Scientific paper

Conformational Stability of 3-aminopropionitrile: DFT and *Ab initio* Calculations

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Abstract

Many conformers of 3-aminopropionitrile are known. Due to the biomedical importance of 3-aminopropionitrile a full investigation of structural, vibrational, and other associated properties of all possible conformers was performed. The geometrical structures, relative stability, and vibrational frequencies of the gauche and trans 3-aminopropionitrile conformers have been studied using *ab initio* (CCSD/6-311+G(d,p)) and DFT (B3LYP and M06 functionals at 6-311+G(d,p) and aug-cc-pVDZ basis set) calculations. The conformational and vibrational studies of 3-aminopropionitrile molecule were presented here are in very good interpretation of the calculated data compared with very poor interpretation in previous studies. The results showed that the gauche 2 conformer is more stable by 0.19 kcal/mol than gauche 1, outlined as enthalpy change ΔH between the conformers, at CCSD/6-311+G(d,p). Additionally, the population analysis shows that the gauche conformers are more prevalent than the trans conformers in the gas phase, present at 72.8%, with gauche 2 being the dominating gauche conformer at 40.1%. These results are in good agreement with earlier experimental and theoretical conclusions. All minima conformers' thermodynamic characteristics have also been studied. The relevant bond lengths, bond angles, and dihedral angles were calculated at a different level of theory for all possible conformers. The geometrical outcomes of the conformers agree very well with the previous experimental results. Electrostatic potential surface (ESP) has been used to interpret the structure-activity relationship. The atomic charges are examined, together with the energy difference between HOMO (Highest Occupied Molecular Orbital) and LUMO (Lowest Unoccupied Molecular Orbital). Additionally, the HOMO-LUMO energy gap and other relevant molecular properties are computed. The most stable conformers' stabilization energy has been determined by the Natural Bond Orbital (NBO) analysis.

Keywords: 3-aminopropionitrile, HOMO-LUMO, ESP, conformer, vibrational frequencies, relative stability.

1. Introduction

Numerous chemical and physical properties of a chemical molecule with various functional groups are influenced by conformational isomerism. Examples include determining the phase of the substances under ambient conditions[1,2] and determining the activity of particular enzymes.[3–5] Nitriles play a significant role in both chemistry and astrochemistry. For instance, succinonitrile is a crucial component of research on solid state batteries[6–9] and is utilized as a solvent of inorganic salts. Additionally, it has been utilized to improve the conductivity of composite polymers as succinonitrile-poly(methyl methacrylate).[10] Interstellar clouds are anticipated to contain some small chain nitriles, which are thought to react with water to create amino acids.[11–13] Numerous organoamines play crucial roles in biomolecules including proteins and amino acids. An organic substance possessing both amine and nitrile functional groups is 3-aminopropionitrile (BAPN), $NH_2CH_2CH_2CN$ (also called 2-cyanoethylamine). It is a colorless liquid. The compound is present naturally and is of interest to the biomedical field.[14] As a result of 3-aminopropionitrile significance in the biomedical field, it can be important for research to estimate its conformational stabilities.

Organoamines play essential roles in biomolecules including proteins and amino acids. As an illustration, β-aminopropionitrile is injected into a tendon that has been wounded 30 to 90 days after the injury in order to bind to the lysyl oxidase enzyme and prevent lysine from being deaminated. To forecast the result of these binding, one must have a thorough understanding of the β-aminopropionitrile's structure, conformation, reactivity, and interactions. The purpose of this study is to explain the theoretical methods that have been used to interpret the main characteristics of β-aminopropionitrile, particularly its structure.

The results of conformational analysis of 1,2-disubstituted ethane molecules are largely strange to free intra-single-bond rotations. Over time, there have been some intriguing difficulties in determining the conformational stability of 1,2-disubstituted ethane molecules.[15] The 1,2-dihaloethane molecules served as good examples, with 1,2-difluoroethane[16] having a gauche conformer that is (3.35 ± 0.36) kJ mol^{-1} more stable than the trans form and 1,2-dichloroethane having a trans conformer that is (3.87 ± 0.09) kJ mol^{-1} more stable than the gauche from a variable temperature infrared studies of xenon solutions.[17] Trans conformer of butyronitrile ($CH_3CH_2CH_2CN$) is more stable than the gauche, according to a microwave investigation by Hirota,[18] while IR investigation, claimed that the vapor phase of gauche conformer is dominant.[19]

Conformers' relative stabilities can be calculated by vicinal interactions between functional groups revolving around a single free-rotated bond. These interactions can be repulsive (destabilizing), as in the case of the methyl-methyl strain energy in n-butane,[20] or attractive (stabilizing), as in the case of the gauche effect of 1,2-difluoroethane.[21] Based on their relative free energies, which define their relative abundances according to the Boltzmann distribution, the conformers are in equilibrium with one another. The thermodynamic characteristics of the conformers exchange determine its dynamics. Whenever a chemical reaction occurs, the structure and shape of the product are influenced by reactants' thermochemical properties.

Determining the appropriate 3-aminopropionitrile requires investigation, just like the molecules mentioned above, as it has more than one minima conformers (gauche and trans).[22] The conformational study of 3-aminopropionitrile has received little theoretical attention.[15, 22, 23] The most recent one[15] by James et al. employed just two minima for the MP2 (full) *ab initio* and B3LYP density functional theory (DFT) computations. They discovered that the gauche conformer is 0.87 kcal/mol more stable than the trans conformer at their greatest level of theory, MP2 (full)/aug-cc-pVTZ. Enthalpy[15] is the only thermochemical data available for 3-aminopropionitrile.

Due to a lack of information, it is decided to investigate the thermodynamics, structure, and stability of five, three gauche, and two trans minima conformers.[15,22] In this research, the structural details and conformational stabilities of conformers of 3-aminopropionitrile were examined. Additionally, the conformers' thermodynamic data were computed. The results were compared to experimental and theoretical data that had previously been published. The outcomes of this research should aid in elucidating conformational changes.

2. Computational Details

Gaussian09 software was used for all geometry optimization and energy computations.[24] Different theoretical levels, including CCSD,[25] B3LYP and M06,[24] have been employed. These basis sets include 6-311+G(d,p) and aug-cc-pVDZ.[24] Frequency calculations are used to describe the stationary points (minima and transition states; saddle point of first order). Mathematically, the transition states have one imaginary eigenvalue while the minima have none. The vibrational frequency and thermodynamic data were gained using the frequency calculations. The equation described in my earlier work[26] is used to calculate the relative stability between the most stable conformer and the less stable ones or the transition states.

$$\Delta H_{rel} = (E_0 + H_{cor})_{(less)} - (E^0 + H_{cor})_{(most)} \quad (1)$$

$$\Delta G_{rel} = (E_0 + G_{cor})_{(less)} - (E^0 + G_{cor})_{(most)} \quad (2)$$

Where ($E_o + H_{corr}$) and ($E_o + G_{corr}$) are, respectively, the corrected electronic energy (E_o + enthalpy correction, H_{corr}), and the corrected electronic energy (E_o + Gibbs correction, G_{corr}), which includes the zero-point energy. Natural bond orbital (NBO) analysis was used to determine the electronic atomic charges.[27] The data collected were utilized to determine the stabilization energy of the conformer that was determined to be the most stable. The Coulomb's potential is used to calculate the electrostatic interaction between the staggered NH_2 group and the point-charged N and C atoms of the nitrile group for this purpose.

$$U_E = k_e \sum_{i}^{N} \frac{q_i Q}{r_i} \quad (3)$$

Where r is the distance between the point charges q of the nitrile group and the point charge of the closest H atom on the NH_2 group (Q), $k_e = \frac{1}{4\pi\varepsilon_0} = 8.988 \, x \, 10^9 Nm^2C^{-2}$ is Coulomb's constant.

