

UDC 547 + 544.18

STUDY OF THE PROTONATION OF 1, 2, 4-TRIAZOLE. DFT CALCULATIONSAbdelahad El Addali^{1*}, Zakaryae El-Kiri^{2**}, Abdellah El Boukili¹, Hamid Saufi¹, Lahcen Boudad³¹*Ibn Tofail University, Laboratory of Advanced Material, Engineering Process, Department of Chemistry, Faculty of Sciences in Kenitra, Morocco*²*Mohammed V University in Rabat, Centre Sciences des Matériaux, Laboratoire de Physico-Chimie des Matériaux Inorganiques et Organiques (LPCMIO), Ecole Normale Supérieure (E.N.S.), Rabat, Morocco*³*Engineering Laboratory of Organometallic, Molecular Materials, Environment, and Innovative Pedagogy. Faculty of Science, Sidi Mohamed Ben Abdellah University, 3000, Fez. Morocco.*

Received 24 March 2024; accepted 9 October 2024; available online 25 January 2025

Abstract

In this work, we study the reaction of 1,2,4-triazole with hydrochloric acid (HCl), leading to the formation of the protonated triazole (TAH⁺). We utilize density functional theory (DFT) calculations to gain insights into the structural analysis of optimized molecules for both neutral and protonated 1,2,4-triazole. Various reactivity descriptors, such as electron affinity, HOMO-LUMO energy gap, dipole moment, and Fukui indices, are analyzed for these compounds to identify nucleophilic regions where interactions with HCl may occur. Additionally, we examine their infrared (IR) and Raman spectra to highlight hydrogen bonding. The IR and Raman spectra of both neutral and protonated 1,2,4-triazole are specifically analyzed at the N2 and N4 sites. The objective is to determine the preferred site of protonation, particularly at nitrogen N4.

Keywords: DFT; electron affinity; HOMO-LUMO energy gap; Fukui indices; nucleophilic.

ДОСЛІДЖЕННЯ ПРОТОНУВАННЯ 1,2,4-ТРИАЗОЛУ. DFT-РОЗРАХУНКИАбделахад Ель-Аддалі¹, Захарія Ель-Кірі², Абделлах Ель-Букілі², Хамід Сауфі², Лахсен Будад²¹*Університет ім. Ібн Тофайла в Кенітрі, Лабораторія органічної хімії, каталізу та навколишнього середовища (LOCCE), факультет природничих наук, Кенітра, Марокко*²*Університет Мохаммеда V в Рабаті, Центр наук про матеріали, Лабораторія фізико-хімії неорганічних і органічних матеріалів (LPCMIO), Вища нормальна школа (E.N.S.), Рабат, Марокко*³*Університет Тофайль, Лабораторія передових матеріалів, інженерних процесів, хімічний факультет, факультет природничих наук в Кенітрі, Марокко***Анотація**

У цій роботі досліджена реакція між 1,2,4-тріазолом і хлоридною кислотою (HCl) з метою синтезу протонованого 1,2,4-тріазолу (TAH⁺). Ми використовували розрахунки теорії функціоналу густини (DFT), щоб отримати уявлення про структурний аналіз молекули. Кілька дескрипторів реакційної здатності, включаючи спорідненість до електрона, різниця енергій HOMO-LUMO, дипольний момент та індекси Фукуї проаналізовані з метою визначення нуклеофільних ділянок, де найімовірніше відбуваються взаємодії з HCl. Крім того, спрогнозовані ІЧ- та КР-спектри для вивчення водневого зв'язку, проаналізовані ІЧ- та КР-спектри як нейтральних, так і протонуваних 1,2,4-тріазолів по N2 та N4-місцях. Нашою метою було визначення найімовірнішого місця протонування, зокрема за атомом азоту N4.

Ключові слова: DFT; електронна спорідненість; різниця енергій HOMO-LUMO; індекси Фукуї; нуклеофільність.

