

DFT-Based Analysis of 2, 3-dimethyl-2-(3-oxobutyl)-cyclohexanone: Structural, Electronic, Vibrational, and Molecular docking studies for potential anti-cancer applications

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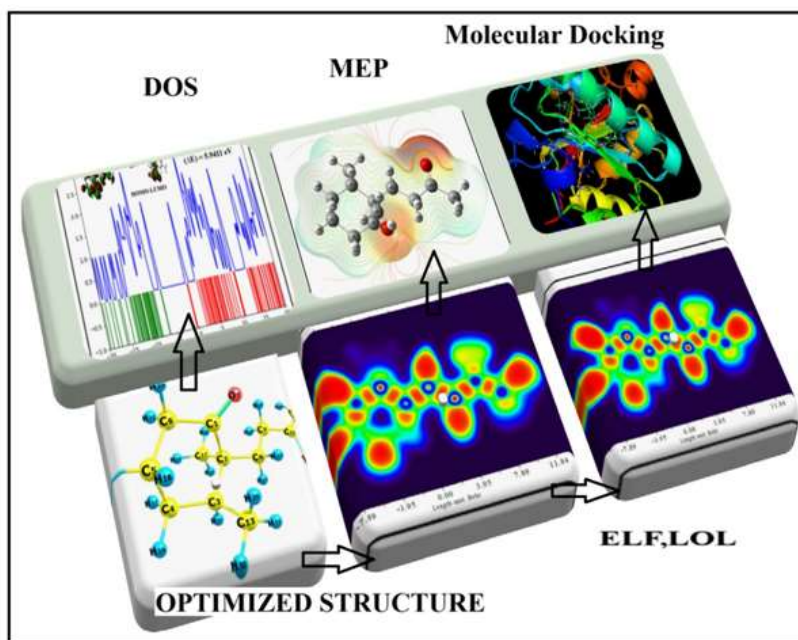
The antimicrobial, antibacterial, antioxidant, anti-inflammatory, and anticancer activities of C2D3O (2, 3-dimethyl-2-(3-oxobutyl)-cyclohexanone) are demonstrated. Through the use of FT-IR, UV-Vis, and DFT methodologies, this study investigates its medical applications. The B3LYP/6-311++G(d, p) approach was used to examine the molecular electrostatic potential (MEP), HOMO-LUMO, and geometrical characteristics. High stabilization interactions, including hydrogen bonding and charge delocalization, were computed in 3TMH molecules using the NBO 3.1 tool. Both single and double-bond stability was demonstrated by the optimized structure, which was in good agreement with XRD results. A strong correlation was found between theoretical and experimental vibrational frequencies, with electronic transitions ($n \rightarrow \pi$, $n \rightarrow \sigma$ transitions**) identified via TD-DFT. The Veda 04 software confirmed an excellent match between observed and predicted FT-IR spectra. Chemical interactions were examined through ELF-LOL projection mapping, while RDG analysis (using Multiwfn 3.4.1) highlighted strong attraction, repulsion, and weak interactions. Finally, molecular docking of C2D3O with 8D59 demonstrated a binding energy of -4.94 kcal/mol, suggesting potential biomedical applications.

Keywords: 8D59, Drug-likeness, FT-IR, Topological properties, UV-visible

Colon cancer is the second leading cause of cancer-related death worldwide. Colorectal cancer is one type of cancer that affects the rectum or colon (large intestine). It is one of the most common types of cancer worldwide. It may cause fatalities or severe injuries. Many people will show no symptoms in the early stages of the illness. Over 1.9 million new cases of colorectal cancer and over 930, 000 deaths from the disease were predicted to occur worldwide in 2020. Mortality and incidence rates showed notable regional variations¹. According to the literature review, the cyclohexanone 2, 3-dimethyl-2-(3-oxobutyl)-correlated has anti-cancer properties². The extra descriptors imply certain groups connected to the cyclohexanone ring, which is a six-membered cyclic ketone. One ketone functional group is present in the six-membered ring of cyclohexanone, and the second and third carbon atoms

of the ring are joined by 2, 3-dimethyl CH₃ a 3-oxobutyl group joined to the cyclohexanone ring's second carbon. A ketone (oxo) group is present on the third carbon of the four-carbon chain that makes up the 3-oxobutyl group. The carbons in the cyclohexanone ring are represented by the letters C₁ to C₆. Methyl groups (CH₃) are joined to C₂ and C₃, while the 2-CO-CH₃ chain (3-oxobutyl) is joined to C₂. The way the groups are joined to the cyclohexanone ring is shown graphically by this structure. Its molecular weight is 196.29 g/mol, and its molecular formula is C₁₂H₂₀O₂. Because of their capacity to interact with biological molecules and processes implicated in the growth of cancer cells, cyclohexanone derivatives have been investigated for their possible anticancer effect. Ways such as inducing apoptosis, inhibiting cell growth, having anti-angiogenic qualities, and preventing metastases. Because cyclohexanone and its derivatives can disrupt the development and survival of cancer cells, they have potential use in anticancer

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Graphical abstract

treatment. Although there may not be much precise data on the 2-(3-oxobutyl) group's anticancer action on its own, the fact that it is present in several bioactive compounds points to promise. New anticancer medications can be developed with the help of ongoing research into related substances and their processes³. To the best of our knowledge, the density functional computation (DFT) has not yet been performed, according to the study work mentioned above. By using the Soxhlet procedure, which falls under the Gas Chromatography-Mass Spectrometry (GC-MS) technology, the C2D3O compound was extracted from *Hybanthus enneaspermus* crude. The C2D3O compound was then reported for its structure and conformation. Infrared data on C2D3O molecules was connected with the optimized structural attributes, simulated FT-IR, and UV-vis spectra produced by the B3LYP/6-311++G (d,p) procedure. DFT was used to assess the reported biological activity from the NBO study, MEP surface, Fukui function, PES scan, and energy gap. Physical-chemical properties that demonstrated favorable aspects of drug-likeness were also estimated using the topological parameter, RDG analysis, and Lipinski's criteria. Good ligand-protein interaction on C2D3O molecules against anti-cancer activity was found by the docking studies.

Experimental techniques detail

The Shimadzu QP2010 Plus gas chromatography-mass spectrometry (GC-MS) method was used to

evaluate the crude material. With an injection temperature of 250°C, a non-polar MS capillary column covered with polydimethylsiloxane (30 m in length, 0.25 mm inner diameter, and 0.25 μm film thickness) was employed. A retention duration of 25 minutes was shown by the GC-MS spectra⁴. A lot of bio-compounds were detected in the GC-MS data; however, because of its possible anti-cancer effects, one measurable phytochemical compound, C2D3O, was chosen for more study. Sigma-Aldrich provided a 99% pure C2D3O sample for examination. Fourier-transform infrared (FT-IR) spectroscopy was used to investigate the C2D3O sample in the 4000–400 cm⁻¹ region. At room temperature, measurements were made using a Perkin Elmer FT-IR spectrophotometer that used the KBr pellet technique with a spectral resolution of 4.0 cm⁻¹. Furthermore, a Shimadzu UV-3600+ equipment was used for ultraviolet-visible (UV-Vis) spectroscopy, recording wavelengths between 300 and 100 nm. For the analysis, a quartz cell measuring 1 cm in diameter and 0.5 nm in slit width was used⁵. At SRM College of Science in Kattankulathur, Chengalpattu district, Tamil Nadu, India, the GC-MS, FT-IR, and UV-Vis spectral analyses were carried out.