In order to explain the orbital overlaps and the possibility for charge transfer inside the five minima conformers, the energies of the highest occupied molecular orbital (HOMO) and the lowest unoccupied molecular orbital (LUMO) were also calculated using the CCSD/6-311+G(d,p) level of theory.

3. Results and Discussion

3. 1. Geometry

Figure 1 displays the minima's and transition states' optimized structures. Tables 1 and 2 display the relevant bond lengths, bond angles, and dihedral angles. At a different level of theory, all conformer bond lengths are comparable to one another, with a maximum variation of (0.023 Å). The C≡N bond lengths of the minima and transition states are remarkably similar, with a maximum difference of 0.001 Å, at the same level of theory. With the exception of gauche 1, 2, and TS4, where there is a maximum difference of 0.001 Å, all minima and transition state conformers' C≡N bond lengths are identical at the DFT (B3LYP/aug-cc-pVDZ, M06/aug-cc-pVDZ) and CCSD/6-311+G(d,p) levels of theory. All levels of theory's transition states have C1-C6 bond lengths that are longer than those of minima conformers. At both the B3LYP and M06 levels of theory of DFT, the gauche 2 conformer's C1–C6 bond lengths are the identical. All conformers' C1-C6 bond lengths vary slightly across levels of theory, with the largest differences (0.019 Å) occurring between B3LYP/6-311+G(d,p) and M06/aug-cc-pVDZ in TS3.

All conformers have somewhat varied C1-C4 bond lengths at the same levels of theory, with the M06/aug-cc-pVDZ in TS1 and TS3 having the largest variance (0.011 Å). The lengths of the C1-C4 bonds vary slightly depending on the level of theory, with the greatest difference (0.023 Å) between the M06/6-311+G(d,p) CCSD/6-311+G(d,p) basis fixed for all conformers. The C1-C4 bond's longest length is revealed via a CCSD/6-311+G(d,p) level of theory for all conformers. Out of all the different levels of theory, TS3 has the shortest C1-C4 bond lengths. In Gauche 1, Trans 1, TS1, and TS3 on the one hand, and in Gauche 2, Gauche 3, Trans 2, TS2, TS4, and TS5 on the other, the C6-N9 bond lengths of the various levels of theory are quite closed. All conformers' C6-N9 bond lengths calculated using B3LYP are the ones that come closest to the lengths determined with the CCSD.

Table 2 lists the bond angles as well as the torsional (dihedral) angles. The bond angle C4-C1-C6 is smaller in the minima conformers of the various levels of theory than it is in the conformers of the transition state, particularly in the gauche conformers. The greatest values of the bond angles C1-C6-N9 for minima conformers are found in the gauche 1 and trans 1 conformers. The most conformer has bond angle C1-C4≡N5 approaches 180° of all different levels of theory for minima is trans 1 and for transition states are TS2 and TS5. The differences between the bond angles C1-C4≡N5 are between 0 and 1° for theories at different levels, and between 0 and 1.9° for theories at the same levels. The range of bond angle variances among the various levels of theory is 0 to 1.2°. By comparing the values of the dihedral angle N9-C6-C1-C4 obtained before optimization (gauche = 60°, trans = 180°, TS1, TS2, and TS5 = 120°, TS3 and TS4 = 0°) with those obtained after optimization, we can see that the conformers trans 1 and its interconversion transition state (TS3) had no deformation of any of the different levels of theory, whereas the maximum distortion that occurred on the minima and transition states conformers is in gauche 3 (B3LYP/aug-cc-pVDZ) and TS5 (B3LYP/6-311+G(d,p)) respectively.

In general, all of the bond lengths, bond angles, and dihedral angles of the minimum conformers are compared to the theoretical results,[22] and both the gauche 1 and gauche 2 conformers' parameters agree well with the microwave spectrum results.[23] Given these values, it is obvious that the bond lengths discovered in this study are identical to or extremely close to those observed theoretically or empirically. C1-C6, C1-C4, C4≡N5 and C6-N9 bond lengths of gauche 1 and gauche 2 conformers are 1.548 Å, 1.463 Å, 1.157 Å and 1.475 Å, respectively, are in good agreement with my results. For gauche 1: C1-C6 of CCSD/6-311+G(d,p), C1-C4 of B3LYP/aug-cc-pVDZ, C4≡N5 of B3LYP/6-311+G(d,p) and C6-N9 of CCSD/6-311+G(d,p) with difference 0.001 Å, 0.002 Å, 0.003 Å and 0.018 Å, respectively. For gauche 2: C1-C6 of B3LYP/6-311+G(d,p) and aug-cc-pVDZ, C1-C4 of B3LYP/6-311+G(d,p), C4≡N5 of B3LYP/6-311+G(d,p) and C6-N9 of CCSD/6-311+G(d,p) with difference 0.008 Å, 0.001 Å, 0.003 Å and 0.012 Å, respectively. Unfortunately, to my knowledge, in literature, there are no experimental data about the other minima conformers (gauche 3, trans 1 and trans 2) to compare my theoretical results with. But we can see the significant similarity between the results obtained theoretically [22] with the results of this study. The difference is in the arrange 0 – 0.023 Å.

If the bond angles are considered, the C4-C1-C6 and C1-C6-N9 bond angles in both gauche 1 and gauche 2 obtained by microwave method are near more to the values obtained by M06/aug-cc-pVDZ in this study with difference (0.6°) for C4-C1-C6 and (1.8°) for C1-C6-N9 in each conformer. The C1-C4≡N5 bond angle should be 180°, but there is a small deviations from linearity ranged from 2.1° – 3.0° in gauche 1 and 1.7° – 2.7° in gauche 2. The dihedral angle N9-C6-C1-C4 in both gauche 1 and gauche 2 conformers are closed to that obtained by microwave method especially through M06 and CCSD. For all different levels of theory the difference is in the arrange 0° – 1° for gauche 1 and 3° – 1.7° for gauche 2.

