package at the DFT/B3LYP level of calculation. UV–Visible spectra, electronic transitions, vertical excitation energies and oscillator strengths were computed with the time-dependent DFT method with 6-31G(d,p) basis set in gas phase and using ethanol as solvent. The \(^1\)H and \(^13\)C NMR isotropic shielding were calculated with the GIAO method [12] using the optimized parameters obtained from B3LYP/6-31G(d,p) method.

3.1. Prediction of Raman intensities

The Raman activities \( (S_{Ra}) \) calculated with Gaussian 03W program [7] converted to relative Raman intensities \( (I_{Ra}) \) using the following relationship derived from the intensity theory of Raman scattering [13,14]

\[
I_i = \frac{f(v_o - v_i)^4 S_i}{v_i [1 - \exp(-hcv_i/kt)]}
\]

Where, \( v_o \) is the laser exciting wavenumber in cm\(^{-1}\) (in this work, we have used the excitation wavenumber \( v_0 = 9398.5 \) cm\(^{-1}\), which corresponds to the wavelength of 1064 nm of a Nd-YAG laser), \( v_i \) the vibrational wavenumber of the \( i^{th} \) normal mode (cm\(^{-1}\)) while \( S_i \) is the Raman scattering activity of the normal mode \( v_i \) [15].

4. RESULTS AND DISCUSSIONS

4.1. Conformational stability

In order to describe conformational flexibility of the title molecule, the energy profile as a function of N13–C15–C16–O17 torsion angle was achieved with B3LYP/6-31G(d,p) level of calculation as shown in Fig. 1. All the geometrical parameters were simultaneously relaxed during the calculations while the N13–C15–C16–O17 torsional angle was varied in steps of 10°, 20°, 30°... 360°. The energy values obtained from the scan output show that, the structure has a minimum energy (-794.609 Hartree), when the dihedral angle N13–C15–C16–O17 is 0° or 360° (global minimum) and -794.994 Hartree (local minimum) when the dihedral angle N13–C15–C16–O17 is
160°. Therefore, in the present work we have focused on the most stable form of VGB molecule to clarify molecular structure and assignments of vibrational spectra.

![Relative energy (Hartree) vs. Dihedral angle (°) for T(N13-C15-C16-O17)](image)

**Fig. 1.** Dihedral angle-relative energy curves of the Voglibose by B3LYP/6-31G (d,p) level of theory

### 4.2. Molecular geometry

The optimized geometrical parameters such as bond length, bond angles and dihedral angles calculated by B3LYP/6-31G(d,p) level of calculation using Gaussian 03W program package. To the best of our knowledge, the experimental data on geometric structure of VGB is not available in the literature. Therefore, the theoretical results of VGB have been compared together with closely related molecule 1-Cyclohexylmethoxymethyl-5-[2-hydroxy-1-(hydroxymethyl) ethylamino]cyclohexane-1, 2, 3, 4-tetraol [16] as given in Table 1. The C-C bond length of the cyclohexane ring varies from 1.534 Å-1.565 Å. Due to the O-H group substitution on the C1, C2, C3 and C4th position of the cyclohexane ring, the C-C bond lengths are not same for example C1-C2=1.565 Å, C1-C6=1.536 Å, C2-C3=1.544 Å, C3-C4=1.538 Å calculated by DFT method. The C-O bond length on the cyclohexane ring varies from 1.416 Å -1.429 Å by DFT method is good agreement with experimental value 1.429 Å -1.439 Å. The N13-H32 bond length is 1019 Å calculated by DFT method. N-C bond lengths are C5-N13=1.481 Å / 1.480 Å, N13-C15=1.480 Å /1.467 Å calculated by DFT/XRD respectively, this result shows good agreement between Theoretical and experimental values. The C-H bond lengths of ethyl alcohol (CH2OH) group is C11-H29=1.100 Å, C11-H30=1.094 Å and C14-H33=1.092 Å, C14-H34=1.096 Å calculated by DFT method.

As shown in Fig. 2, the molecular structure of title compound contains one six-membered ring this ring (from C-1 to C-6) adopt chair conformations. The cyclohexane ring is disordered, with three of the C atoms distributed on two sites with approximately equal occupancy. In addition, one of the hydroxymethyl groups attached to C1 is disordered over the positions. The bond angle at point on the substitution is C2-C1-C6=110.9 °/109.0 ° calculated by DFT/XRD respectively. The unit –N13–C15–C16–O17- connected with C5 by the way of an equatorial bond, and the angles of N13-C5-H22 show 110.9 ° (DFT), C6-C5-N13 show 112.0 ° (DFT), 110.9 ° (XRD) and C4-C5-N13 show 106.2 ° (DFT), 108.9 ° (XRD). The N13-C15–C16 was like a bridge that aligned with cyclohexane ring and CH2OH.

Dihedral angles of cyclohexane part are found as C1-C2-C3-C4=−50.92 °, C2-C3-C4-C5=53.78 °, C3-C4-C5-C6=−54.98 ° and C4-C5-C6-C1=54.89 °. In case of twist form, the N-atom with the attached carbon 5 was considered are twisted about N13-C5-C6-C1=173.04 ° and C3-C4-C5-N13=−176.63 °. Meanwhile in the molecule, hydrogen bonded N13–H32...O10 appeared in the crystal with a bond length 2.803 (2) Å and bond angle 117.3° [17]. From the theoretical values, we found the idea most of our optimized bond lengths are slightly larger than experimental values due
to be able to fact that the theoretical calculations belong to be able to isolated molecules throughout gaseous phase as well as the experimental results belong for molecules in the solid state.