Computational details

In this study, the molecular structure of C2D3O was analyzed using the B3LYP/6-311++G(d, p) method within the DFT framework⁶. For geometry

visualization, HOMO-LUMO analysis, PES scan, and MEP charting, GaussView 5.0 and ChemCraft 1.8 were utilized⁷. MEP, Fukui function, and NPA charges were among the structural and electronic characteristics that were investigated. Vibrational analysis was conducted using Veda 04, with PED% interpretation and frequency scaling. The HOMO-LUMO gap and reactivity indices were ascertained by molecular orbital analysis, whereas TD-DFT was utilized for UV-Vis spectra in the gas and solvent phases. Intermolecular and intramolecular interactions were examined using NBO 3.1 software⁸. MULTIWFN 3.7 was used to calculate topological parameters (RDG, ELF, LOL), and Auto Dock 1.5.6 was used to conduct molecular docking studies for ligand-protein binding energy^{9,10}.

Results and Discussion

GC-MS analyse

Mass spectrometry and chromatography are excellent tools for quantitative and qualitative analysis and for efficiently separating multicomponent mixtures at low concentrations. Purified bio-compounds (fatty acids, lipids) from medicinal plants, forensic investigations, and pollution studies are just a few of the many fields used for the GC-MS. A bio-component identified by mass spectrometry, C2D3O, was reported by the GC-MS analysis of the carbinol extract of the *H. Enneaspermus* plant in the current investigation. The results were compared and matched with data from the National Institute of Standards and Technology (NIST) data library and the PubChem databases¹¹. Because of the chemical C2D3O's anticancer properties. Based on FT-IR, UV-Vis, and DFT spectral

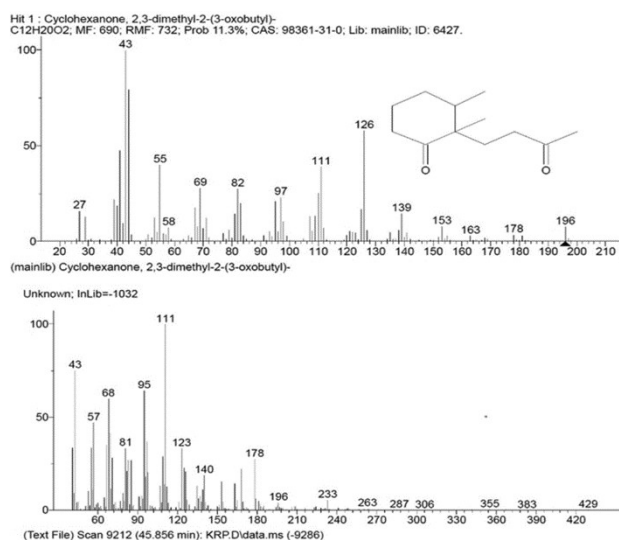


Fig. 1 — GC-MS analysis of C2D3O

analysis. According to Figure 1, the CMIO chemical structure matched the molecular formula C12H20O2, molecular weight 196.14 g/mol, and retention time 21.48 min.

Molecular geometry

In both biological and inorganic crystal formations, the ground-state geometrical parameters, such as bond lengths and angles are essential.

To investigate the optimal molecular shape and electrical characteristics of C2D3O, the DFT method more especially, the B3LYP/6-311++G(d, p) approach was used to identify its optimized geometry¹². The ChemDraw program¹³ was used to illustrate the molecular structure of C2D3O, and Figure 2 shows a scaled ball-and-stick model that represents its ideal shape. The molecule has a trigonal planar long-chain structure made up of one O-H bond, one C₃=C₂ link, five methyl (CH₃) groups, one C-O bond, 19 C-C bonds, 39 C-H bonds, and one hydroxymethyl (CH₂OH) group¹⁴. These bond parameters offer important information on how strong and stable the molecular interactions are inside the chemical complex¹⁵. Table 1 displays the findings of comparing the computed parameters of C2D3O with the values reported in the literature using XRD data.

A total of 60 bond lengths were discovered. Between C₂₁ and H₅₉, the shortest bond length, 1.0914 (Å), is seen. C₇-C₈ show the greatest bond length of 1.5514 (Å). This title compound contains 115 bond angles. C₁-C₂-C₃ is linked to the largest bond angle of 128.322 (Å), whereas H₃₉-C₁₂-H₄₀ has the lowest bond angle of 105.45 (Å). For the C-C and C-H bonds, the corresponding bond lengths range from 1.3407 Å to 1.551 Å, 1.091 Å to 1.103 Å, and 1.432 Å. The following bond lengths appear to match with XRD experimental values: C₁-O₁₇ (1.432/1.425), C₃-C₄

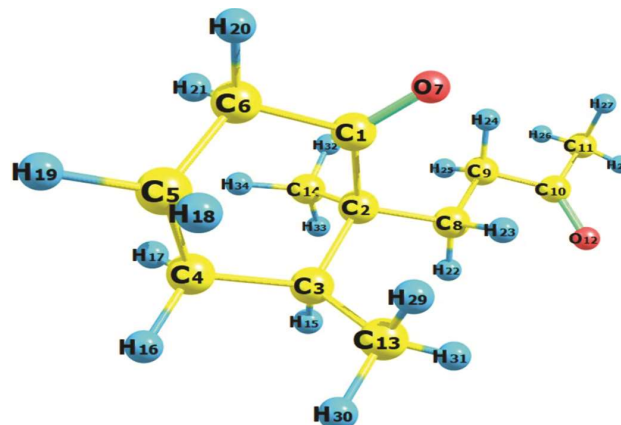


Fig. 2 — Optimized structure of C2D3O

(1.518/1.516), C₄-C₅ (1.531/1.523), C₅-C₆ (1.534/1.526), C₁₁-C₁₉ (1.538/1.527), C₁₂-H₃₉ (1.099/0.990), C₁₂-H₄₀ (1.098/0.990), C₉-H₃₄ (1.099/0.990), and C₉-H₃₅ (1.094/0.990)¹⁶⁻¹⁸. The chemically determined bond angle values that match with the calculated XRD experimental bond angle are C₂-C₁-O₁₇ (107.684 / 106.05), C₂-C₁-H₂₃ (109.426 / 109.1), O₁₇-C₁-H₂₃ (109.924 / 109.3), C₁₀-C₁₁-C₁₉ (109.3049 / 109.17), and H₅₀-C₁₈-H₅₁ (107.842 / 107.9)¹⁹. The number of shared electron pairs in C₂D₃O enhanced the molecular system's bond strength as well as the stability and strength of the attraction between C₃=C₂ (C₃=C₂>C₄-C₅). The acetyl group is denoted by CH₃CO.