3. 2. The Relative Stability and Thermal Properties

The relative energies of the gauche 1, gauche 3, trans 1, trans 2 and the transition states conformers (relative to the gauche 2 conformer), outlined by their ΔH_{rel} and ΔG_{rel}, are listed in Table 3. 3-aminopropionitrile has five possible minima conformers, three gauche conformers and two trans conformers as shown in Figure 1. Gauche 1 and gauche 2 are more stable than any one of gauche 3, trans 1 and trans 2 by at least 0.23 kcal/mol between gauche 2 and trans 2 and up to 1.49 kcal/mol between gauche 2 and gauche 3 through B3LYP/6-311+G(d,p) and M06/aug-cc-pVDZ, respectively. The enthalpy differences between gauche 2- gauche 1 and gauche 2-trans 1 conformers were determined in the range 0 – 0.19 kcal/mol and 0.23 – 0.70 kcal/mol, respectively, through all different levels of theory. This values were closed to that given by previous microwave and infrared studies.[15, 23]

Through the highest level of theory used in this study, CCSD/6-311+G(d,p) and M06/aug-cc-pVDZ, the more stable conformer is gauche 2 by 0.19 kcal/mol than gauche 1. This is result is correspond with infrared study, where gauche 2 is more stable than gauche 1 by 75 cm^{-1} (0.21 kcal/mol), outlined as enthalpy change H between the two conformers. Per N. Skancke [22] has studied the same system using *ab initio* with 4-21, 4-31G and 6-31G basis set, his results show that gauche 1 is more stable than gauche 2 by 1.8, 1.2 and 0.8 kJ/mol

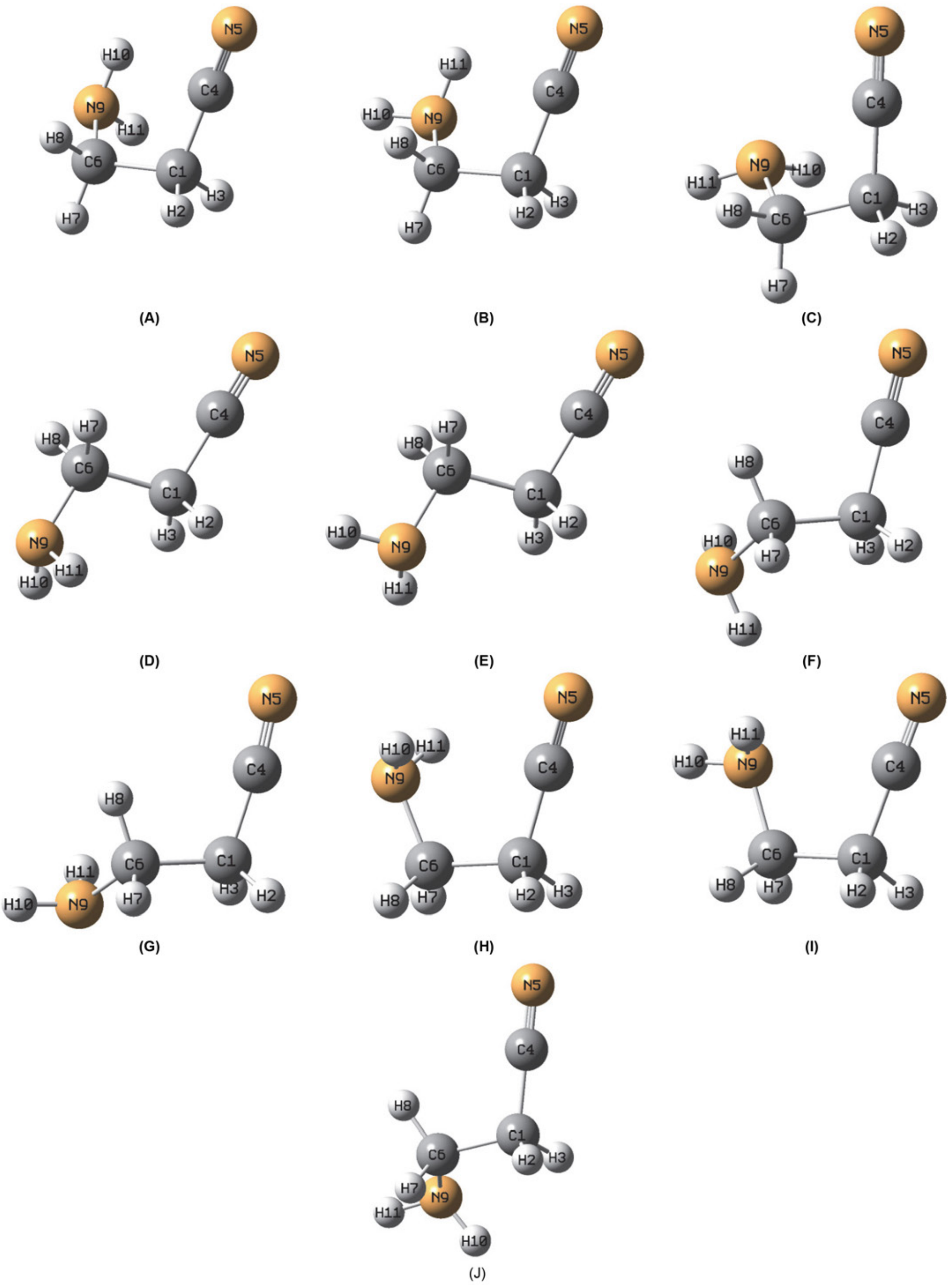

Figure 1. The optimized stationary points of 3-aminopropionitrile conformers. (A) Gauche 1(H8-C6-N9-H11 = –180°), (B) Gauche 2 (H8-C6-N9-H11 = 60°) , (C) Gauche 3 (H8-C6-N9-H11 = –60°), (D)Trans 1(eclipsed H8-C6-N9-H11), (E) Trans 2 (staggered H8-C6-N9-H11), (F) TS1 (eclipsed H8-C6-N9-H11 (-180°), staggered C4-C1-C6-N9), (G) TS2 (staggered H8-C6-N9-H11, staggered C4-C1-C6-N9), (H) TS3 (eclipsed H8-C6-N9-H11, eclipsed C4-C1-C6-N9), (I) TS4 (staggered H8- C6-N9-H11, eclipsed C4-C1-C6-N9), (J) TS5 (eclipsed H8-C6-N9-H11 (0°), staggered C4-C1-C6-N9). The related optimized parameters are shown in Table 1.

(0.43, 0.29 and 0.19 kcal/mol), respectively, which contradicts the infrared and my own results. This may be attributed to the use of low level of theory. Trans 2 conformer is more stable than trans 1 conformer using all different levels of theory as shown in Table 3. The difference between two trances conformer determined by the theoretical side of the infrared study, using B3LYP/6-311+G(d,p), was 67 cm^{-1} (0.19 kcal) which is very closed to that obtained in this study (0.17 kcal/mol) through same level of theory.

Relative populations (N_i) (100%, 70.2%, 11.5%, 21.2% and 46.8%) of the conformers (gauche 2, gauche 1, gauche 3, trans 1 and trans 2), respectively, were calculated using ΔG_{rel} values [$\Delta G_{rel} = -RT \ln(Ni)$]. The population distribution (N_i/N_{total}) at 298.15 K (ambient temperature) were calculated by the Boltzmann distribution.[28]

Table 1. Selected bond lengths (Å) of the optimized gauche, trans and transition states (TS) geometries of 3-aminopropionitrile at the B3LYP, M06, CCSD/6-311+G (d,p), (aug-cc-pVDZ) levels of theory.