Fig.2. Optimized Molecular structure and atomic numbering of Voglibose

Table 1. Comparison of experimental and theoretical optimized parameter values of the Voglibose [bond length in (Å), angles in (°)]

| Bond length | B3LYP | Exp* | Bond angle | B3LYP | Exp* | Dihedral angle | B3LYP | Exp* |
|-------------|-------|------|------------|-------|------|----------------|-------|------|
| C1-C2       | 1.565 |      | C2-C1-C6   | 110.9 | 109.0| C6-C1-C2-C3    | 49.45 |      |
| C1-C6       | 1.536 |      | C2-C1-07   | 110.4 | 109.1| C6-C1-C2-O8    | -74.16|      |
| C1-O7       | 1.421 | 1.436| C2-C1-C11  | 111.1 | 106.2| C6-C1-C2-H19   | 168.77|      |
| C1-C11      | 1.539 |      | C6-C1-07   | 104.7 | 110.9| O7-C1-C2-C3    | 165.13|      |
| C2-C3       | 1.544 |      | C6-C1-C11  | 112.0 | 112.1| O7-C1-C2-O8    | 41.51 |      |
| C2-O8       | 1.416 | 1.431| O7-C1-C11  | 107.3 | 108.8| O7-C1-C2-H19   | -75.54|      |
| C2-H19      | 1.094 |      | C1-C2-C3   | 113.1 |      | C1-C1-C2-C3    | -75.82|      |
| C3-C4       | 1.538 |      | C1-C2-08   | 112.0 |      | C1-C1-C2-O8    | 160.55|      |
| C3-O9       | 1.429 | 1.430| C1-C2-H19  | 107.8 |      | C1-C1-C2-H19   | 43.48 |      |
| C3-H20      | 1.098 |      | C3-C2-08   | 108.8 |      | C2-C1-C6-C5    | -51.99|      |
| C4-C5       | 1.540 |      | C3-C2-H19  | 107.9 |      | C2-C1-C6-H23   | -176.27|      |
| C4-O10      | 1.428 | 1.429| O8-C2-H19  | 106.6 |      | C2-C1-C6-H24   | 69.08 |      |
| C4-H21      | 1.106 |      | C2-C3-C4   | 111.9 |      | O7-C1-C6-C5    | -171.12|      |
| C5-C6       | 1.534 |      | C3-C2-09   | 109.7 |      | O7-C1-C6-H23   | 64.60 |      |
| C5-N13      | 1.481 | 1.480| C2-C3-H20  | 106.3 |      | O7-C1-C6-H24   | -50.04|      |
| C5-H22      | 1.101 |      | C4-C3-09   | 109.8 |      | C1-C1-C6-C5    | 72.77 |      |
| C6-H23      | 1.094 |      | C4-C3-H20  | 108.1 |      | C1-C1-C6-H23   | -51.49|      |
| C6-H24      | 1.094 |      | O9-C3-H20  | 110.7 |      | C1-C1-C6-H24   | -166.14|      |
| O7-H25      | 0.969 |      | C3-C4-C5   | 112.4 |      | C2-C1-O7-H25   | 72.08 |      |
| O8-H26      | 0.971 |      | C3-C4-O10  | 108.3 |      | C6-C1-O7-H25   | -168.45|      |
| O9-H27      | 0.965 |      | C3-C4-H21  | 108.1 |      | C1-C1-C7-H25   | -49.19|      |
| O10-H28     | 0.973 |      | C5-C4-O10  | 109.8 |      | C2-C1-C11-O12  | -66.01|      |
| C11-O12     | 1.431 | 1.417| C5-C4-H21  | 108.5 |      | C2-C1-C11-H29  | 175.37|      |
| C11-H29     | 1.100 |      | O10-C4-H21 | 110.4 | 110.2| C6-C1-C11-O12  | 169.32|      |
| C11-H30     | 1.094 |      | C4-C5-C6   | 110.4 | 110.2| C6-C1-C11-H29  | 50.71 |      |
| O12-H31     | 0.964 |      | C4-C5-N13  | 106.2 | 108.9| C6-C1-C11-H30  | -69.69|      |
| N13-C15     | 1.480 | 1.467| C4-C5-H22  | 107.7 |      | C6-C1-C11-H30  | 175.79|      |
| N13-H32     | 1.019 |      | C6-C5-N13  | 112.0 | 110.9| O7-C1-C11-O12  | 50.81 |      |
| C14-C15     | 1.533 |      | C6-C5-H22  | 109.3 |      | O7-C1-C11-H29  | -63.79|      |
| C14-O18     | 1.427 |      | N13-C5-H22 | 110.9 |      | O7-C1-C11-H30  | 175.79|      |
| C14-H33     | 1.092 |      | C1-C6-C5   | 114.0 |      | C1-C2-C3-C4    | -50.92|      |
| C14-H34     | 1.096 |      | C1-C6-H23  | 108.4 |      | C1-C2-C3-O9    | 71.29 |      |
| C15-C16     | 1.548 |      | C1-C6-H24  | 106.8 |      | C1-C2-C3-H20   | -168.86|      |
| C15-H35     | 1.100 |      | C5-C6-H23  | 111.0 |      | O8-C2-C3-C4    | 74.43 |      |
| C16-O17     | 1.411 |      | C5-C6-H24  | 109.4 |      | O8-C2-C3-O9    | -163.33|      |
| C16-H36     | 1.101 |      | H23-C6-H24 | 106.6 |      | O8-C2-C3-H20   | -43.50|      |
| C16-H37     | 1.095 |      | C1-C7-H25  | 106.0 |      | H19-C2-C3-C4   | -170.15|      |
| O17-H38     | 0.969 |      | C2-O8-H26  | 107.0 |      | H19-C2-C3-O9   | -47.92|      |
4.3. Vibrational assignments

The Vogliose molecule consists of 39 atoms, which undergoes 111 normal modes of vibrations. The molecule belongs to C\textsubscript{1} point group symmetry. On the assumption of C\textsubscript{1} group of symmetry, the 111 fundamental vibrations of the molecule can be distributed as 38 stretching, 75 in-plane bending and 26 out-of-plane bending modes. The calculated wavenumbers, observed IR, Raman bands and assignments are given in Table 2 and their experimental and simulated spectra of IR and Raman are plotted in the Fig. 3 and Fig. 4, respectively.
4.3.1. Cyclohexane ring vibrations

The C-C stretching vibration of the Cyclohexane ring observed the FTIR band at 1070, 892 cm\(^{-1}\) and FT-Raman band at 698 cm\(^{-1}\) and the computed scaled wavenumbers at 1397, 1070, 895, 698 cm\(^{-1}\) by DFT method. These modes are good agreement with literature [18,19]. Guirgis et al.,2012 [20] assigned C-C-C in-plane bending vibration at 450, 349, 354 cm\(^{-1}\) by DFT method. In our present work C-C-C in-plane bending vibration observed at 937, 426, 421 cm\(^{-1}\) in FTIR spectrum and 440 cm\(^{-1}\) in FT-Raman spectrum and theoretically predicted wavenumbers at 939, 444 and 416 cm\(^{-1}\) by DFT method, which is good agreement with Cyclohexane derivatives [18,19,20].