Mulliken atomic charge distribution

The distribution of atomic charges in molecular wave functions can be explained via the development of Mulliken charges investigations. The net atomic population is intimately related to the molecule's vibrational characteristics and the electronic structural changes brought on by atomic displacement. Its popular charge-splitting scheme effectively illustrates this link. The natural charge affects several characteristics of the molecular system, such as electronic structure, polarizability, and dipole moment. Title molecules C₂D₃O were obtained in the current investigation employing the B3LYP-D/6-311++G (d, p) level of theory, as shown in (Table 2).

Table 1 — Bond length, Bond angle

Bond length (Å)	B3LYP /6-311++G (d,p)	Experimental Data	Bond length (Å)	B3LYP /6-311++G (d,p)	Experimental Data
C1-C2	1.542	1.538	C8-C9	1.531	1.532
C1-C6	1.524	1.529	C8-H22	1.096	1.070
C1-O7	1.219	1.214	C8-H23	1.091	-
C2-C3	1.577	1.566	C9-C10	1.523	1.519
C2-C8	1.547	1.532	C9-H24	1.095	-
C2-C14	1.551	1.562	C9-H25	1.099	-
C3-C4	1.546	1.550	C10-C11	1.520	1.528
C3-C13	1.541	1.532	C10-O12	1.217	1.217
C3-H15	1.099	1.070	C11-H26	1.095	-
C4-C5	1.534	1.527	C11-H27	1.096	1.090
C4-H16	1.096	1.090	C11-H28	1.090	-
C4-H17	1.096	1.090	C13-H29	1.095	-
C5-C6	1.541	1.537	C13-H30	1.095	-
C5-H18	1.096	1.060	C13-H31	1.091	1.090
C5-H19	1.095	1.060	C14-H32	1.093	1.090
C6-H20	1.093	-	C14-H33	1.095	1.090
C6-H21	1.098	1.070	C14-H34	1.091	1.090
C2-C1-O6	116.7	117.5	C2-C8-C9	116.6	117.6
C2-C1-O7	122.4	122.6	C2-C8-H22	108.4	109
C6-C1-O7	120.8	121.6	C2-C8-H23	109.2	109.1
C1-C2-C3	107.9	-	C9-C8-H22	108.5	109.2
C1-C2-C8	110.8	110.4	C9-C8-H23	107.2	-
C1-C2-C14	108.8	108.8	H22-C8-H23	106.1	107.8
C3-C2-C8	110.0	110.5	C8-C9-C10	112.7	-
C3-C2-C14	109.2	-	C8-C9-H24	110.5	109.4
C8-C2-C14	109.8	109.8	C8-C9-H25	112.1	109.2
C2-C3-C4	111.9	111.5	C10-C9-H24	108.5	108.8
C2-C3-C13	113.1	112.4	C10-C9-H25	106.5	-
C2-C3-H15	106.0	-	H24-C9-H25	105.9	107.9
C4-C3-C13	110.4	-	C9-C10-C11	116.2	116.4
C4-C3-H15	107.6	108.8	C9-C10-O12	122.2	121.7
C13-C4-H15	107.2	107.7	C11-C10-O12	121.4	120.8
C3-C4-C5	112.6	113.4	C10-C11-H26	111.2	-
C3-C4-H16	108.7	108.9	C10-C11-H27	109.6	109.3
C3-C4-H17	110.2	110.8	C10-C11-H28	109.8	109.6
C5-C4-H16	109.8	-	H26-C11-H27	106.8	107.9
C5-C4-H17	109.1	-	H26-C11-H28	110.0	109.5
H ₁₆ -C ₄ -H ₁₇	105.8	-	H27-C11-H28	109.2	109.5

(Contd.)

Table 1 — Bond length, Bond angle (*Contd.*)

Bond length (Å)	B3LYP /6-311++G (d,p)	Experimental Data	Bond length (Å)	B3LYP /6-311++G (d,p)	Experimental Data
C ₄ -C ₅ -C ₆	111.1	111	C ₃ -C ₁₃ -H ₂₉	112.3	-
C ₄ -C ₅ -H ₁₈	110.0	-	C ₃ -C ₁₃ -H ₃₀	109.9	109.4
C ₄ -C ₅ -H ₁₉	110.4	-	C ₃ -C ₁₃ -H ₃₁	111.9	-
C ₆ -C ₅ -H ₁₈	109.0	109.1	H ₂₉ -C ₁₃ -H ₃₀	107.5	109.5
C ₆ -C ₅ -H ₁₉	109.7	109.6	H ₂₉ -C ₁₃ -H ₃₁	107.3	109.5
H ₁₈ -C ₅ -H ₁₉	106.2	-	H ₃₀ -C ₁₃ -H ₃₁	107.4	109.5
C ₁ -C ₆ -C ₅	111.5	-	C ₂ -C ₁₄ -H ₃₂	111.6	110.3
C ₁ -C ₆ -H ₂₀	107.7	-	C ₂ -C ₁₄ -H ₃₃	109.5	109.5
C ₁ -C ₆ -H ₂₁	108.5	-	C ₂ -C ₁₄ -H ₃₄	112.9	-
C ₅ -C ₆ -H ₂₀	112.0	114.5	H ₃₃ -C ₁₄ -H ₃₃	107.7	107.3
C ₅ -C ₆ -H ₂₁	109.1	109.5	H ₃₂ -C ₁₄ -H ₃₄	107.2	107.9
H ₂₀ -C ₆ -H ₂₁	107.6	107.7	H ₃₃ -C ₁₄ -H ₃₄	107.5	107.8

A comprehensible qualitative image of chemists may be obtained from the natural Mulliken atomic charge distribution²⁰. While atoms C₂, C₃, C₄, C₅, C₆, C₇, C₈, C₉, C₁₁, C₁₂, C₁₃, and C₁₄ have nucleophilic charges and act as electron donors, atoms C₁ and C₁₀ have electrophilic charges and act as electron acceptors. Hydrogen has the largest positive charge among the hydrogen atoms (H₁₅-H₃₄)²¹. H₂₃, which has the largest positive charge (0.149 a.u.), is the main site for nucleophilic attack, whereas the O₇ and O₁₂ sites are most vulnerable to electrophilic attack. Strong intermolecular bonding interactions are indicated by the O₇ and O₁₂ sites having the most negative charge (-0.447 a.u.)²². Both the cyclohexanone and the butyl group are attached to the second carbon atom of the cyclohexanone, which is symbolized by a double bond in oxygen, including ketone groups. C₁ has a higher positive charge (0.423 a.u.) than the other carbon atoms, whereas C₁₁ and C₁₃ are associated with electro-negative charges (-0.379, -0.339)²³.