Structure		Bond (Å)		B3LYP		M06		CCSD
		Ref[a]	Ref[b]	6-311+G (d,p)	aug-cc-pVDZ	6-311+G (d,p)	aug-cc-pVDZ	6-311+G (d,p)
Gauche 1	C1–C6	1.548	1.560	1.555	1.553	1.539	1.538	1.547
	C1–C4	1.463	1.460	1.460	1.465	1.452	1.456	1.474
	C4≡N5	1.157	1.140	1.154	1.161	1.152	1.161	1.162
	C6–N9	1.475	1.460	1.452	1.454	1.442	1.445	1.457
Gauche 2	C1–C6	1.548	1.540	1.540	1.540	1.527	1.527	1.536
	C1–C4	1.463	1.470	1.462	1.467	1.453	1.458	1.475
	C4≡N5	1.157	1.140	1.154	1.161	1.152	1.161	1.161
	C6–N9	1.475	1.470	1.461	1.462	1.450	1.452	1.463
Gauche 3	C1–C6		1.540	1.541	1.540	1.527	1.526	1.536
	C1–C4		1.460	1.462	1.467	1.453	1.458	1.475
	C4≡N5		1.140	1.153	1.161	1.152	1.160	1.160
	C6–N9		1.460	1.459	1.461	1.447	1.450	1.462
Trans 1	C1–C6		1.560	1.555	1.553	1.538	1.537	1.546
	C1–C4		1.460	1.460	1.466	1.451	1.456	1.474
	C4≡N5		1.140	1.154	1.161	1.152	1.161	1.161
	C6–N9		1.460	1.453	1.455	1.443	1.445	1.458
Trans 2	C1–C6		1.540	1.542	1.541	1.527	1.527	1.537
	C1–C4		1.460	1.460	1.466	1.451	1.456	1.474
	C4≡N5		1.140	1.153	1.161	1.152	1.161	1.161
	C6–N9		1.470	1.462	1.464	1.450	1.453	1.465
TS1	C1–C6			1.574	1.572	1.557	1.572	1.565
	C1–C4			1.459	1.464	1.450	1.464	1.473
	C4≡N5			1.154	1.161	1.153	1.161	1.161
	C6–N9			1.453	1.456	1.442	1.456	1.459
TS2	C1–C6			1.558	1.557	1.543	1.543	1.553
	C1–C4			1.460	1.465	1.451	1.456	1.474
	C4≡N5			1.154	1.161	1.152	1.161	1.161
	C6–N9			1.465	1.467	1.453	1.456	1.467
TS3	C1–C6			1.583	1.581	1.566	1.564	1.573
	C1–C4			1.457	1.463	1.449	1.453	1.472
	C4≡N5			1.154	1.161	1.153	1.161	1.161
	C6–N9			1.450	1.453	1.441	1.444	1.456
TS4	C1–C6			1.562	1.561	1.548	1.546	1.558
	C1–C4			1.461	1.466	1.452	1.457	1.475
	C4≡N5			1.153	1.161	1.152	1.160	1.160
	C6–N9			1.459	1.461	1.447	1.450	1.463
TS5	C1–C6			1.559	1.558	1.543	1.543	1.553
	C1–C4			1.460	1.465	1.451	1.456	1.473
	C4≡N5			1.154	1.161	1.152	1.161	1.161
	C6–N9			1.463	1.466	1.452	1.455	1.467

$$\frac{N_i}{N_{total}} = \frac{e^{-E_i/RT}}{\sum_{k=1}^{M} e^{-E_k/RT}} \qquad (4)$$

The population distribution is approximately (40.1%, 28.1%, 4.6%, 8.5% and 18.7%), respectively.

The Gibb's free energies $\Delta G^{\#}$ of the transition states TS1, TS2, TS3, TS4 and TS5 are 4.92, 4.22, 4.84, 6.29 and 4.77 kcal/mol obtained by CCSD/6-311+G(d,p), respectively, relative to the most stable gauche conformer.

The results reveal that TS4 has a higher energy compared to the other transition states through CCSD/6-311+G(d,p) and all other different levels of theory. TS4 Figure 1C has a higher strain than other transition states due to NH_2 and CN eclipsing configuration. The interaction between the electron rich CN region and the N9

Table 2. Selected angles (°) and dihedral angles (torsion angles) (°) of the optimized gauche, trans and transition states (TS) geometries of 3-aminopropionitrile at the B3LYP, M06, CCSD/6-311+G (d,p), (aug-cc-pVDZ) levels of theory.

Structure		**Angles (°)**		**B3LYP**		**M06**		**CCSD**
		Ref[a]	**Ref[b]**	**6-311+G (d,p)**	**aug-cc-pVDZ**	**6-311+G (d,p)**	**aug-cc-pVDZ**	**6-311+G (d,p)**
Gauche 1	C4–C1–C6	110.5	111.0	112.3	112.2	111.2	111.1	111.5
	C1–C6–N9	114.0±15	114.8	116.7	116.5	115.8	115.8	115.8
	C1–C4≡N5	180.0	178.3	177.9	177.7	177.3	177.0	177.8
	N9–C6–C1–C4	59±3	57.4	60.2	60.0	59.2	58.6	59.0
Gauche 2	C4–C1–C6	110.5	111.3	112.3	112.1	111.2	111.1	111.2
	C1–C6–N9	108.0±15	109.3	110.5	110.4	109.9	109.8	109.8
	C1–C4≡N5	180.0	178.6	178.3	178.2	177.6	177.3	177.9
	N9–C6–C1–C4	63±3	64.2	64.7	64.5	63.4	63.3	62.4
Gauche 3	C4–C1–C6		111.5	111.4	113.4	112.6	112.6	112.4
	C1–C6–N9		109.8	110.9	110.8	110.1	110.1	110.0
	C1–C4≡N5		179.1	178.3	178.3	178.4	178.5	178.2
	N9–C6–C1–C4		61.0	65.1	65.7	63.8	64.3	62.9
Trans 1	C4–C1–C6		112.0	112.5	112.4	112.1	(112.1	111.9
	C1–C6–N9		113.1	115.0	114.9	114.7	114.6	114.6
	C1–C4≡N5		178.7	178.1	178.0	177.9	177.8	178.3
	N9–C6–C–C4		180	180.0	180.0	180.0	180.0	180.0
Trans 2	C4–C–C6		112.0	112.5	112.4	112.2	112.1	111.8
	C1–C6–N9		108.0	109.2	109.1	109.0	108.9	108.9
	C1–C4≡N5		179.1	178.9	178.8	178.6	178.5	178.8
	N9–C6–C1–C4		179.9	179.4	179.4	180.0	179.7	179.9
TS1	C4–C1–C6			113.4	113.3	113.1	113.3	112.6
	C1–C6–N9			116.5	116.4	116.3	116.4	116.0
	C1–C4≡N5			178.4	178.2	178.3	178.2	178.7
	N9–C6–C1–C4			121.1	121.3	121.0	121.3	120.7
TS2	C4–C1–C6			113.6	113.5	113.3	113.2	112.8
	C1–C6–N9			110.2	(110.0	110.0	109.9	109.6
	C1–C4≡N5			179.1	179.0	178.9	178.7	179.1
	N9–C6–C1–C4			123.0	123.2	122.9	123.3	122.2
TS3	C4–C1–C6			113.7	113.6	113.2	113.0	113.0
	C1–C6–N9			118.7	118.5	118.3	118.1	118.2
	C1–C4≡N5			178.8	178.6	178.5	178.0	178.9
	N9–C6–C1–C4			0.0	0.0	0.0	0.0	0.0
TS4	C4–C1–C6			115.1	115.1	114.7	114.6	114.4
	C1–C6–N9			112.7	112.5	112.3	112.1	112.4
	C1–C4≡N5			177.2	177.2	177.4	177.5	177.3
	N9–C6–C1–C4			2.5	2.9	2.8	3.4	2.4
TS5	C4–C1–C6			113.4	113.3	113.1	113.1	112.7
	C1–C6–N9			110.6	110.3	110.3	110.2	109.9
	C1–C4≡N5			179.0	178.9	178.9	(178.7	179.1
	N9–C6–C1–C4			115.9	116.6	116.3	116.8	116.1