*Corresponding author: e-mail: hioaddali@gmail.com

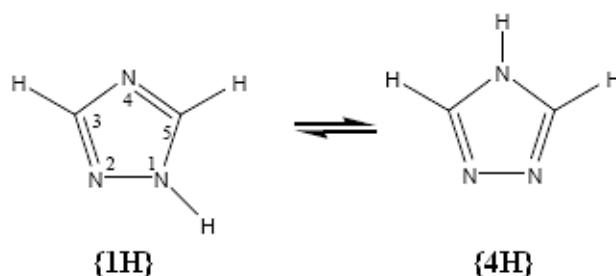
© 2024 Oles Honchar Dnipro National University;

doi: 10.15421/jchemtech.v32i4.300540

Introduction

1, 2, 4-triazole exists in a solid form and is soluble in polar solvents, while being slightly soluble in nonpolar solvents. It is also flammable and can emit irritating or toxic smoke or gas in case of a fire. The finely dispersed particles of this compound can create explosive mixtures in the air. It is a five-membered, π -excessive, aromatic nitrogen heterocycle, composed of two carbon and three nitrogen atoms arranged at the 1-, 2-, and 4-

positions of the ring. All atoms in the structure of 1, 2, 4-triazole are indeed sp^2 hybridized, and it possesses aromatic character due to the delocalization of 6π electrons over the ring. Furthermore, 1, 2, 4-triazole exhibits tautomerism, existing in two tautomeric forms: 1H-1, 2, 4-triazole and 4H-1, 2, 4-triazole. These forms involve the reversible migration of a hydrogen atom and a double bond within the ring structure,



The parent 1H-1, 2, 4-triazole has been prepared by the reaction of hydrazine obtained in situ from the hydrolysis of 1,2-di (butan-2-ylidene)hydrazine with formamide at 170 °C.

The 1, 2, 4-triazole (TA) and its derivatives are among the azoles that have received considerable attention due to their applications in various fields. In medicine, they exhibit a broad spectrum of activities, including analgesic [1], anti-inflammatory [2; 3], antidepressant [4], anticancer [5-9], antimicrobial [5; 10-13], and antibacterial [11-16] properties.

In the industry, examples of their use include improving the stability and heat resistance of macromolecular materials [17], acting as corrosion inhibitors for metals and alloys [18-20], and also in the field of chemical engineering for the construction of superconductive compounds [21; 22]. Applications in agriculture are known for these systems. Several triazoles are used as herbicides [23], insecticides [24], bactericides [25], fungicides [24; 26; 27], or plant growth regulators [27; 28].

In this paper, we have conducted a theoretical study on the reaction between 1,2,4-triazole and hydrochloric acid (HCl) $TA + H^+ \rightarrow TAH^+$.

With: TA and TAH^+ represent respectively the 1,2,4 triazole and the protonated 1,2,4-triazole.

Using the Density Functional Theory (DFT) calculation method, employing the B3LYP function in conjunction with the 6-311G basis set [29-31]. Our investigation involved the optimization of both neutral and protonated forms of 1,2,4-triazole, and included structural analysis as well as the computation of various global reactivity indices. These indices encompass HOMO-LUMO energy gaps

and dipole moments. Additionally, we employed Fukui indices to identify the electrophilic sites most favorable for proton attack, namely N2 or N4.

Subsequently, a mechanistic study was carried out to explore the protonation of the neutral molecule. We identified this process using Infrared (IR) and Raman spectra of 1,2,4-triazole in both its neutral and protonated forms.

Computational details

This research employed GAUSSIAN 09 W to determine the chemical and thermodynamic properties of 1,2,4-triazole in its neutral form when exposed to HCl acid. Density Functional Theory (DFT) calculations were performed using the Becke-Lee-Yang-Parr three-parameter hybrid functional (B3LYP) in conjunction with the 6-311G basis set (The combination of B3LYP and the 6-311G basis set offers a good balance between accuracy and cost, making this pairing popular for studies in quantum chemistry, particularly for applications in organic chemistry) [32; 33]. We conducted an investigation into the lengths and angles of 1,2,4-triazole in its neutral state, which yielded data on frontier molecular orbitals such as the energy of the highest occupied molecular orbital (EHOMO) and the energy of the lowest unoccupied molecular orbital (ELUMO). as well as the IR and RAMAN spectra of the 1,2,4-triazole in both its neutral and protonated states to analyze hydrogen bonding at the sites N2 and N4. The energy gap is calculated from HOMO and LUMO, and electron affinity (EA) is calculated from the energy of HOMO.

Results and discussion

Structural analysis

The geometry-optimization of the 1,2,4-triazole neutral and protonated molecule illustrated in Figure 1.