HOMO-LUMO

A molecule's HOMO and LUMO orbitals are essential for assessing its chemical stability, reactivity, softness, and hardness²⁴. The most interactive orbital pair in a molecule is the HOMO, which donates electrons, and the LUMO, which accepts them. ELUMO indicates the molecule's ability to take electrons, while EHOMO indicates its ability to donate electrons. The investigated molecule has HOMO and LUMO energy values of -0.4465 eV and -6.3876 eV, respectively. These energy values aid in the explanation of hyper-polarizability and intramolecular charge transfer. 5.9411 eV is the determined value of the HOMO-LUMO energy gap (ΔE), a crucial measure of chemical reactivity. Higher kinetic stability and decreased reactivity are indicated by a bigger ΔE . The B3LYP/6-

Table 2 — Mulliken atomic charge distribution

Atoms	Charges (a.u)	Atoms	Charges (a.u)
C ₁	0.423	H ₁₈	0.107
C ₂	-0.007	H ₁₉	0.100
C ₃	-0.053	H ₂₀	0.114
C ₄	-0.191	H ₂₁	0.116
C ₅	-0.187	H ₂₂	0.112
C ₆	-0.243	H ₂₃	0.149
O ₇	-0.447	H ₂₄	0.138
C ₈	-0.171	H ₂₅	0.130
C ₉	-0.322	H ₂₆	0.099
C ₁₀	0.418	H ₂₇	0.144
C ₁₁	-0.379	H ₂₈	0.141
O ₁₂	-0.432	H ₂₉	0.130
C ₁₃	-0.339	H ₃₀	0.097
C ₁₄	-0.332	H ₃₁	0.106
H ₁₅	0.083	H ₃₂	0.111
H ₁₆	0.094	H ₃₃	0.102
H ₁₇	0.087	H ₃₄	0.097

31+G(d) level of theory was used to investigate the frontier molecular orbitals (FMOs) of ADMA; (Fig. 3 & Table 3) show the relevant energy levels.

A theoretical method for forecasting the energy differential between the highest occupied and lowest empty molecular orbitals is the HOMO-LUMO computation^{25, 26}. Based on its HOMO-LUMO energy values, Table 3 demonstrates the compound's strong electro negativity and electrophilic character. In industries including organic electronics, photovoltaics, telecommunications, imaging, and optical data processing, these electrical characteristics are crucial. According to the theoretical interpretation of the Mayr equation using the FMO and Eyring equations, a molecule's electrophilicity is defined by its LUMO energy, whereas its nucleophilicity is determined by its HOMO energy²⁷. The investigated chemical shows improved stability because of its high ΔE value, which makes it a good option for optical applications like solar cells.

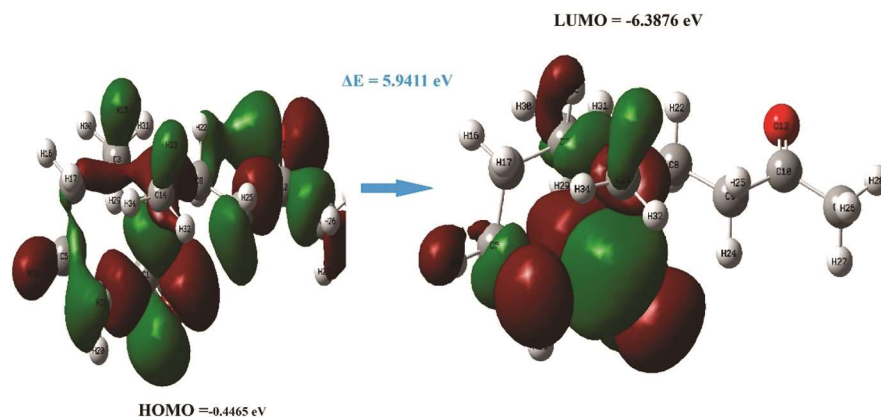


Fig. 3 — HOMO-LUMO parameters of C2D3O

Table 3 — HOMO-LUMO parameters of C2D3O

Parameters	Values	Parameters	Values
E_{HOMO} (eV)	-0.4465 eV	Chemical Potential (μ)	-3.0700 eV
E_{LUMO} (eV)	-6.3876 eV	Global electrophilicity (ω)	1.4537 eV
Energy Gap (ΔE)	5.9411 eV	Electron Acceptor Power (ω^+)	0.6281 eV
Ionization Potential (IP)	6.3876 eV	Electron donor power (ω^-)	4.0451 eV
Electron Affinity (EA)	0.4465 eV	Nucleofugality ΔE_n	1.9002 eV
Absolute Hardness (η)	3.0700 eV	Electrofugality ΔE_e	7.8413 eV
Absolute Softness (σ)	$0.3366eV^{-1}$	$\Delta E_{back-donation}$	-0.7426 eV

Drug likeness for C2D3O

A crucial first stage in the drug-development process, drug similarity aids researchers in locating possible lead compounds with advantageous pharmacokinetic and pharmacodynamic characteristics. In pharmacokinetics objects absorption, distribution, metabolism and excretion processes of drugs move through the body over time. It can be through the PKCSM analysis of this compound had descriptors with values in the (Table 4). Nevertheless, more experimental verification is required to evaluate the compound's true efficacy and safety. Rules and criteria have been devised to evaluate a compound's drug similarity.

One of the most often used criteria for determining whether a substance is likely to be orally active in humans is Lipinski's rule. This molecule conforms to the rule since it has two hydrogen bond acceptors, zero hydrogen bond donors, a molecular weight of 196.29 g/mol, a partition coefficient (logP) of less than 5, and a molecular weight of less than 500 g/mol²⁸. According to Veber's Rules, the title compound's rotational bond is ≤ 10 , which yields a value of 3. Polar surface area $< 140 \text{ \AA}^2$ restrictions also show that this compound has an achieved value of 86.071 \AA^2 . As an alternative, a molecule already meets the donors and acceptors of hydrogen bonds listed above. Additional parameters for drug similarity are provided

Table 4 — C2D3O Parameters of Drug Likeness

Descriptor	Value
Molecular Weight	196.29 g/mol
LogP	2.751
Rotatable Bonds	3
Acceptors	2
Donors	0
Surface Area	86.071 \AA^2

by the Ghose filter. The number of atoms in this molecule is limited to 20–70, and the molecular weight between LogP and 34 is already satisfied.

MEP Analysis

This compound complies with the rule, as its molecular weight (196.29 g/mol) is below 500 g/mol, its logP (partition coefficient, indicating lipophilicity) is under 5, it has zero hydrogen bond donors, and it possesses two hydrogen bond acceptors²⁹. For medicinally significant compounds, the MEP diagram is well known for offering extremely helpful information for understanding or forecasting the chemical reactivity behavior of any molecular system³⁰. The highest negative electrostatic potential in (Fig. 4) is shown by red patches, which are electron-rich regions, mostly surrounding the oxygen atoms in the carbonyl (C=O) functional groups. Because of their high electron density, these sites are conducive to electrophilic assault. Blue patches, on the other hand, indicate the strongest electrostatic potential and are usually found near

hydrogen atoms that are joined to carbonyl groups or other areas that lack electrons, making them more vulnerable to nucleophilic assault. A balanced distribution of charges is indicated by green patches, which denote neutral electrostatic potential. Molecular docking studies and other molecular interactions can be greatly impacted by the existence of lone pairs on oxygen (LP (1) and LP (2) of O7 and O12), which indicate strong donor properties. A molecule's chemical reactivity and its uses in biological systems, especially in drug design where binding interactions are essential, are greatly influenced by the charge distribution seen in the MEP analysis. This technique is a useful tool for anticipating reactive sites and directing additional computational and experimental research.

Natural bond orbital (NBO) analysis

Using the natural bond orbital (NBO) analysis, the conjugative and hyper-conjugative interactions, intramolecular and intermolecular hydrogen bonds, and the electron density distribution between bonding and antibonding orbitals in the molecular system were identified³¹. For a select group of donors and

acceptors, Table 5 displays the NBO computation along with the $E(2)$, $E(j)-E(i)$, and $f(i, j)$ values.