[a] Experimental value of gauche conformers are taken from reference [23] [b] Theoretical value of minima conformers are taken from reference [22]

lone-pair is clearly present in TS4, which is inferred by the high energy value. This interaction appears weaker in other transition states. Through all different levels of theory, except M06/aug-cc-pVDZ. TS2 has the lowest strain among all the transition states, indicated by the lower energy value (4.22 kcal/mol). The energies of the transition states are considered to be the energy barriers between gauche and trans conformers or the energy of the rotation around the N9-C6-C1-C4 dihedral angle.

According to more stable gauche conformer through CCSD/6-311+G(d,p), the rate constants *k,* of each rotational step, are ~1.5×10^9 s^{-1}, 5×10^9 s^{-1}, 2×10^9 s^{-1}, 1.5×10^8 s^{-1} and 2×10^9 s^{-1} calculated by using $\Delta G^\#_{TS1}$, $\Delta G^\#_{TS2}$, $\Delta G^\#_{TS3}$, $\Delta G^\#_{TS4}$ and $\Delta G^\#_{TS5}$ respectively, in following equation.[29]

$$k(T) = \frac{k_B T}{hc^{\circ}} e^{-\frac{\Delta G^{\#}}{RT}} \quad (5) \tag{5}$$

Where the temperature is T=298.15 K and the concentration is c° = 1. The Boltzmann, Planck, and universal gas constants are denoted as kB, h, and R, respectively. The calculated rate constants indicate that at room temperature, the rotation around the dihedral angle occurs quite quickly.

The point charges of each atom have been determined using the NBO analysis by the CCSD/6-311+G(d,p) level of theory, Figure 2, to look more closely at the cause of the stabilization energy of the gauche 1 and gauche 2 conformers. The contact between the CN group and the eclipsed hydrogen (H10 atom in gauche 1) and (H11 atom in gauche 2) is attractive and has a value of 0.26 and 0.23 kcal/mol, respectively, according to Coulomb's potential in equation (3). This is taken to be the SE of the two gauche conformers' stabilization energy. These findings support the preceding relative energies discovery by demonstrating that the gauche 2 is somewhat more stable than the gauche 1. This is assumed to be the stabilization energy SE of the gauche 2 conformer.

Additionally, the electrostatic potential ESP contours in Figure 3 also depict the alluring contact between the nitrile group on the one hand, and the H10 atom in conformer 1, and the H11 atom in conformer 2. Due to the absence of appealing interactions between functional groups, the SE is missing in gauche 3 and trans conformers.

Additionally, the electrostatic potential ESP contours in Figure 3 demonstrate the attractive interaction between the nitrile group and the H10 (gauche 1) and H11 (gauche 2) atoms. The other conformers lack the SE because there are no alluring interactions between functional units. With

Table 3. The relative energies of each conformer compared with conformer (gauche 2).

Geometry	Method	Basis set	ΔH^a_{rel}	ΔG^a_{rel}	Geometry	Method	Basis set	ΔH^a_{rel}	ΔG^a_{rel}
Gauche 1	CCSD	6-311+G(d,p)	0.19	0.21	TS2[b]	CCSD	6-311+G(d,p)	3.7	4.22
	M06	6-311+G(d,p)	−0.07	−0.16		M06	6-311+G(d,p)	3.71	4.18
		aug-cc-pVDZ	0.07	0.02			aug-cc-pVDZ	3.62	4.08
	B3LYP	6-311+G(d,p)	−0.12	−0.1		B3LYP	6-311+G(d,p)	3.16	3.65
		aug-cc-pVDZ	0	−0.01			aug-cc-pVDZ	3.15	3.66
Gauche 3	CCSD	6-311+G (d,p)	1.35	1.28	TS3[b]	CCSD	6-311+G(d,p)	4.39	4.84
	M06	6-311+G (d,p)	1.38	1.27		M06	6-311+G(d,p)	3.74	4.14
		aug-cc-pVDZ	1.49	1.37			aug-cc-pVDZ	3.57	3.99
	B3LYP	6-311+G (d,p)	1.32	1.22		B3LYP	6-311+G(d,p)	3.66	4.13
		aug-cc-pVDZ	1.33	1.23			aug-cc-pVDZ	3.71	4.17
Trans 1	CCSD	6-311+G(d,p)	0.97	0.92	TS4[b]	CCSD	6-311+G(d,p)	5.87	6.29
	M06	6-311+G (d,p)	1.07	1.02		M06	6-311+G(d,p)	5.5	5.92
		aug-cc-pVDZ	1.01	0.9			aug-cc-pVDZ	5.29	5.76
	B3LYP	6-311+G(d,p)	0.4	0.39		B3LYP	6-311+G(d,p)	5.48	5.91
		aug-cc-pVDZ	0.46	0.44			aug-cc-pVDZ	5.35	5.79
Trans 2	CCSD	6-311+G(d,p)	0.65	0.45	TS5[b]	CCSD	6-311+G(d,p)	4.32	4.77
	M06	6-311+G(d,p)	0.68	0.61		M06	6-311+G(d,p)	4.22	4.58
		aug-cc-pVDZ	0.7	0.61			aug-cc-pVDZ	4.15	4.55
	B3LYP	6-311+G(d,p)	0.23	0.18		B3LYP	6-311+G(d,p)	3.7	4.13
		aug-cc-pVDZ	0.25	0.2			aug-cc-pVDZ	3.63	4.08
TS1[b]	CCSD	6-311+G(d,p)	4.42	4.92					
	M06	6-311+G(d,p)	4.14	4.61					
		aug-cc-pVDZ	4.16	4.66					
	B3LYP	6-311+G(d,p)	3.47	4.01					
		aug-cc-pVDZ	3.5	4.03					

[a] All energies are in kcal/mol. [b] $\Delta H_{rel} \equiv \Delta H^{\#}$ and $\Delta G_{rel} \equiv \Delta G^{\#}$ for transition state.