The optimization process was carried out using monomer wave functions at the B3LYP/6-311G

level. The optimization procedure involved visual observations and sets approximation in the GAUSSIAN 09 W software. The resulting structural parameters are presented in Table 1.

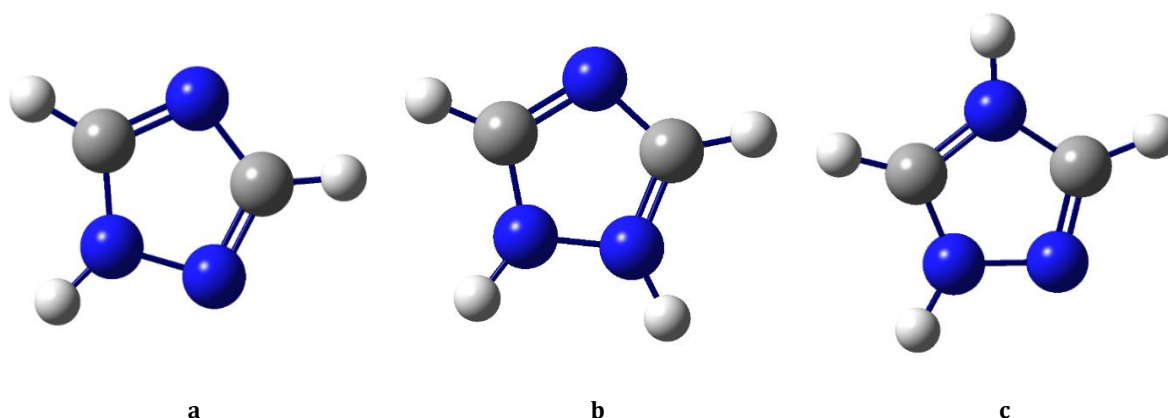


Fig. 1. Geometry optimized of: a - 1,2,4-triazole, b- 1,2,4-triazole H⁺(N2), c- 1,2,4-triazole H⁺(N4)

In Table 1, the values of interatomic distances and angles for the studied molecules are reported.

Table 1

Calculated Geometric Parameters (bond lengths in Ångströms, valence angles, and dihedral angles in degrees)

Structural parameters	{1H}	{1H}	{1H}
	1,2,4-triazole A	1,2,4-triazole H ⁺ (N2) B	1,2,4-triazole H ⁺ (N4) C
N1-N2	1.387	1.374	1.391
N1-C5	1.360	1.350	1.331
N2-C3	1.338	1.350	1.319
C3-H	1.071	1.074	1.073
C5-H	1.073	1.074	1.075
H-N2		1.011	
H-N1	1.002	1.011	1.008
C3-N4	1.382	1.347	1.387
N4-C5	1.335	1.347	1.349
H-N4			1.010
N1N2C3	101.84	106.68	103.76
N2C3N4	114.61	110.43	110.42
C3N4C5	103.67	105.77	107.88
N4C5N1	109.46	110.43	105.57
HN1N2	119.31	122.35	118.86
HN1C5	130.28	130.97	128.76
HN2C3		130.98	
HN4C3			126.33
HN4C5			125.79
HN1C5H	0.01	0.02	0.01
HC3N2N1	179.98	179.97	179.96
HN4C3H			0.10
HN4C5H			0.01
HN1N2H		0.03	
HN2C3H		0.00	

The values of the dihedral angles obtained for the atoms forming the cycle confirm that the 1.2.4 triazole neutral and protonated molecule is planar. The HN1N2 angle is approximately 120° in all three structures. Within the cycle, the angles have decreased due to the presence of three nitrogen atoms. This is the case for the N2C3N4 angle, which measures 114.61°, and the N4C5N1 angle, which is even smaller (109.46°).

An analysis of the distances indicates that the H-N2 bond length is equal to that of H-N4. Furthermore, the length of the N-N bond is slightly shorter than what is reported in the literature. Protonation of the 1,2,4-triazole on the N2 and N4 atoms did not lead to a significant alteration in the original geometry.

Study of global reactivity

The energies were calculated in the gas phase using DFT/B3LYP 6-311G and are presented in Table 2. The calculations showed that protonation is a highly exothermic reaction.