The heteroaromatic structure shows the presence of C–H stretching vibration in the region 3100–3000 cm\(^{-1}\) which is the characteristics region for the ready identification of C–H stretching vibration [21]. In our present work C-H symmetric and anti symmetric stretching vibrations in ring CH\(_2\) identified at 2988 and 2976 cm\(^{-1}\) by DFT calculation. The ring CH\(_2\) anti symmetric stretching vibration observed at 2979 cm\(^{-1}\) in FT-Raman spectrum. The computed wavenumbers at 2970, 2948, 2917 and 2816 cm\(^{-1}\) by DFT method have been identified as C2-H19, C5-H22, C3-H20 and C4-H21 stretching vibrations respectively. The FTIR band at 1436 and 1233 cm\(^{-1}\) have been identified as scissoring and twisting type CH\(_2\) inplane bending vibration in ring respectively and computed wavenumbers at 1449 and 1216 cm\(^{-1}\) for this mode. The C–H in-plane bending frequencies occur in the region 1300–1000 cm\(^{-1}\). The out-of-plane bending vibrations are strongly coupled vibration and occur in the region 1000–750 cm\(^{-1}\) [22]. In our present work C-C-H in-plane bending vibrations observed at 1263 cm\(^{-1}\) in FT-Raman spectrum and the predicted wavenumbers at 1356, 1287, 1286 and 1260 cm\(^{-1}\) by DFT method. Mode nos 78 and 93 has been identified as CH out-of plane bending vibration, which is good agreement with expected values [22].

4.3.2. O-H vibrations

Hydrogen bonding alerts the frequencies of the stretching and bending vibrations. The O–H stretching bands move to lower frequencies usually with increase intensity and band broadening in the hydrogen bonded species. Hydrogen bonding present in five or six member ring system would reduce the O–H stretching bands to 3550 to 3200 cm\(^{-1}\) region [23]. Our title molecule contains six O-H groups, so we expect six O-H stretching vibrations. From the Table 2 which is evident that the mode no: 1-7 has been identified as O-H stretching vibrations, these are pure modes and the PED exactly contributes to 100%. The O–H in-plane-bending vibration in phenol, in general, lies in the region 1250 to 1150 cm\(^{-1}\). In our present work, C-O-H in-plane bending vibrations observed at 1070 cm\(^{-1}\) in FT-IR spectrum and 1411, 1377 cm\(^{-1}\) in FT-Raman spectrum. The calculated wavenumbers at 1415, 1382, 1374, 1371, 1360, 1179, 1168 and 1156 cm\(^{-1}\) by DFT method has been identified as C-O-H in-plane bending vibrations. The OH out-of-plane deformation vibration for phenol lies in the 290 to 320 cm\(^{-1}\) region for free OH [21]. In our work 4 OH groups directly attached to the Cyclohexane ring. The computed wavenumbers at 463, 438, 279 and 234 cm\(^{-1}\) by DFT method has been identified as the O-H out-of plane bending vibrations. Mode no: 63, 66, 68, 70 and 73 has been identified as the O-H out-of plane bending vibrations of the CH\(_2\)OH group.

4.3.3. Methylene group vibrations

For the assignments of CH\(_2\) group frequencies, basically six fundamentals vibration can be associated to each CH\(_2\) group namely, CH\(_2\) symmetric stretch, antisymmetric stretch, scissoring and rocking modes, which belong to polarized in-plane vibrations. In addition to that, wagging and twisting mode of CH\(_2\) group would be expected to be depolarized for out-of-plane bending vibration. The asymmetric CH\(_2\) stretching vibration generally observed in the region 3000–2900 cm\(^{-1}\), while the CH\(_2\) symmetric stretch will appear between 2900 cm\(^{-1}\) and 2800 cm\(^{-1}\) [24]. For title molecule CH\(_2\) anti symmetric and symmetric stretching vibrations observed at 2979, 2889 cm\(^{-1}\) and 2895 cm\(^{-1}\) in FT-Raman and FT-IR spectrum respectively. The computed wavenumbers at 3001, 2976 and 2963 cm\(^{-1}\) and 2988, 2888, 2882 and 2876 cm\(^{-1}\) are assigned as CH\(_2\) anti symmetric and symmetric stretching vibrations. The CH\(_2\) scissoring vibrations appear normally in the region 1490–
1435 cm\(^{-1}\) as medium intense bands [25]. In our present investigation FT-Raman band at 1460 cm\(^{-1}\) and computed wavenumbers at 1465, 1464 and 1457 cm\(^{-1}\) have been identified as CH\(_2\) scissoring vibrations. Absorption of hydrocarbons due to CH\(_2\) twisting and wagging vibration is observed in the 1350-1150 cm\(^{-1}\) region [26]. For title molecule the FT-IR band at 1233 cm\(^{-1}\) and 1216 cm\(^{-1}\) by DFT calculation gives the CH\(_2\) twisting vibrations. Mode no: 53 have been identified as the CH\(_2\) Rocking mode.

### 4.3.4. N-H and C-N vibrations

The N-H stretching vibrations generally give rise to bands at 3500–3400 cm\(^{-1}\) [27]. For title molecule N-H stretching vibration observed at 3254 cm\(^{-1}\) in FT-Raman spectrum and computed at 3334 cm\(^{-1}\) by DFT method. The observed FT-Raman band at 3254 cm\(^{-1}\) and calculated scaled wavenumber at 3334 is cm\(^{-1}\) is red shifted by 146 cm\(^{-1}\) and 66 cm\(^{-1}\) respectively. The reason for this long deviation is due to presence of the N13–H32...O10 intra molecular interaction. This red shifting is got enhanced by the reduction in the N-H bond values occurring in the hydrogen bonding interactions. The CNH vibration where N and H atoms move in the same direction relative to the carbon atom gives rise to a weaker band [25] near 1250 cm\(^{-1}\). In our present study the theoretically predicted wave number at 1458 cm\(^{-1}\) gives the CNH in-plane bending vibration.