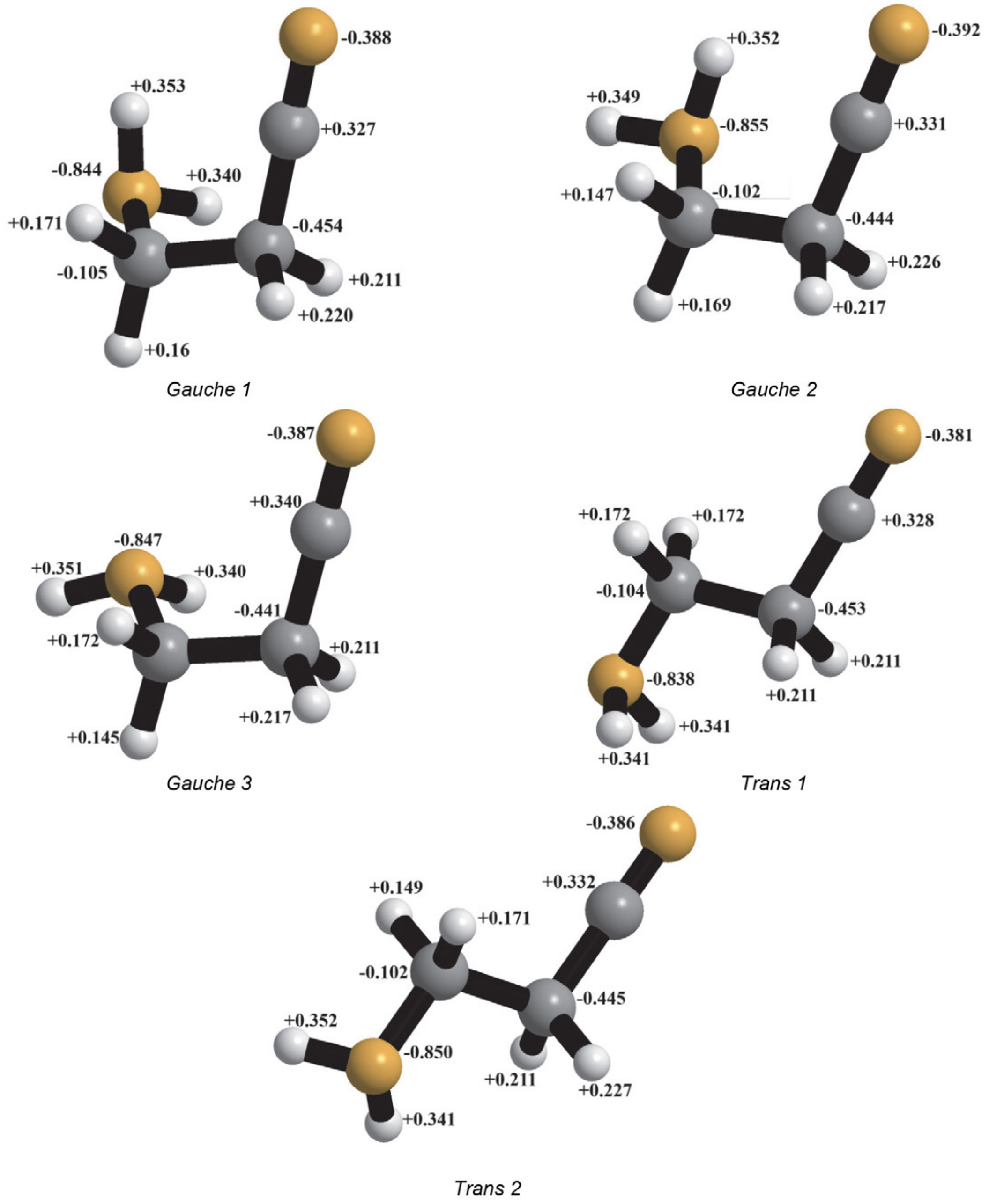

Figure 2. The NBO analysis of atomic charge distributions of the gauche and the trans 3-aminopropionitrile conformers using CCSD/6-311+G(d,p) method.

the help of the CCSD/6-311+G(d,p) method, the SE of gauche 2 was calculated as follows: SE = H_{rel} + ZPE + H_{corr} = 0.12 kcal/mol. This also took into account the addition of the difference between the zero-point energy and the thermal enthalpy correction. This number and the one determined using Coulomb's potential agree rather well.

3. 3. Vibrational Analysis

To show the 3-aminopropionitrile's conformational dynamics at ambient temperature, five minima conformers' vibrational frequencies were calculated using the high accuracy *ab initio* method CCSD with 6-311+G(d,p) basis sets,[30,31] since CCSD demonstrated greater accuracy in the prediction of the geometrical parameters, it is used as the primary computational method in this vibrational analysis. In Table 4, the calculated (CCSD/6-311+G(d,p)) vibrational modes wavenumbers for the five minima conformers (Fig. 2(and an assignment of the observed bands are also presented. The main experimental infrared intensities are also presented. The computed frequencies of more stable conformer are uniformly scaled by 0.934 for a better