Table 2

Energy and dipole moment					
Species	Energy (ua)	E_{HOMO} (eV)	E_{LUMO} (eV)	ΔE (eV)	μ (Debye)
{1H} Triazol	-242.21581	-7.62362	-0.47981	7,14381	3.0247
{1H} Triazol H ⁺ (N2)	-242.55300	-13.74715	-7.37773	6.36942	4.9717
{1H} Triazol H ⁺ (N4)	-242.57496	-14.28680	-6.89194	7.39486	3.9315

The examination of the table 2 above reveals that the values associated with the dipole moment of protonated molecules are higher. This observation helps explain the greater polarization compared to the case of the neutral molecule. It can also be demonstrated that both protonated systems on N2 and N4 are energetically favorable.

The structure minimization (most stable/lowest energy), HOMO and LUMO distributions are depicted in Figure 2.

As analyzed in this figure, the total distribution of HOMO/LUMO is almost entirely occupied by 1,2,4-triazole structure. This signals the presence of various major active electron donor/acceptor sites. Therefore, this shows high molecular chemical reactivity with the H⁺ proton.

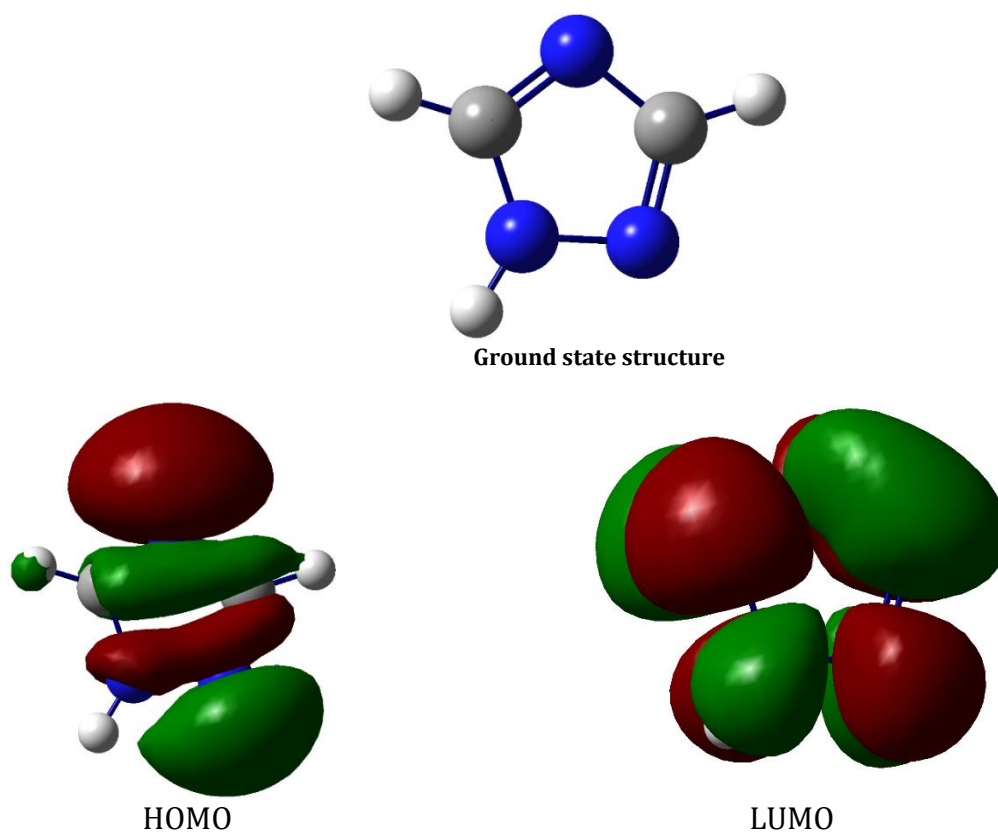


Fig. 2 :3-D plots of optimized geometry, HOMO and LUMO for the 1,2,4 triazole neuter