Silverstein et al., [26] assigned the C-N stretching absorption in the region 1382 to 1286 cm\(^{-1}\) for aromatic amines. For title molecule C-N stretching vibration observed at 1134 cm\(^{-1}\) in FT-IR spectrum and 1136 and 1086 cm\(^{-1}\) in FT-Raman spectrum. The calculated wave numbers at 1135 and 1087 cm\(^{-1}\) has been identified as C-N stretching vibration, which is good agreement with experimental values. The calculated scaled wavenumber at 505 cm\(^{-1}\)by DFT method gives CNC in-plane bending vibrations. The observed FT-Raman band at 377 cm\(^{-1}\) and computed wave number at 379 cm\(^{-1}\) by DFT method has been identified as CCNC out-of plane bending vibration.

### 4.3.5. C-O vibrations

The C–O stretching vibration in phenol occurs as a strongest band in the region 1300 to 1200 cm\(^{-1}\) [28]. For title molecule C-O stretching vibration observed at 1026 cm\(^{-1}\) in FT-IR spectrum and 1047 cm\(^{-1}\) in FT-Raman spectrum. The calculated wavenumbers by DFT method at 1100, 1063, 1057, 1049, 1045, 1032 and 1008 cm\(^{-1}\) are assigned C-O stretching vibrations. The observed FT-Raman band at 630 cm\(^{-1}\) and theoretically predicted wavenumbers at 649, 629, 333, 331, 316 and 234 cm\(^{-1}\) are identified as C-C-O in-plane bending vibrations. The C-C-C-O out-of-plane bending vibration observed at 397 cm\(^{-1}\) in FT-Raman band and calculated wavenumbers at 398, 339, and 251 cm\(^{-1}\) by DFT calculation. Mode nos: 105-109 has been identified as C-C-C-O torsional modes.
Fig. 3. Comparison of experimental and theoretical B3LYP/6-31G(d,p) FT-IR spectrum for Voglibose
Fig. 4. Comparison of experimental and theoretical B3LYP/6-31G(d,p) FT-Raman spectrum for Voglibose.
| Mode No | Experimental wave numbers/cm\(^{-1}\) | Theoretical wave numbers/cm\(^{-1}\) | Vibrational assignments with PED (\(\geq 10\%\)) |
|---------|--------------------------------------|--------------------------------------|--------------------------------------|
|         | FT-IR Raman FT-Raman                | B3LYP/6-31G(d,p)                     |                                      |
| 1       | 3846 3695 44.46 3.09                | V113H32(98)                          |                                      |
| 2       | 3816 3666 33.39 2.82                | V99H27(100)                          |                                      |
| 3       | 3784 3636 31.97 1.67                | V113H39(100)                         |                                      |
| 4       | 3779 3631 51.69 2.45                | V113H25(100)                         |                                      |
| 5       | 3775 3627 49.99 1.87                | V113H38(100)                         |                                      |
| 6       | 3730 3584 72.26 1.33                | V113H39(100)                         |                                      |
| 7       | 3684 3540 90.59 2.65                | V98H26(100)                          |                                      |
| 8       | 3254 3470 3334 4.93 2.95            | V113H32(98)                          |                                      |
| 9       | 3123 3001 37.79 3.89                | V14H3(96) anti.sym in CH2            |                                      |
| 10      | 3110 2988 32.98 2.82                | V12H25(64) sym in ring CH2           |                                      |
| 11      | 2979 3097 33.48 3.00                | V12H24(32) anti.sym in ring CH2      |                                      |
| 12      | 3091 2970 34.62 4.99                | V1C2H1(93)                           |                                      |
| 13      | 3084 2963 45.7 4.22                 | V113H28(68) sym in ring CH2          |                                      |
| 14      | 2951 3068 2948 40.31 5.38           | V99H2(27) in ring                    |                                      |
| 15      | 3055 2935 49.46 3.39                | V12H2(46) in ring                    |                                      |
| 16      | 2912 3036 2917 48.4 5.54            | V13H20(73) in ring                   |                                      |
| 17      | 2895 2889 3006 2888 49.19 2.89      | V14H3(91) sym in CH2                 |                                      |
| 18      | 3000 2882 54.89 4.62                | V113H9(95) sym in CH2                |                                      |
| 19      | 2993 2876 44.4 3.63                 | V14H3(91) sym in CH2                 |                                      |
| 20      | 2985 2868 47.69 4.85                | V15H3(93)                            |                                      |
| 21      | 2931 2816 71.28 5.33                | V14H21(93) in ring                   |                                      |
| 22      | 1525 1465 18.85 4.93                | δ113H36C11H37(56)                    |                                      |
| 23      | 1524 1464 22.43 5.48                | δ113H34C14H34(56)                    |                                      |
| 24      | 1518 1458 29.11 3.61                | δ113H32N13C15(63)                    |                                      |
| 25      | 1460 1516 1457 20.99 7.64           | δ113H36C11H37(56)                    |                                      |
| 26      | 1436 1508 1449 17.22 5.98           | δ113H26C24H24(84) in ring+γ113C10H12H38(42) |                                      |
| 27      | 1411 1473 1415 58.17 4.35           | δ128O10C45(65)-γ113C10H12H38(28)     |                                      |
| 28      | 1458 1401 21.16 4.65                | δ126O2C20(20)-γ113C40H24(10)         |                                      |
| 29      | 1454 1397 52.62 4.47                | γ12C23(11) in ring+δ17H27O8C31(14)   |                                      |
| 30      | 1438 1382 46.56 3.83                | δ126O7C12(11)-γ114H33C15H34(20)      |                                      |
| 31      | 1377 1430 1374 43.12 2.51           | δ113H30C17C16(22)-γ113C15H17H36(11)+ |                                      |
| 32      | 1428 1372 52.23 7.79                | δ113H36C10H17(41)                    |                                      |
| 33      | 1419 1363 45.79 4.09                | δ113H38O17C16(20)                    |                                      |
| 34      | 1416 1360 35.84 4.04                | δ112C3O9(45)                         |                                      |
| 35      | 1411 1356 33.92 4.11                | δ112H2C3C6(24)                       |                                      |
| 36      | 1399 1344 39.13 4.85                | δ112H2C3C6(24)                       |                                      |
| 37      | 1329 1334 27.87 7.85                | δ112H2C3O9(37)-γ115C16H13H35(30)     |                                      |
| 38      | 1368 1314 40.48 3.71                | δ112H2C7C12(29)-γ115C16H13H35(30)    |                                      |
| 39      | 1358 1305 51.23 3.73                | δ112H2C7C12(29)-γ115C16H13H35(30)    |                                      |
| 40      | 1339 1287 29.93 7.98                | δ112C4C5(37)                         |                                      |
| 41      | 1338 1286 48.2 6.00                 | δ112H2C3C6(11)+γ115C16H13H35(30)     |                                      |
| 42      | 1326 1274 35.09 6.99                | γ113H19OB8C2(60)                     |                                      |
| 43      | 1263 1311 37.6 6.66                 | δ112H2C3C6(13)                       |                                      |
| 44      | 1307 1256 17.37 9.09                | δ112H29C11H30(39)                    |                                      |
| 45      | 1301 1250 20.21 11.09               | γ113C5O10H21(14)                     |                                      |
| 46      | 1233 1266 1216 32.67 9.10           | δ112H26C11H33(53)+δ112H23C5H24(43) in ring |                                      |
| 47      | 1244 1195 51.12 5.88                | δ113C2C30(20)-γ114C50H24(11)         |                                      |
| 48      | 1185 1236 1188 47.36 7.95           | δ112C6C15(13)+γ113C40H24(16)         |                                      |
| 49      | 1227 1179 15.77 4.51                | δ113H10C14(15)                       |                                      |
| 50      | 1216 1168 33.03 7.59                | δ113C14H18(39)                       |                                      |
| 51      | 1203 1156 48.55 8.98                | δ113C11C12(59)                       |                                      |
| 52      | 1134 1136 1181 1135 10.62 9.19      | VN13C11(11)                          |                                      |
| 53      | 1169 1123 25.65 7.53                | δ913H8C11H30(39)                     |                                      |
| 54      | 1145 1110 37.97 4.75                | δ113C10C4(11)                         |                                      |
A table with chemical shifts and intensities is presented, followed by explanations of the terms and their abbreviations. The terms include:

- \( \nu \): stretching
- \( \delta \): in-plane bending
- \( \gamma \): out-of-plane bending
- \( \tau \): torsion
- \( w \): weak
- \( s \): strong
- \( \nuN13C5(23) \)
- \( \nuC2C3(16)+ \)
- \( \deltaH31O12C11(11) \)

The abbreviations for intensity include:

- ai: IR Intensity (Kmmol\(^{-1}\))
- aiR: Raman intensity (Arb units) (intensity normalized to 100%)

The table includes chemical shifts for various molecules and their associated intensities, with notes on very weak (vw), medium (m), very strong (vs), and strong (s) intensity levels.
4.4. NBO analysis

In the NBO analysis [29], all possible interactions between ‘filled’ (donor) Lewis-type NBOs and ‘empty’ (acceptor) non-Lewis NBOs were investigated. The energies of these interactions were calculated second-order perturbation theory. These interactions (or energetic stabilizations) are named as ‘delocalization’ corrections to the zeroth-order natural Lewis structure.

For each donor NBO (i) and acceptor NBO (j), the stabilization energy E associated with i→j delocalization, is explicitly estimated by the following equation:

\[ E_2 = \Delta E_{ij} = q_i \sum \frac{F(i,j)^2}{\varepsilon_i - \varepsilon_j} \]

where \( q_i \) is the donor orbital occupancy, are \( \varepsilon_i \) and \( \varepsilon_j \) diagonal elements and \( F(i,j) \) is the off diagonal NBO Fock matrix element.

The interactions \( \sigma \) (C2-H19) → \( \sigma^* \) (C1-C6) and \( \sigma^* \) (C3-C4) having the stabilization energy is 3.08, 3.27 KJ mol\(^{-1}\) and \( \sigma \) (C3-H20) → \( \sigma^* \) (C1-C2) having the stabilization energy is 3.24 KJ mol\(^{-1}\) are responsible for conjugation of respective \( \sigma \)-bonds in Cyclohexane ring (Table 3). The intramolecular interaction is formed by the orbital overlap between LP(1)N13→\( \pi^* \) (O10-H28) bond orbital, which results intramolecular charge transfer causing stabilization energy 4.86 KJ mol\(^{-1}\) of the system. The energy contribution of LP(2)O17→\( \pi^* \) (C15-C16), LP(2)O18→\( \pi^* \) (C15-H35), LP(2)O10→\( \pi^* \) (C4-H21) are 9.07, 6.38, 7.65 KJ mol\(^{-1}\), respectively, and hence there is a possibility for delocalization of lone pair (LP) of electrons between O17 and C15-C16 and O10 and C4-H21.

Table 3. Second order Perturbation theory analysis of Fock Matrix in NBO basis for Voglibose.