The stabilization energy $E(2)$ of the NBO analysis is used to characterize the interaction between occupied and unoccupied NBO type Lewis's orbitals because they facilitate the electron delocalization from bonding (BD) or lone pair (LP) orbitals to anti-bonding (BD*) or lone pair (LP*) orbitals³². With O_7 LP (2) $\rightarrow C_1-C_6 \sigma^*$ and O_{12} LP (2) $\rightarrow C_9-C_{10} \sigma^*$ contributing $22.19 \text{ kcal/mol}^{-1}$ and $20.72 \text{ kcal/mol}^{-1}$, respectively, the higher stabilization energies are found in the lone pair (LP) interactions of oxygen atoms (O_7 and O_{12}) with adjacent σ^* orbitals. Strong electron delocalization is suggested by these interactions, which greatly stabilizes the molecule structure. The relevance of hyper conjugative interactions in molecule stability is further demonstrated by their noteworthy stabilization energies of $4.68 \text{ kcal/mol}^{-1}$ for $C_6 - H_{21} \sigma \rightarrow C_1 - O_7 \pi^*$ and $4.55 \text{ kcal/mol}^{-1}$ for $C_9 - H_{24} \sigma \rightarrow C_{10} - O_{12} \pi^*$. The observed hyperconjugation and charge delocalization support the molecule's overall electronic stability, which may affect its optoelectronic characteristics, chemical reactivity, and biological activity. The results obtained from this NBO analysis offer a better grasp of the electronic structure of the molecule and can be used as a starting point for additional experimental and computational research.

Topological analysis

A complete understanding of electron distribution and bonding is provided by the Electron Localization Function (ELF) and Localized Orbital Locator (LOL), which are frequently employed for surface and topological investigations of molecular systems. ELF $\tau(r)$ and LOL $\rho(r)$, which explain electron localization in terms of density and orbital interactions, are the

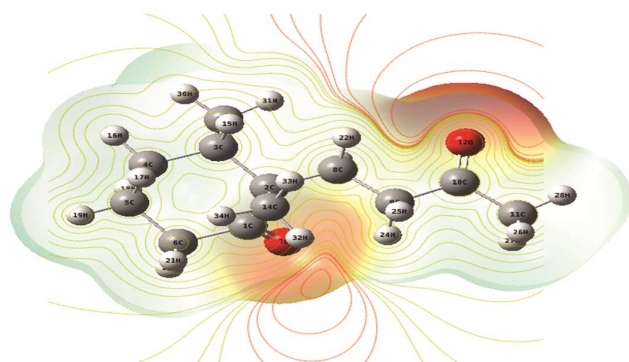


Fig. 4 — The MEP map surface on C2D3O compound

Table 5 — Second-order perturbation theory analysis of fock matrix in C2D3O

Donor(i)	Type	Acceptor(j)	Type	$E(2)$ (Kcal/ mol ⁻¹)	$E(j)-E(i)$ (a. u.)	$F(i, j)$ (a. u.)
C ₂ - C ₃	σ	C ₁ - O ₇	π^*	2.08	0.62	0.032
C ₁ - C ₆	σ	C ₂ - C ₈	σ^*	1.93	1.04	0.040
C ₆ -H ₂₁	σ	C ₁ - O ₇	π^*	4.68	0.53	0.045
C ₈ - H ₂₃	σ	C ₉ - H ₂₅	σ^*	3.10	0.86	0.046
C ₉ - H ₂₄	σ	C ₁₀ - O ₁₂	π^*	4.55	0.53	0.044
C ₉ - H ₂₅	σ	C ₁₀ - O ₁₂	π^*	4.52	0.53	0.044
C ₁₁ -H ₂₆	σ	C ₁₀ - O ₁₂	σ^*	4.69	1.13	0.065
C ₁₁ -H ₂₇	σ	C ₁₀ - O ₁₂	π^*	4.64	0.53	0.045
C ₁₁ - H ₂₈	σ	C ₁₀ - O ₁₂	π^*	4.62	0.53	0.045
O ₇	LP (1)	C ₁ - C ₂	σ^*	2.61	1.07	0.048
O ₇	LP (2)	C ₁ - C ₂	σ^*	21.27	0.66	0.107
O ₇	LP (2)	C ₁ - C ₆	σ^*	22.19	0.65	0.109
O ₁₂	LP (2)	C ₉ - C ₁₀	σ^*	20.72	0.67	0.107
O ₁₂	LP (2)	C ₁₀ - C ₁₁	σ^*	20.88	0.65	0.106

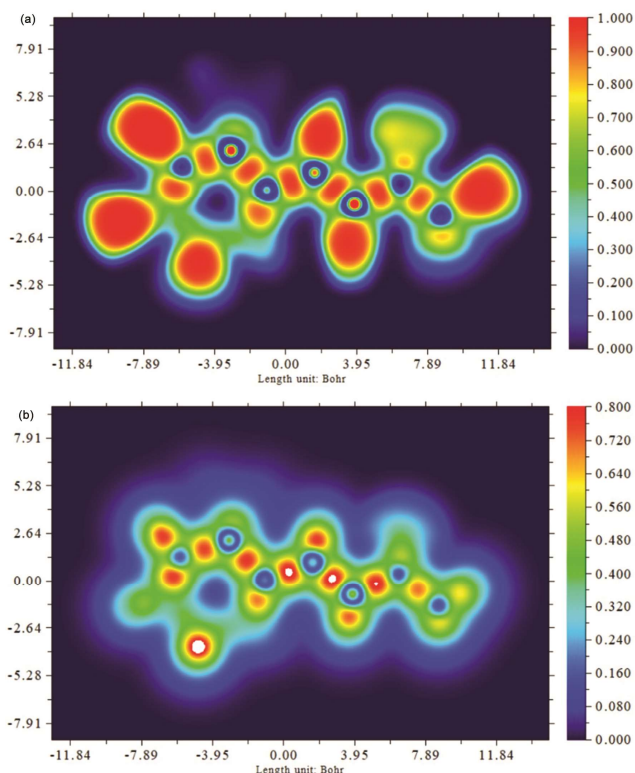


Fig 5 — (a) ELF map of C2D3O; and (b) LOL map of C2D3O

foundation of these techniques, which help interpret covalent bonds and electronic structures [33, 34]. Using Multiwfn 3.7 software, ELF and LOL analyses were performed on the title chemical in this study. The results are displayed in Figure 5a and b as color field projection maps and contour maps. The blue-to-red color gradient represents the ELF values, which range from 0.0 to 1.0. Aside from the regions that surround atomic nuclei, red areas denote regions with high electron localization, like lone pairs, whereas blue regions that join atoms show lesser electron localization, which is typical of covalent bonds. This is enhanced by the LOL analysis, which offers further information for values between -11.84 and 11.84 Bohr. Electron localization is shown by the matching colour scale, which ranges from blue to red 0.0 to 0.80^{35, 36}. Whereas blue regions, which frequently have wider contour spacing, indicate areas of poorer electron localization, red portions in LOL maps indicate electron-rich places, such as lone pairs and bonding regions. In addition to disclosing the molecule's electrical structure, these investigations offer important insights into the system's atomic connections and biological interactions. Combining ELF and LOL research improves knowledge of bonding properties and electron density distribution, which makes it a crucial method for molecular research.