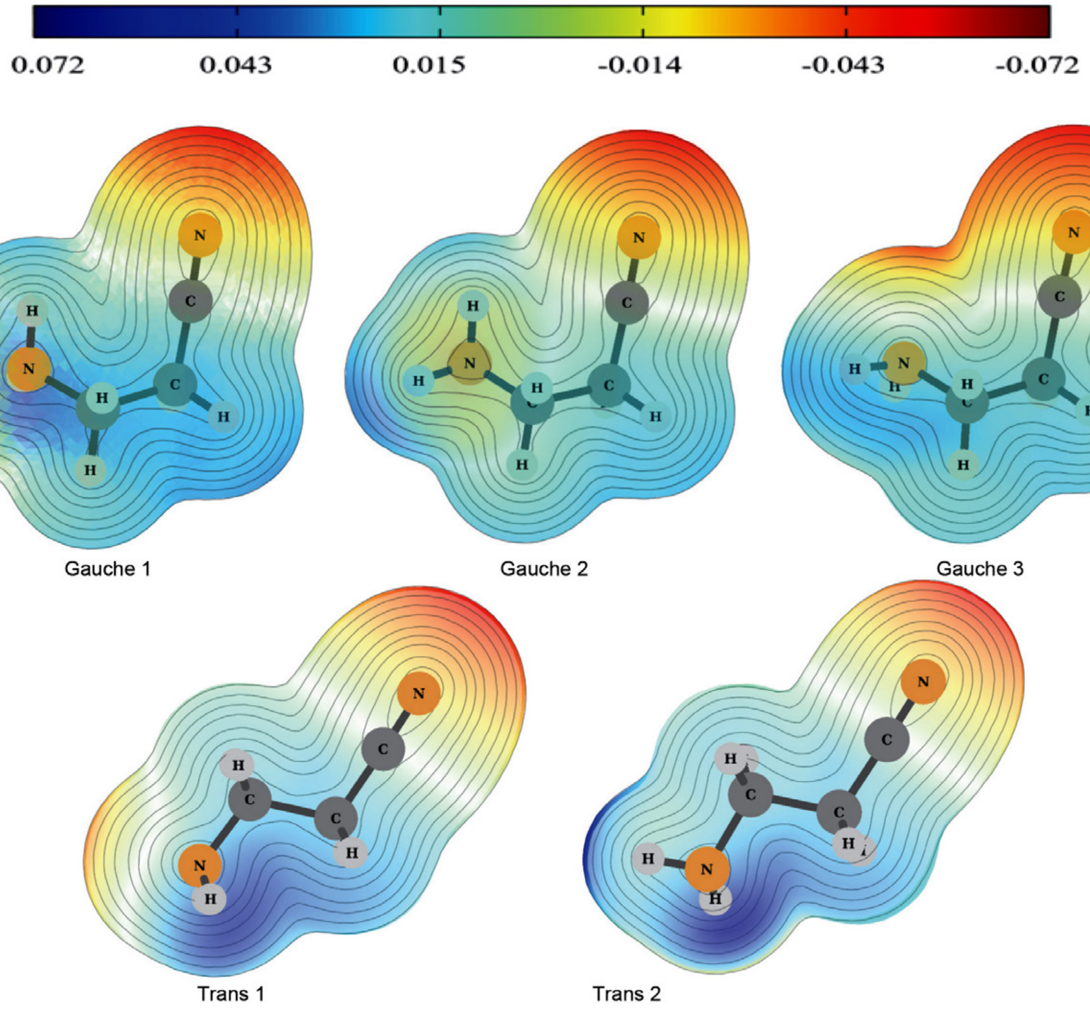

Figure 3. The NBO analysis of the electrostatic potential (ESP) of the gauche and the trans 3-aminopropionitrile conformers using CCSD/6-311+G(d,p) method.

comparison of the calculated frequencies with the observed frequencies.[32]

3-aminopropionitrile molecule has 11 atoms which create 27 internal normal vibrational modes. It has been clearly shown in various earlier research on organic-inorganic and hydrogen-bonded materials that the NH_3 torsion mode is extremely sensitive to changes in hydrogen bonds and conformational states.[33–35] Several conclusions from this study about the NH_3 vibrational modes are important to note: The bands that appear at 1603 cm^{-1} are thought to be the result of the NH_3 groups deforming symmetrically. This vibrational mode occurs at 1572, 1569, and 1565 cm^{-1} for the gauche 1, gauche 2, and gauche 3, respectively, according to the CCSD/6-311+G(d,p) calculations. Modes at 3317 and 3380 cm^{-1} described as symmetric and anti-symmetric deformation modes of the NH_3 groups, respectively. This modes are observed at (3304, 3302, and 3307 cm^{-1}) and (3384, 3382 and 3389 cm^{-1}) for the gauche 1, gauche 2, and gauche 3, respectively, according to this study. The NH_3 rocking and NH_3 twisting modes are at 856 cm^{-1} and 1313cm^{-1} respectively. These modes are observed at 830, 839, and 851 cm^{-1} and 1281, 1273, and 1257 cm^{-1} for the gauche 1, gauche 2, and gauche 3, respectively, according to my CCSD/6-311+G(d,p) calculations.

The more appropriate vibrations of the three conformers with respect to experimental vibrations are that of the conformer 1 as we can see from the difference between the scaled vibrations by CCSD/6-311+G(d,p) and the experimental vibrations (Table 4). Vibrational modes of NH_2 anti-symmetric stretch, α–CH_2 symmetric stretch, deformation, rocking, twisting and wagging, β–CH_2 anti-symmetric stretch, symmetric stretch and wagging, C–N stretch, C–C–C, C –C –N bending and C–C≡N out-of-plane bending of gauche 2 are closer to the experimental vibrations than others conformers.

3. 4. Frontier Molecular Orbitals

The frontier molecular orbitals (FMOs) of the highest occupied molecular orbital (HOMO) and lowest unoc-

Table 4: Calculated vibrational frequencies (cm^{-1}) at the CCSD/6-311+G(d,p) levels of theory.

	Vibration (cm^{-1})/ 6-311+G(d,p)								Vibration (cm^{-1})
Approximate description	**Gau 1**	**Scaled^a**	**Gau 2**	**Scaled^a**	**Gau 3**	**Scaled^a**	**Trans 1**	**Trans 2**	**Experimental^b**
NH_2 anti-symmetric stretch	3623	3384	3621	3382	3629	3389	3625	3623	3380
NH_2 symmetric stretch	3537	3304	3536	3302	3541	3307	3537	3537	3317
β–CH_2 anti-symmetric stretch	3131	2924	3142	2935	3127	2921	3138	3140	2994
α–CH_2 anti-symmetric stretch	3118	2912	3109	2904	3110	2905	3114	3112	2967
β–CH_2 symmetric stretch	3078	2875	3088	2884	3078	2875	3084	3083	2937
α–CH_2 symmetric stretch	3073	2870	3022	2822	3018	2819	3074	3030	2840
C≡N stretch	2338	2184	2338	2184	2344	2189	2338	2341	2244
NH_2 deformation	1683	1572	1680	1569	1676	1565	1682	1679	1603
α–CH_2 deformation	1513	1413	1535	1434	1534	1433	1519	1539	1474
β–CH_2 deformation	1494	1395	1489	1391	1494	1395	1496	1500	1423
α–CH_2 rock	1418	1324	1454	1358	1452	1356	1430	1461	1386
β–CH_2 rock	1415	1322	1383	1291	1399	1307	1411	1371	1334
NH_2 twist	1372	1281	1363	1273	1346	1257	1329	1343	1313
β–CH_2 twist	1274	1190	1259	1176	1299	1213	1322	1290	1216
α–CH_2 twist	1191	1112	1195	1116	1184	1106	1174	1185	1155
C–C(–N) stretch	1142	1067	1134	1059	1130	1055	1134	1125	1085
C–N stretch	1040	971	1093	1021	1046	977	1054	1089	1044
C–C(≡ N) stretch	977	913	986	921	1001	935	989	1004	973
NH_2 rock	889	830	898	839	911	851	956	948	856
β–CH_2 wag	868	811	876	819	869	812	856	883	850
α–wag	809	756	829	774	819	765	770	793	801
C–C–C bend	574	536	574	536	574	536	519	527	572
C–C–N bend	386	361	401	374	383	358	378	390	419
C–C≡N out-of-plane bend	372	347	371	347	368	344	376	372	375
NH_2 torsion	312	291	268	250	248	232	287	229	–
C–C≡N in-plane bend	190	177	195	182	178	166	164	166	–
C≡C(N) torsion	118	110	118	110	122	114	107	105	–

[a] Scaling coefficient =0.934.[32] [b] Observed vibrations.[15]