The HOMO energy level, which represents nucleophilicity, indicates the ability of the 1,2,4-triazole neutral molecule to donate electrons to the LUMO (an acceptor with an unoccupied 1s orbital for an H⁺ proton). This explains the attack on this proton through the delocalized free electron pairs in the N2 and N4 atoms. The LUMO

energy level, representing electrophilicity, reflects its capacity to accept electrons from the HOMO, signifying the electron-receiving tendency of a 1,2,4-triazole neutral molecule. This demonstrates the proton's greater ability to accept electrons, leading to enhanced reactivity efficiency [34]. Therefore, by increasing the HOMO energy level

and decreasing the LUMO energy level, the binding ability of 1,2,4-triazole to the proton increases. However, The figure X shows that the distribution of the highest occupied molecular orbitals (HOMO) and lowest unoccupied molecular orbitals (LUMO) is heterogeneous throughout the molecule, highlighting regions of increased reactivity. The HOMO orbitals are primarily concentrated around the nitrogen atoms N2 and N4, where the electron density is particularly high. This localization is reinforced by the presence of non-bonding pairs and multiple bonds, which enhance the nucleophilic potential of these atoms. According to Fukui's work (1982) on the role of frontier orbitals in chemical reactivity, sites with high HOMO density are especially prone to interactions with electrophiles such as protons (H^+). Furthermore, Parr and Yang's research (1989) on density functional theory (DFT) confirms that electron-rich heteroatoms, such as nitrogen atoms, exhibit an increased affinity for protonation in acid-base reactions. These findings support the idea that the localized reactivity around N2 and N4 arises directly from these electronic and structural characteristics, explaining their crucial role in chemical reactivity processes [35]

That protonation via N4 is favored and is slightly more exothermic. The electron affinity (EA), denoting the released energy due to the capture of an electron, has been estimated using the following relation: $EA = -ELUMO$

($EA(N4) > EA(N2)$). On the other hand, one can also note that the values associated with the dipole moment of protonated molecules are higher, and this helps explain a greater polarization compared to the case of the neutral molecule. The Triazole H^+ (N4) has a maximum energy gap of 7.39486 eV, contributing to superior stability compared to Triazole H^+ (N2).

Natural Bond Orbital (NBO) Analysis

The calculations were performed on 1,2,4-triazole, as shown in Fig 1, to evaluate the NBO charges on each atom. We attempted to determine

the likely sites for proton attacks, aiming to identify the atom(s) carrying the most negative charge, which would provide a clue about the proton's approach direction. The molecule contains three nitrogen atoms. The lone electron pair of one of them contributes to the aromaticity of the ring and is more likely to be atom N1. The other two, N2 and N4, represent two probable protonation sites [36].

In this current application, we used the quantum method of density functional theory (DFT) B3LYP/6-311G to determine the optimization of the previous molecule, using local reactivity indices (Fukui indices). We will now elucidate how this process enables the integration of a proton.

The Fukui function f_K , corresponding to site K of a molecule in its condensed form of Fukui functions in a molecule with N electrons, was proposed by Yang and Mortier. [37].

- The Fukui index f_K^+ : Measures the susceptibility of an electronic site to act as an electron donor, and electronic sites with high positive Fukui indices have a greater likelihood of reacting with electron acceptors, such as empty sites or electrophiles. It is defined by the equation:

$$f_K^+ = [q_K(N + 1) - q_K(N)],$$

- the Fukui index f_K^- : The receptivity of an electronic site to receive electrons is expressed by its Fukui index. Electronic sites with high negative Fukui indices are more likely to interact with electron donors, such as nucleophiles. It is defined by the equation:

$$f_K^- = [q_K(N) - q_K(N - 1)],$$

$q_K(N)$: "Electron population of the K atom in the neutral molecule".

$q_K(N + 1)$: "Electronic population of the K atom in the anionic molecule".

$q_K(N - 1)$: "Electronic population of atom K in the cationic molecule."

The values of f_K^+ and f_K^- of the nitrogen atoms N2 and N4 confirm this. See Table 3.

Table 3

Values of the Fukui indices of 1.2.4 triazole

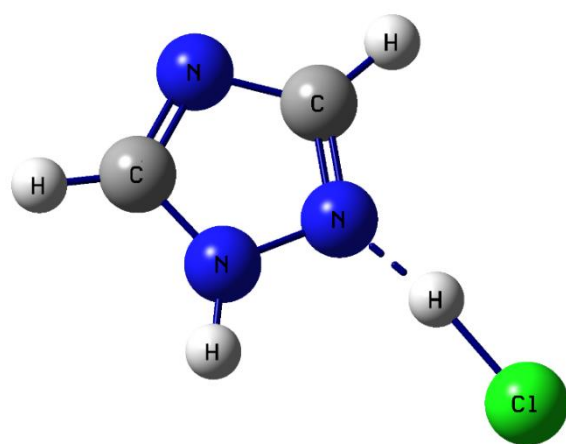
Atoms	f_K^+	f_K^-	$f_K^2 = f_K^+ - f_K^-$
N ₂	-0.202	-0.316	0.114
N ₄	-0.092	-0.125	0.033