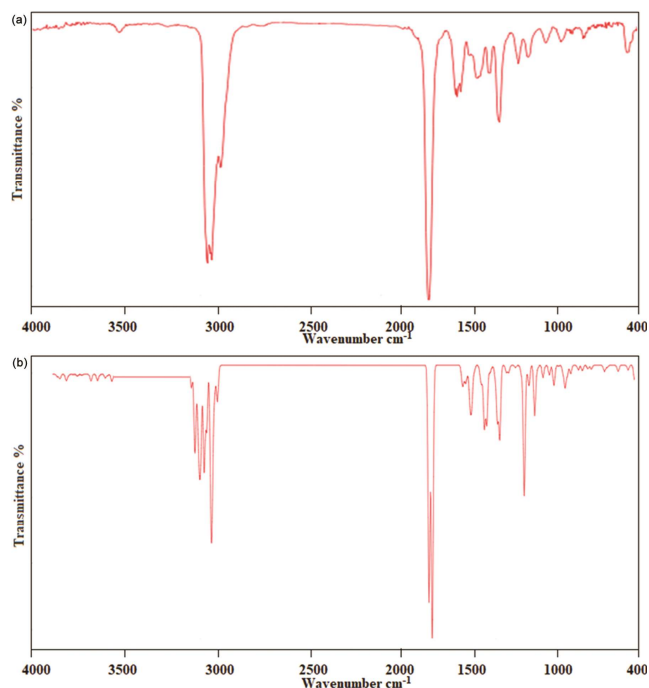


Fig 6 — FT-IR of C2D3O

FT-IR of C2D3O

Vibrational analysis of C2D3O was to be used to identify different types of vibrations inside the molecule. The vibrational frequencies for two distinct basis sets, 6-31G (d, p) and 6-311++G (d, p), were computed using the B3LYP technique³⁷. The VEDA 4 software was used to calculate the PED, which determines the relative contributions of various molecular components to each vibration. Table 6 displays the findings of these investigations. After deducting the three translational and three rotational degrees of freedom, the formula $3N-6$ provides the total number of possibly visible vibrational modes for a nonlinear molecule with N atoms³⁸. Since the molecular structure of C2D3O is symmetric in the $C1$ point group, it is not possible to considerably simplify the vibrational modes based on symmetry. All vibrations are active in both the Raman and infrared (IR) spectra. The force constants derived from the vibrational analysis were used to calculate the PED, which allowed each vibrational mode to be linked to distinct molecular movements. This is because the 34 atoms in C2D3O are expected to exhibit 96 typical vibrational modes. Figure 6 shows a high correlation between the measured C2D3O FT-IR spectra and the calculated vibrational frequencies. For the vibrational study of MMDT, several vibrational modes—including C=C, C-C, CH₃, CH₂, CO, C-H,

Table 6 — FT-IR of C2D3O

B3LYP/6-311++G (d,p)	Experimental	Vibrational Assignment +PED		B3LY P/6-311++G (d,p)	Experimental	Vibrational Assignment +PED	
3162		ν CH	70	1159	1151	δ HCC	15
3144	3144	ν CH	71	1112	1100	ν CC	11
3139		ν CH	77	1070	1180	ν CC	36
3126		ν CH	65	1019		ν CC	11
3118		ν CH	95	994	1000	ν CC	28
3117		ν CH	79	968		ν CC+ τ HCCC	16+14
3110		ν CH	46	957		τ HCCC	15
3108		ν CH	45	925		δ HCC	14
3091	3098	ν CH	65	859	850	δ HCC+ τ HCCC	10+10
3077	3070	ν CH	39	810		ν CC	16
3056	3061	ν CH	65	736		τ HCCC	12+10
3053		ν CH	21	720		τ HCCC+ γ OCCC	12+21
3050	3049	ν CH	50	604		ν CC	25
3046		ν CH	85	568	550	δ OCC	26
3045		ν CH	57	531	530	δ CCC	16
3044	3038	ν CH	70	494		δ CCC	11
3031		ν CH	92	477		τ HCCC+ γ OCCC	16+52
3016	3000	ν CH	91	477		γ OCCC	52
1810		ν OC	90	442	420	δ CCC	10
1792		ν OC	91	412		δ CCC+ τ CCCC	26+10
1535	1540	δ HCH	55	401	401	δ CCC	12
1529	1528	δ HCH	29	333		δ CCC	19
1521		δ HCH	20	318		ν CC+ δ CCC	10+34
1514	1514	δ HCH	30	283		δ CCC	11
1509	1503	δ HCH	38	283		τ CCCC	10
1501	1500	δ HCH	56	271		δ CCC	13
1491	1495	δ HCH+ τ HCCC	47	271		τ HCCC	32
1488		δ HCH	65	244		δ CCC	14
1483		δ HCH	74	244		τ HCCC	10
1479		δ HCH+ τ HCCC	32	244		τ HCCC	13
1466	1463	δ HCH	69	221		δ CCC	14
1432	1440	δ HCH	47	221		δ CCC	15
1425		δ HCH	55	215		ν CC	11
1410	1412	τ HCCC+ δ HCH	32	215		δ CCC	14
1396		δ HCH	10	215		τ HCCC	16
1394		δ HCC+ γ CCCH + τ HCCC	29	196		δ CCC	17
1379	1380	γ CCCH	14	150		δ HCH	20
1369		τ HCCC	32	144		τ HCCC	11
1350	1350	δ HCC	12	134		δ HCC	15
1346		δ HCC+ τ HCCC	26	123		δ HCC	21
1336		δ HCC	31	108		δ CCC	34
1323		δ HCC+ τ HCCC	32	108		τ HCCC	10
1286	1280	δ HCC	24	97		τ HCCC	36
1273		δ HCC	23	64		δ CCC	33
1196		τ CCCC	10	13		δ HCC	50
1186		δ OCC+STRECC	13 + 14				

HCC, HCCC, CCCH, and HCH—were mapped in order to examine their contributions to molecular dynamics. According to FTIR spectroscopy, a molecule's single bond status (saturated) or double or triple bond status (unsaturated) is described by its saturation and unsaturation. These structural features affect the apparent absorption peaks in the FTIR spectrum.

CH Vibrations

Typically, C-H stretching vibrational bands are seen in the 3100–3000 cm^{-1} range³⁹. In the experimental FT-IR spectrum, the CH stretching vibrations in the investigated molecule are detected at 3144 cm^{-1} , 3098 cm^{-1} , 3070 cm^{-1} , 3061 cm^{-1} , 3049 cm^{-1} , 3038 cm^{-1} , and 3000 cm^{-1} . Density Functional Theory (DFT) with the B3LYP/6-311++G (d, p) basis set

yielded the following related computational values: 30144 cm^{-1} , 3091 cm^{-1} , 3077 cm^{-1} , 3056 cm^{-1} , 3050 cm^{-1} , 3044 cm^{-1} , and 3016 cm^{-1} . The theoretical approach correctly depicts the vibrational properties of the CH groups, as evidenced by the strong agreement between the experimental and computational values, respectively. These modes' relative contributions from the Potential Energy Distribution (PED) study are 71%, 65%, 39%, 65%, 50%, 70%, 55%, and 29%, indicating that they are primarily CH stretching vibrations with little to no mixing with other modes. The reliability of the computational technique in analysing the vibrational characteristics of the CH bonds in the molecule is demonstrated by this alignment of experimental and computational data.