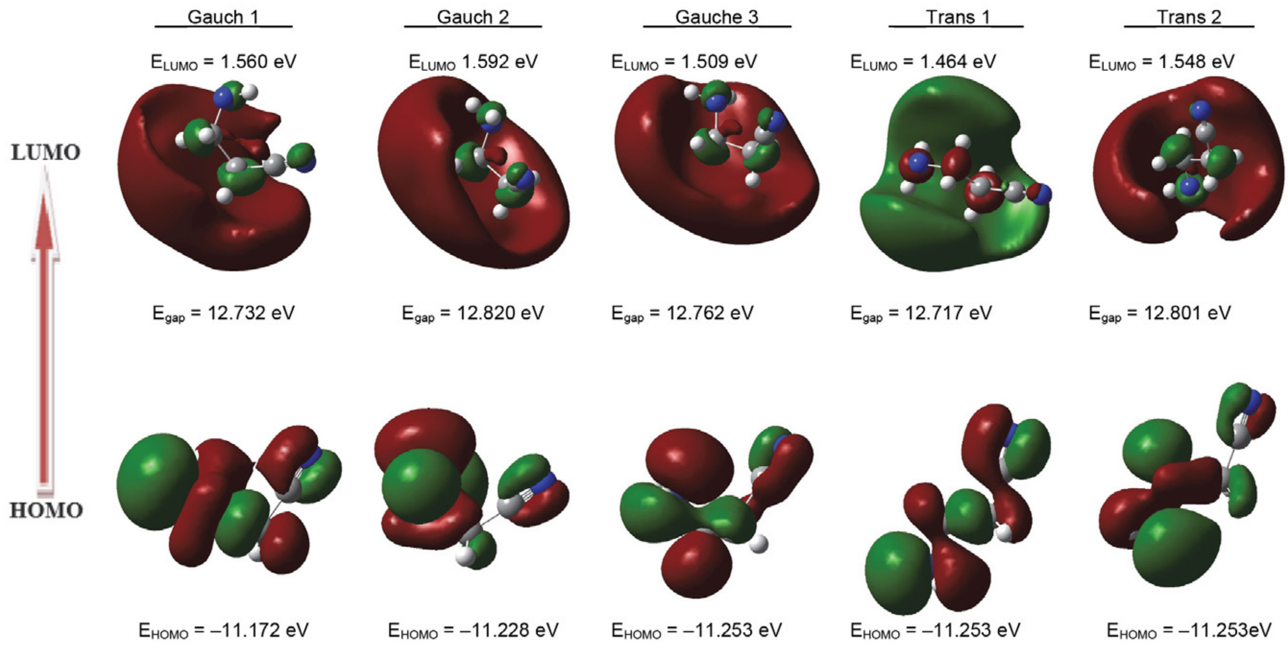

Fig. 4 Frontier molecular orbital of gauche 1, gauche 2, gauche 3, trans 1 and trans 2 conformers.

cupied molecular orbital (LUMO) of chemical species (using CCSD/6-311+G(d,p)) are essential pointers for chemical reactivity together with the stability of conformers (Figure 4). The results revealed that the gauche 2 conformer showed higher energy gap ($E_{LUMO} - E_{HOMO} = 1.592$ eV – (– 11.228 eV), $E_{gap} = 12.820$ eV. This implies superior stability and lower chemical reactivity compared to its other conformers. The chemical potential (μ) = 0.5 * ($E_{LUMO} + E_{HOMO}$); showed negative values for the gauche 1, gauche 2, gauche 3, trans 1 and trans 2: −4.806, −4.818, −4.872, −4.895 and −4.853 eV conformers, respectively.

The phases of the lobes are indicated by the red and green colors. The molecular orbital wave function's positive and negative signs are represented by the colors red and green, respectively. Although there is a minor similarity in the frontier molecular orbitals of the gauche conformers and trans conformers individually, their HOMO and LUMO spatial positions are different. Using HOMO and LUMO orbital energies, the hardness $\eta = 0.5^*(E_{LUMO}-E_{HOMO})$ is as follows; gauche 1, gauche 2, gauche 3, trans 1 and trans 2: 6.366, 6.41, 6.381, 6.3585 and 6.4005 eV, respectively. The softness $S = 1/\eta$; gauche 1, gauche 2, gauche 3, trans 1 and trans 2: 0.1571, 0.1560, 0.1567, 0.1573 and 0.1562 eV, respectively. Chemical hardness is a good indicator of probable chemical stability. A smaller energy gap results in a molecule with a higher softness value. Global electrophilicity index $\omega = \mu^2/2\eta$ for gauche 2 is less electrophilic than another conformers with the lowest electrophilicity index of 1.811eV. High softness and low hardness values from the result's electrophilicity index are predictors of a good electrophile.

4. Conclusion

The geometry and relative stability of the 3-aminopropionitrile have been calculated theoretically using *ab initio* (CCSD/6-311+G(d,p)) and DFT (B3LYP and M06 functionals at 6-311+G(d,p) and aug-cc-pVDZ basis sets. The results show that 3-aminopropionitrile has five conformers, three gauche and two trans conformers. The geometrical outcomes of the gauche conformer agree very well with the experimental microwave and infrared results. Also, the thermal properties of the five conformers have been studied in the gas phase. Gauche 2 is the most stable conformer, according to recent study results, which agree with the accumulated experimental results. The results of the geometrical optimizations also closely match previous results that have been described in the literature. The vibrational modes of the five conformers were then computed and compared to past experimental results published in the literature, and the obtained results are in good agreement with the reported data with and without using scaling factor. As HOMO–LUMO gap implies high stability for a molecule, gauche 2 has a high HOMO-LUMO gap (12.820 eV), implies high stability for gauche 2 in the sense of its lower reactivity in chemical reactions. The positive potential sites are found close to the hydrogen atoms, while the negative potential sites are on the nitrile group, according to the ESP map.

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Declaration of Interest Statement

I declare that I do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

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Povzetek

Poznanih je veliko konformer 3-aminopropionitrila. Zaradi biomedicinske pomembnosti smo obširno preiskali strukturne, vibracijske in druge lastnosti možnih konformer. Geometrijske strukture, relativna stabilnost in vibracijske frekvence konformer 3-aminopropionitrila v gauche in trans obliki smo preučili z *ab initio* računi (CCSD/6-311+G(d,p)) in DFT (B3LYP in M06 ter bazna seta 6-311+G(d,p) in aug-cc-pVDZ). Interpretacija predstavlja znatno izboljšanje preteklih študij. Izračun CCSD/6-311+G(d,p) pokaže, da je gauche 2 konformera za 0,19 kcal/mol bolj stabilna od gauche 1 (izraženo v razliki entalpij med konformerama). Analiza verjetnostne porazdelitve kaže, da so v plinski fazi gauche konformere pogostejše kot trans konformere (72,8 % delež) pri čemer je gauche 2 prevladujoča gauche konformera (40,1 % delež). Ti rezultati se dobro ujemajo s prejšnjimi eksperimentalnimi in računskimi študijami. Proučili smo tudi geometrijske značilnosti vseh optimiziranih konformer, ki se zelo dobro ujemajo z prejšnjimi eksperimentalnimi rezultati. Zvezo med strukturo in aktivnostjo smo opisali z izračunom ploskve elektrostatskega potenciala. Analizirali smo tudi atomske naboje ter energijsko vrzel med najvišjo zasedeno in najnižjo nezasedeno molekulsko orbitalo (HOMO-LUMO vrzel). Elektronsko strukturo najbolj stabilnih konformer smo analizirali z metodo naravnih veznih orbital (NBO).