| Donor (i)  | E\(_D\) (j)(e) | Acceptor(j)  | E\(_D\) (j)(e) | \(E^{(2)}\) KJ mol\(^{-1}\) | \(E(j)-E(i)\) KJ mol\(^{-1}\) | \(F(i,j)\) a.u |
|-----------|---------------|--------------|---------------|----------------|----------------|-------------|
| \(\sigma\) (C2-H19) | 1.973 | \(\sigma^*\) (C1-C6) | 0.029 | 3.08 | 0.87 | 0.046 |
| \(\sigma\) (C3-H20) | 1.978 | \(\sigma^*\) (C1-C2) | 0.070 | 3.24 | 0.86 | 0.048 |
| LP(2)O7  | 1.947 | \(\pi^*\)(C1-C2) | 0.070 | 8.65 | 0.63 | 0.066 |
| LP(1)O7  | 1.976 | \(\pi^*\)(1)(C1) | 0.008 | 4.29 | 1.52 | 0.072 |
| LP(2)O7  | 1.947 | \(\pi^*\)(C1-C11) | 0.043 | 4.22 | 0.64 | 0.046 |
| LP(1)O8  | 1.977 | \(\pi^*\)(1)(C2) | 0.007 | 3.36 | 1.38 | 0.061 |
| LP(2)O8  | 1.946 | \(\pi^*\)(C1-C2) | 0.070 | 9.09 | 0.62 | 0.067 |
| LP(2)O8  | 1.946 | \(\pi^*\)(C2-C3) | 0.015 | 3.86 | 0.63 | 0.044 |
| LP(2)O9  | 1.957 | \(\pi^*\)(C3-C4) | 0.042 | 7.40 | 0.67 | 0.063 |
| LP(2)O9  | 1.957 | \(\pi^*\)(C3-H20) | 0.026 | 3.72 | 0.76 | 0.048 |
| LP(1)O10 | 1.974 | \(\pi^*\)(1)(C4) | 0.007 | 3.13 | 1.49 | 0.061 |
| LP(1)O10 | 1.974 | \(\pi^*\)(C4-C5) | 0.038 | 3.97 | 0.92 | 0.054 |
| LP(2)O10 | 1.941 | \(\pi^*\)(C4-H21) | 0.034 | 7.65 | 0.77 | 0.069 |
| LP(2)O10 | 1.941 | \(\pi^*\)(O8-H26) | 0.028 | 7.14 | 0.84 | 0.069 |
| LP(2)O12 | 1.965 | \(\pi^*\)(C11-H29) | 0.026 | 5.22 | 0.75 | 0.056 |
| LP(2)O12 | 1.965 | \(\pi^*\)(C11-30) | 0.027 | 5.50 | 0.77 | 0.058 |
| LP(1)N13 | 1.908 | \(\pi^*\)(C5-H22) | 0.032 | 6.31 | 0.76 | 0.063 |
| LP(1)N13 | 1.908 | \(\pi^*\)(O10-H28) | 0.027 | 4.86 | 0.76 | 0.055 |
| LP(1)N13 | 1.908 | \(\pi^*\)(C14-C15) | 0.040 | 3.46 | 0.69 | 0.044 |
| LP(1)N13 | 1.908 | \(\pi^*\)(C15-H35) | 0.028 | 4.21 | 0.76 | 0.051 |
| LP(2)O17 | 1.948 | \(\pi^*\)(C15-C16) | 0.039 | 9.07 | 0.65 | 0.069 |
| LP(2)O17 | 1.948 | \(\pi^*\)(C16-H36) | 0.028 | 4.43 | 0.72 | 0.051 |
| LP(2)O18 | 1.954 | \(\pi^*\)(C14-H34) | 0.023 | 4.83 | 0.67 | 0.051 |
| LP(2)O18 | 1.954 | \(\pi^*\)(C15-H35) | 0.028 | 6.38 | 0.77 | 0.063 |
4.5. Electronic properties

4.5.1. UV-Visible spectral analysis

The experimental UV–Visible electronic absorption maxima ($\lambda_{\text{max}}$) of Voglibose recorded in ethanol together with the theoretical results involving the vertical excitation energies, oscillator strength ($f$) and wavelength at maximum absorption calculated at B3LYP/ 6-31G(d,p) basis set in gas phase and in ethanol solvent are given in Table 4. The experimental UV-Vis spectrum of the title compound is shown in Fig. 5. Due to the Frank–Condon principle, the maximum absorption peak ($\lambda_{\text{max}}$) in an UV–visible spectrum corresponds to vertical excitation. The B3LYP/6-31G(d,p) calculations (in ethanol) predict two intense electronic transitions at 7.2622 eV (270.73 nm) with an oscillator strength $f = 0.0014$ and other one 7.5971 eV (234.44 nm) with an oscillator strength $f = 0.0103$, which are in good agreement with the measured experimental data (261 and 227 nm).

![UV-Visible spectrum (Ethanol) of Voglibose](image)

**Fig. 5. UV-Visible spectrum (Ethanol) of Voglibose**

| Experimental | TD-DFT/B3LYP/6-31G(d,p) |
|--------------|-------------------------|
| Ethanol      | Ethanol                 | Gas         |
| $\lambda$ (nm) | Abs. | $\lambda$ (nm) | E(eV) | $f$(a.u) | $\lambda$ (nm) | E(eV) | $f$(a.u) |
| 261          | 2.9868 | 270.73 | 7.2622 | 0.0163 | 268.84 | 6.9325 | 0.0014 |
| 227          | 3.0363 | 223.20 | 7.5971 | 0.0006 | 234.44 | 7.1077 | 0.0103 |
| -            | - | 160.52 | 7.7240 | 0.0404 | 170.09 | 7.2894 | 0.0026 |

4.5.2. HOMO-LUMO Analysis

The highest occupied molecular orbital (HOMO) is the orbital that primarily acts as an electron donor and the lowest unoccupied molecular orbital (LUMO) is the orbital that largely acts as the electron acceptor. The frontier orbital energy gap helps characterize the chemical reactivity
and kinetic stability of the molecule. According to Fig. 6, the HOMO is spread heavily over the Cyclohexane ring region and LUMO is spread over the entire molecule. For title molecule the calculated HOMO energy is -6.3460 eV and LUMO energy is 1.1263 eV and the HOMO-LUMO energy gap is 5.2179 eV.

![Fig. 6. The atomic orbital compositions of the frontier molecular orbital for Voglibose](image)

**Fig.6.** The atomic orbital compositions of the frontier molecular orbital for Voglibose

### 4.5.3. Molecular Electrostatic Potential (MEP) Analysis

In order to grasp the molecular interactions, the molecular electrostatic potentials (MEPs) are used. Recently, the MEPs have been used for interpreting and predicting relative reactivities sites for electrophilic and nucleophilic attack, investigation of biological recognition, hydrogen bonding interactions, studies of molecular cluster, crystal behavior, correlation and prediction of a wide range of macroscopic properties [30]. The MEP diagram (front and back view) of the voglibose molecule is shown in **Fig. 7**. The color scheme for the MEP surface will be partially negative charge or maybe red-electron rich; partially positive charge or maybe blue-electron deficient; yellow slightly electron packed region; light blue-slightly electron deficient region, Additionally, green color parts represent also regions of zero potential respectively. For the title molecule yellow color represents the electron packed region which is mostly cover the oxygen atoms and also the positive region is actually over the NH group. Green color represents the zero potential regions mostly over the all protons.