HCCC, HCC Vibration

The C-H bond's bending modes in HCCC torsion and HCC scissoring mode in-plane bending are frequently located in the range of 1460–1480 cm^{-1} and 600–900 cm^{-1} ⁴⁰. The calculated HCCC, HCC values of 1535 cm^{-1} , 1526 cm^{-1} , 1514 cm^{-1} , 1509 cm^{-1} , 1501 cm^{-1} , 1491 cm^{-1} , 1466 cm^{-1} , 1432 cm^{-1} , 1410 cm^{-1} , 1379 cm^{-1} , 1350 cm^{-1} , 1286 cm^{-1} , 1159 cm^{-1} , 1259 cm^{-1} , and 841 cm^{-1} are correlated with the experimental values of 1540 cm^{-1} , 1503 cm^{-1} , 1500 cm^{-1} , 1495 cm^{-1} , 1463 cm^{-1} , 1440 cm^{-1} , 1412 cm^{-1} , 1380 cm^{-1} has an out of plane bending at this range CCCH, 1350 cm^{-1} , 1280 cm^{-1} and 1151 cm^{-1} to get the PED values of 55%, 29%, 30%, 38%, 56%, 47%, 69%, 47%, 39%, 14%, 12%, 24% and 15%.

CC, OCC, CCCC Vibration

In aromatic compounds, C = C and C - C, CCCC, OCC stretching vibrations usually show bands between around 500 and 700 cm^{-1} ⁴¹. The computational values derived using the B3LYP/6-311++G (d, p) approach and the experimental FT-IR data for the C-C and C=C vibrational modes are found to be in good agreement. A trustworthy forecast is shown by the C-O stretching vibration, which has a computational value of 1792 cm^{-1} , 1810 cm^{-1} . Likewise, the observed FTIR result of 1240 cm^{-1} is consistent with the C=C stretching vibration, which is computed at 1242 cm^{-1} . Since these vibrational modes fall within the anticipated range for C-C and C=C stretching frequencies, it can be demonstrated that there is a strong correlation between the computational predictions and the experimental evidence. The B3LYP/6-311++G (d, p) method's accuracy in predicting vibrational properties is confirmed by this

alignment between theory and experiment, which meets the predicted values for these functional groups. Wave counts of 994 cm^{-1} , 859 cm^{-1} , 568 cm^{-1} , and 531 cm^{-1} have been reported. These match the PED values of 28%, 26%, 16%, 10%, and 12% for the experimental wave numbers of 1000 cm^{-1} , 850 cm^{-1} , 550 cm^{-1} , and 530 cm^{-1} .

C2D3O of UV-Vis

The UV spectrum in the gas phase is shown in (Fig. 7), while Table 6 displays the molecule's predicted wavelength, energy, bond gap, and oscillator strength. The n-p transition is less evident than the p-p transition⁴². The n or p orbitals transition to an excited state using the absorbance spectroscopy technique. In addition, we reported the energy of the orbitals and computed the energy gap between the principal peaks of the molecular orbitals of the spectra and the border HOMO-LUMO orbitals⁴³. The electron transition at 287.53 nm, excitation energy = 4.3121 eV, and oscillation strength $f = 00.0001$ in the current study closely resembles the experimental UV-visible spectra absorption at 269 nm, which represents the $\pi \rightarrow \pi^*$ electronic transition from ground state to excited state in the C2D3O compound. Quantum chemistry theory was used to analyze the electronic transition features of C2D3O utilizing the UV-visible spectra and related properties of oscillation strengths (f), excitation energy (eV), and absorption band (nm). These features are based on the DFT/B3LYP/6-311++G(d, p) method, which was computed in the gas phase and connected to real UV-visible spectra. Nevertheless, further absorption transitions at 289.12 and 226.78 nm, respectively, are

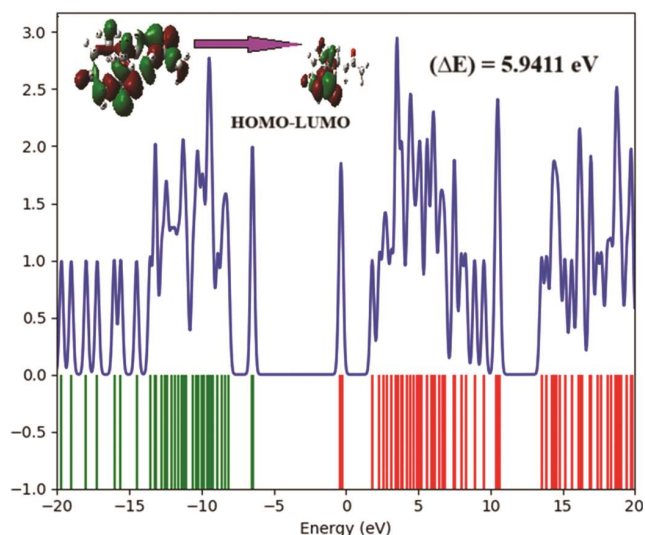


Fig. 7 — Uv-Vis of C2D3O

not consistent with the experimental values listed in (Table 7). The Gauss Sum software found that the largest contributions were HOMO->L+1 (94%), H-1->LUMO (94%), and HOMO->LUMO (94%), whereas the smallest contributions were HOMO->LUMO (4%), H-1->L+1 (3%), and HOMO->L+1 (4%). The Gauss Sum software found that the largest contributions were HOMO->L+1 (94%), H-1->LUMO (94%), and HOMO->LUMO (94%), whereas the smallest contributions were HOMO->LUMO (4%), H-1->L+1 (3%), and HOMO->L+1 (4%).

C2D3O of DOS

The density of states (DOS) is an important word in electronic structure study since it gives information on

how electronic states are distributed across energy levels in material⁴⁴. Knowing how various atoms and orbitals contribute to the electronic structure is necessary to comprehend the material's features, including conductivity, optical behaviour, and bonding properties of the C2D3O. It explains how the distribution pattern around HOMO and LUMO is influenced by the type of acceptor moieties that remove electrons. For DOS interpretation, each structure is separated into donor and acceptor portions⁴⁵. As can be seen in Figure 8, the donor's relative intensity is displayed in green, and the acceptors' relative intensity is displayed in red. On DOS graphs, HOMO is represented by negative values along the x-axis, whereas LUMO is represented by positive numbers.

Table 7 — UV-Vis of C2D3O

Solvents	States	B3LYP/6-311G(d,p)				Major Contributions Energy (%)
		Absorption b and λ (nm)	Excitation energies (cm ⁻¹)	Oscillation Strength f	Energy Gap (eV)	
Gas Phase	S1	289.12	34588.28	0.0001	402884	HOMO->L+1 (94%) HOMO->LUMO (4%)
	S2	287.53	34779.43	0.0000	4.3121	H-1->LUMO (94%) H-1->L+1 (3%)
	S3	226.78	44095.94	0.0000	5.4672	HOMO-> LUMO (94%) HOMO-> L+1 (4%)
Experimental		287	-	-	-	-

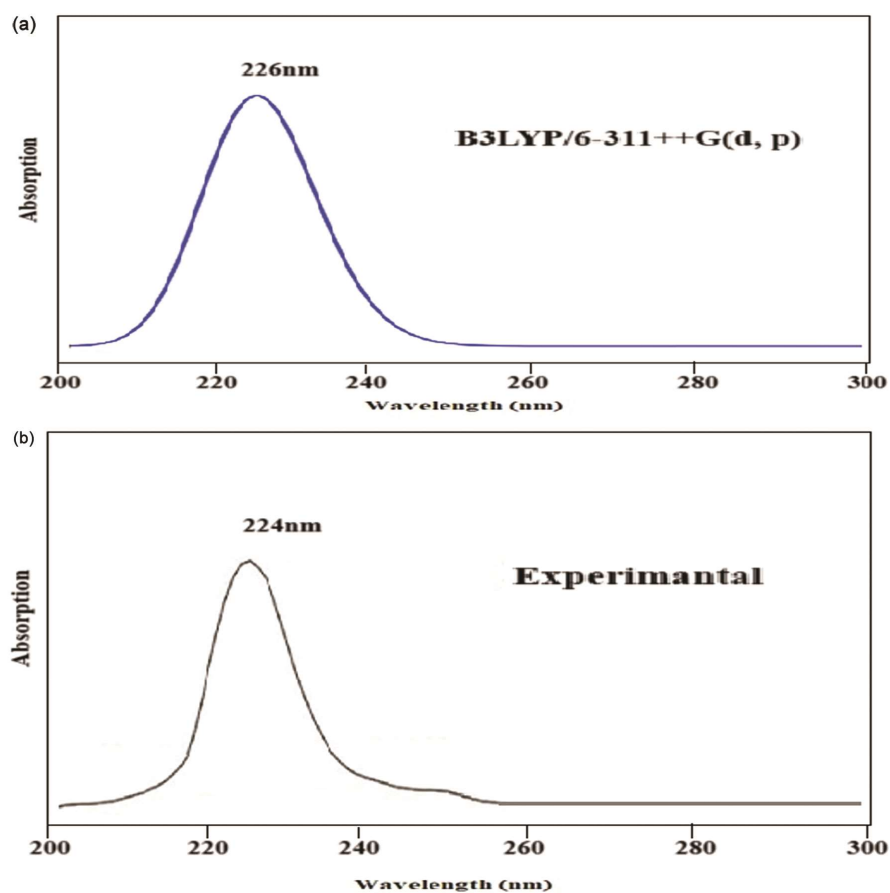


Fig. 8 — C2D3O of DOS

Table 8 — Molecular Docking of C2D3O

Protein (PDB ID)	No. of hydrogen bond	Bond distance (Å)	Bonded residues	Estimated Inhibition Constant (μm)	Binding energy (kcal/mol)	Reference RMSD (Å)
8D59	2	2.2	ARG`124 (O... 2HH1)	237.85	-4.94	4.81
		1.9	ARG`121 (O... 1HH2)			

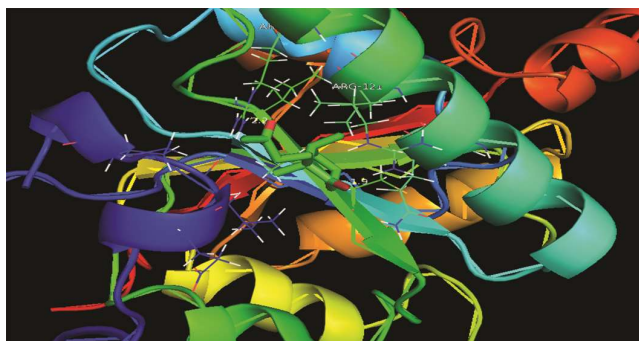


Fig. 9 — Molecular docking of C2D3O

The donor groups in the molecule C2D3O have a somewhat larger concentration of the HOMO's electron density, which is dispersed across the molecule⁴⁶. Although some electron density is linked to the donor groups, the acceptor moiety is the main source of electron density in the LUMO. The acceptor group in the LUMO has a higher electron density than the donor group. These results show that the withdrawing activity of the end-capped acceptor moieties is sufficient.

Molecular Docking

A structure-based method for designing drugs, molecular docking models receptor-ligand interactions to forecast binding affinities and modalities. Examining biomolecular interactions and supporting logical drug design, makes drug discovery easier. This approach is a useful research tool since it calculates binding energy, free energy, and complex stability. The PDB structures of target proteins were obtained from the RCSB protein data library⁴⁷⁻⁴⁹. The downloaded inhibitor protein, identified as 8D59, was selected for docking with the sample compound. AutoDock was used for molecular docking, where the ligand and water molecules were separated from the protein. Additionally, polar hydrogen bonds and Geisterger charges were introduced during the process. Docking parameters, including RMSD value, hydrogen bond count, bond distances, bonded residues, inhibition constant, and binding energy, are summarized in (Table 8 & Fig. 9).

The 8D59 protein inhibitor exhibited a low binding energy of -4.94 kcal/mol and a high RMSD value of 43.81, indicating interaction stability. In docking studies, binding energy represents the energy released

upon ligand-protein interaction, with higher binding energy signifying a stronger bond. The results illustrate that a hydrogen bond is formed between the hydrogen atom of the ligand and the carbon atom of the protein inhibitor⁵⁰. Generally, hydrogen bonds occur when hydrogen is covalently attached to an electronegative atom (such as nitrogen or oxygen) and interacts with another atom possessing a lone pair of electrons. The ligand exhibits a high binding affinity for the target protein, demonstrating structural similarity between the ligand and the inhibitor protein.

Conclusion

Using the gas chromatography-mass spectrometry (GC-MS) approach, the C2D3O molecule is being conformed in *Hybanthus enneaspermus* crude. Optimized structural conformation and electronic characteristics were investigated using the B3LYP method, the 6-311++G (d, p) basis set, and experimental techniques such as UV-Vis and FT-IR. Each atom's vibrational statement may be examined in the analyses. O7 LP (2) \rightarrow C1-C6 σ^* and O12 LP (2) \rightarrow C9-C10 σ^* contribute 22.19 kcal/mol⁻¹ and 20.72 kcal/mol⁻¹ to the C2D3O, respectively, according to NBO. Topological research like ELF and LOL have values between 0.0 and 1.0 and blue to red between 0.0 and 0.80. The present analysis of the UV-visible spectra shows an electron transition at 287.53 nm, an excitation energy of 4.3121 eV, and an oscillation strength of $f = 00.0001$. The density of states (DOS) of material also shows the distribution of electronic states across energy levels, with HOMO- \rightarrow L+1 (94%), H-1- \rightarrow LUMO (94%), and HOMO- \rightarrow LUMO (94%). With an estimated inhibition constant binding distance of 237.85 μm and 2.2 ARG~124, 1.9 ARG`121 residues, the ligand exhibits a high binding affinity for the target protein of -4.94 kcal/mol.

Conflict of interest

All authors declare no conflict of interest.

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