![Fig. 7. a) Front view b) back view of Molecular electrostatic Potential map (MEP) for Voglibose](image)

**Fig.7.** a) Front view b) back view of Molecular electrostatic Potential map (MEP) for Voglibose
4.6. NMR spectral Analysis

NMR spectroscopy has proved to be an exceptional tool to elucidate structure and molecular conformation. The "'gauge-independent atomic orbital'" (GIAO) method [31] has proven to be quite accepted and accurate, in particular when applied in the context of highly correlated ab initio methods. The $^1$H and $^{13}$C theoretical and experimental [2] (water solvent) chemical shifts, isotropic shielding constants and the assignments of voglibose are also given in the Table 5. Taking into account that the range of $^{13}$C NMR chemical shift for analogous organic molecules usually is >100 ppm [32]. The chemical shift of C1,C2,C3,C4 carbon peaks in the rings attached to oxygen atom are observed from 17.10 ppm to 76.28 ppm are calculated from 69.54 ppm to 70.59 ppm at B3LYP/6-31G(d,p) level of theory. For title molecule $^{13}$C chemical values of these carbon atoms are down shifted from the expected values. The reason for the down shift is due to the substitution of oxygen and carbon atoms for C1 atom and oxygen and hydrogen atoms for C2, C3, and C4 atom respectively. Due to the double proton substitution C6 atom get down shifted, the observed / calculated value is 29.34 ppm/29.96 ppm. Similarly, due to electro negative oxygen atom substitution causes C11, C14 and C16 atoms gets down shielding shown in Table 5.

Table 5. Table predicted $^1$H and $^{13}$C NMR isotropic chemical shifts (with respect to TMS, all values in ppm) for Vogliboise

| Atom position | $^{13}$C NMR | $^1$H NMR | Atom position | $^{13}$C NMR | $^1$H NMR |
|---------------|--------------|----------|---------------|--------------|----------|
| C1            | 74.10        | 69.54    | H19           | 3.67         | 3.69     |
| C2            | 65.19        | 66.38    | H20           | 4.01         |          |
| C3            | 72.07        | 67.65    | H21           | 3.48         | 3.38     |
| C4            | 76.28        | 70.59    | H22           | 2.82         |          |
| C5            | -            | 50.59    | H23           | 1.36         | 1.01     |
| C6            | 29.34        | 28.96    | H24           | 1.89         | 1.48     |
| C11           | 62.25        | 63.67    | H25           | 2.29         |          |
| C14           | 58.51        | 58.55    | H26           | 2.70         | 2.68     |
| C15           | 54.46        | 52.83    | H27           | 0.69         |          |
| C16           | 56.51        | 56.89    | H28           | 2.86         |          |
|               |              |          | H29           | 3.23         | 3.21     |
|               |              |          | H30           | 4.19         |          |
|               |              |          | H31           | 0.44         |          |
|               |              |          | H32           | -0.29        |          |
|               |              |          | H33           | 3.56         | 3.57     |
|               |              |          | H34           | 3.25         | 3.31     |
|               |              |          | H35           | 2.61         |          |
|               |              |          | H36           | 3.17         |          |
|               |              |          | H37           | 3.35         | 3.39     |
|               |              |          | H38           | 2.61         |          |
|               |              |          | H39           | 3.17         |          |
5. Conclusion

The optimized molecular structure, vibrational frequencies and corresponding vibrational assignments of Voglibose have been calculated using B3LYP level with 6-31G(d,p) basis set. Considering that experimental and the theoretical studies are performed in different phase, it can be said that there is a good agreement between the experimental and theoretical data. The reduction of N-H stretching wavenumber is attributed to the N-H...O hydrogen bonding interactions. NBO analysis clearly explains the formation of weak H bonded interaction between the LP(1)N13 and π*(O10-H28) antibonding orbitals and charge transfer causing stabilization of energy 4.86 KJmol⁻¹ the system. The energies of important MOs and the max of the compound were also evaluated from TD-DFT method. The ¹³C and ¹H NMR chemical shifts calculated by B3LYP/6-31G(d,p) are closer to the experimental values. Moreover, frontier molecular orbitals and molecular electrostatic potential were visualized. Electronic transition and energy band gap of the title molecule were investigated and interpreted.

References
[1] N.Mallikarjuna Rao, Konda Ravi Kuma, J. Bagyalakshmi, T.K. Ravi, Ramakotaiah Mogili., “RP-HPLC method development and validation for estimation of Voglibose in bulk and tablet dosage forms” Int. J. Res. Pharm. Sci. Vol-1, Issue-2, (2010), 190-194.
[2] Zhang, C.R. Sun, O. Ishurd, Y.J. Pan, L.S. Ding, “Determination of the structures of four new isomeric cyclitols” Carbo-hydr. Res. 339 (2004) 2027-2030.
[3] X. Chen, Y. Zheng, Y.Shen, Curr. “Voglibose (Basen®, AO-128), one of the most important α-glucosidase inhibitors”, Med. Chem. 13 (2006) 109-116.
[4] Y. Iwamoto, A. Kashiwagi, N. Yamada, S. Terao, N. Mimori, M. Suzuki & H. Tachibana, “Efficacy and safety of vildagliptin and voglibose in Japanese patients with type 2 diabetes: a 12-week, randomized, double-blind, active-controlled study”, Diabetes, Obesity and Metabolism 12, (2010), 700–708.
[5] Karunanidhi Lakshmi and Tirumala Rajesh, “Determination of voglibose in pharmaceutical formulations by high performance liquid chromatography using refractive index detection” European Journal of Chemistry 1 (4) (2010) 262-265.
[6] P. Revathi, T. Jeyaseelan Senthinath, K. Prakash Shyam, A Comparative Study of Acarbose and Voglibose on Postprandial Hyperglycemia and serum lipids in Type 2 Diabetic patients” Int J Med Res. 1(2), (2011) 121-129.
[7] Gaussian 03 program, (Gaussian Inc, Wallingford CT), 2004.
[8] National Institute of Standards and Technology. Vibrational Frequency Scaling Factors on the Web. <http://srdata.nist.gov/ccbbdb/vsf.asp> (accessed 24.09.07).
[9] S.M. Islam, S.D. Huelin, M. Dawe, R.A. Poirier, “Comparison of the Standard 6-31G and Binning-Curtiss Basis Sets for Third Row Elements”, J. Chem. Theory Comput. 4 (2008) 86–100.
[10] M.H. Jamroz "Vibrational Energy Distribution Analysis”, VEDA 4 Computer Program”, Poland, (2004).
[11] E.D. Glendening, A.E. Reed, J.E. Carpenter, F. Weinhold, “NBO Version 3.1”, TCI, University of Wisconsin, Madison, (1998).
[12] R.Ditchfield, “Molecular orbital theory of magnetic shielding and magnetic susceptibility”, J. Chem. Phys. 56 (1972) 5688–5691.
[13] G. Kereztury, in: J.M. Chalmers, P.R. Griffith (Eds.), “Raman Spectroscopy: Theory, in Hand book of Vibrational Spectroscopy”, vol. 1, John Wiley & Sons Ltd, New York, (2002).

[14] L.E. Sutton, “Tables of Interatomic Distances, Chemical Society”, London, 1958.

[15] K. Govindarasu, E. Kavitha, “Vibrational spectra, molecular structure, NBO, NMR, UV, first order hyperpolarizability, analysis of (S)-(−)-N-(5-Nitro-2-pyridyl) alaninol by Density functional theory” Spectrochim Acta A 127 (2014) 498–510.

[16] Hong Zhang, Wei-Fen Li, Kui-Wu Wang and Yuan Jiang Pan, “1 Cyclohexylethoxymethyl-5-[2-hydroxy-1-(hydroxymethyl) ethylamino] cyclohexane-1, 2, 3, 4-tetraol” Acta Cryst. (2004). E60, o299-o300.

[17] J.F. Chiang, S.H. Bauer, “Molecular structure of cyclohexene”, J. Am. Chem. Soc. 91 (8) (1969) 1898–1901.

[18] N.H. Andersen , C. J. Nielsen , P.Klaeboe , G.A. Guirgis , J. S. Overby ,S.M. Askarian, “Infrared and Raman spectra, DFT-calculations and spectral assignments of 1,3,5-trisilacyclohexane” J. Mol. Struct. 1076 (2014) 419–425.

[19] G.A. Guirgis, H.W. Dukes, J.K. Wyatt, C.J. Nielsen, A. Horn ,V. Aleksa P.Klaeboe “Vibrational spectra, quantum chemical calculations and spectral assignments of 1,1-difluoro-1-silacyclohexane” Spectro chim. Acta A 136 (2015) 51–57.

[20] G.A. Guirgis, J.K. Wyatt, C.J. Nielsen, A. Horn ,V. Aleksa P.Klaeboe,’ “Infrared and Raman spectra, DFT-calculations and spectral assignments of silacyclohexane” J. Mol. Struct. 1023 (2012) 189–196.

[21] G. Varsanyi, “Assignments for Vibrational Spectra of Seven Hundred Benzene Derivatives”, vol. 1–2, Academic Kiaclo, Budapet, (1973).

[22] M. Govindarajan, S. Periyandy, K. Carthigayen, “FT-IR and FT-Raman spectra, thermo dynamical behavior, HOMO and LUMO, UV, NLO properties, computed frequency estimation analysis and electronic structure calculations on α-bromotoluene” Spectrochim. Acta A97 (2012) 411–422.

[23] V. Krishnakumar, M. Kumar, N. Prabavathi, R. Mathammal, “Molecular structure, spectroscopic studies (FTIR, FT-Raman and NMR) and HOMO–LUMO analysis of 6-chloro-o-cresol and 4-chloro-3-methyl phenol by density functional theory” Spectrochim. Acta A97 (2012) 144–154.

[24] D. Sajan, J. Binoy, B. Pradeep, K.V. Krishnan, V.B. Kartha, I.H. Joe, V.S. Jayakumar, “NIR-FT Raman and infrared spectra and ab initio computations of glycinium oxalate” Spectrochim. Acta A60 (2004) 173.

[25] N.B. Colthup, L.H. Daly, S.E. Wiberly, “Introduction to Infrared and Raman Spectroscopy”, 3rd ed., Academic Press, Boston (1990).

[26] R.M. Silverstein, G.C. Bassler, T.C. Morril, “Spectrometric Identification of Organic Compounds”, ed. 5, John Wiley and Sons, Inc., Singapore (1991).

[27] K. Govindarasu, E. Kavitha, “Structural, vibrational spectroscopic studies and quantum chemical calculations of n-(2,4-dinitrophenyl)-L-alanine methyl ester by density functional theory” J. Mol. Struct. 1088 (2015) 70–84.

[28] M. Jag, “Organic Spectroscopy-Principles and Application”, second ed., Narosa Publishing House, New Delhi, (2001).

[29] A.E. Reed, L.A. Curtiss, F. Weinhold, "Intermolecular Interactions from a Natural Bond Orbital, Donor-Acceptor Viewpoint," Chem. Rev. 88 (1988) 899–926.
[30] J.S. Murray, K.Sen, “Molecular Electrostatic Potential Concepts and Applications, Elsevier Science” B.V, Amsterdaam, The Netherlands (1996).

[31] P.V.R. Schleyer, N.L. Allinger, T. Clark, J. Gasteiger, P.A. Kolmann, H.F. Schaefer, P.R. Schreiner, “The Encyclopedia of Computational Chemistry”, John Wiley and Sons, Chichester, (1998).

[32] H.O. Kalinowski, S. Berger, S. Braun, “Carbon-13 NMR Spectroscopy”, John Wiley & Sons, Chichester, (1988).

[33] F.A. Cotton, C.W. Wilkinson, “Advanced Inorganic Chemistry”, 3rd ed., Interscience publisher, New York, (1972).