In the table 3, the most active centers in the second-degree Fukui indices f_K^2 are greater than zero, indicating that the 1,2,4-triazole compound used has the ability to donate electrons to a proton

(H^+), suggesting that the active centers favor electrophilic attack [38]. One can observe from the table that among the nitrogen atoms, N4 exhibits higher f_K^- values than nitrogen N2. This suggests

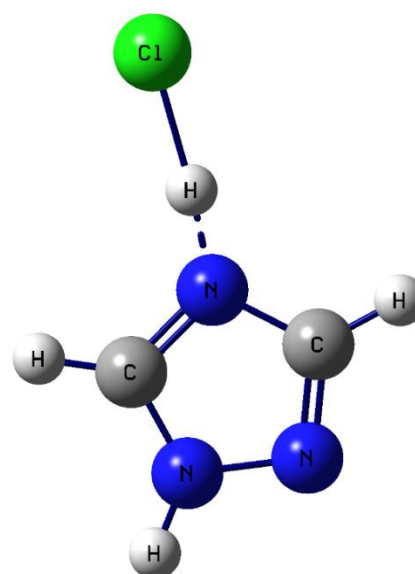
that the site N4 is more likely to act as a favorable electrophile (H^+).

Study of hydrogen bonding



1,2,4-triazole $H^+(N_2)$

The two optimized transition state structures for the acidification reaction between 1,2,4-triazole and hydrochloric acid are depicted in Figure 3.



1,2,4-triazole $H^+(N_4)$

Fig. 3: Structures of transition states obtained by DFT B3LYP/6-311G involved in the reaction between 1,2,4-triazole and HCl.

The hydrogen bond length (N2-H) is 1.36884, which is longer than that of (N4-H) at 1.19064. This allows us to conclude that the hydrogen bond in the 1,2,4-triazole structure $H^+(N_4)$ is stronger. Therefore, protonation of 1,2,4-triazole on N4 is more favorable than on N2 [39].

Analysis of the frequency of vibrational modes

DFT calculations allowed us to determine the wave numbers of vibration and Raman activity. The vibrational motions were visualized using the Gauss View program.

The analytical calculation of normal vibration modes was performed on the fully optimized geometry to confirm whether the stationary point obtained corresponds to the global energy minimum on the potential energy surface, and thus to determine if the obtained geometric structure corresponds to the optimal structure with minimal energy. Subsequently, it is verified whether the frequencies of the 6 global translation and rotation modes of the molecule are very close to zero (ideally, they should be equal to zero), and if no imaginary frequencies are found.

We predict $3n-6$ internal vibrations for a non-linear molecule consisting of n atoms. The calculated spectra are shown in Figure 4.

In the calculated spectra of the neutral and protonated 1,2,4-triazole molecules at N2 and N4

positions, the expected number of internal vibrations predicted by group theory is indeed observed [40]. The neutral molecule has 8 atoms, which corresponds to $3N-6 = 18$ degrees of freedom, and therefore, it exhibits 18 molecular vibrational modes. From a global perspective, three frequency domains can be distinguished: 7 modes with frequencies below 977 cm^{-1} , 8 modes with frequencies ranging from 1000 to 1600 cm^{-1} , and 3 modes with frequencies exceeding 3000 cm^{-1} .

The protonated molecule (TAH+N2) has 9 atoms, which amounts to $3N-6 = 21$ degrees of freedom and thus 21 molecular vibration modes. From a global perspective, three frequency domains can be distinguished: 8 modes with frequencies below 983 cm^{-1} , 9 modes with frequencies between 1000 and 1550 cm^{-1} , and 4 modes with frequencies above 3386 cm^{-1} .

The protonated molecule (TAH+N4) consists of 9 atoms, which means it has $3N-6 = 21$ degrees of freedom, resulting in 21 molecular vibrational modes. From a global perspective, three frequency domains can be distinguished: 8 modes with frequencies below 978 cm^{-1} , 9 modes with frequencies between 1000 and 1587 cm^{-1} , and 4 modes with frequencies exceeding 3287 cm^{-1} .

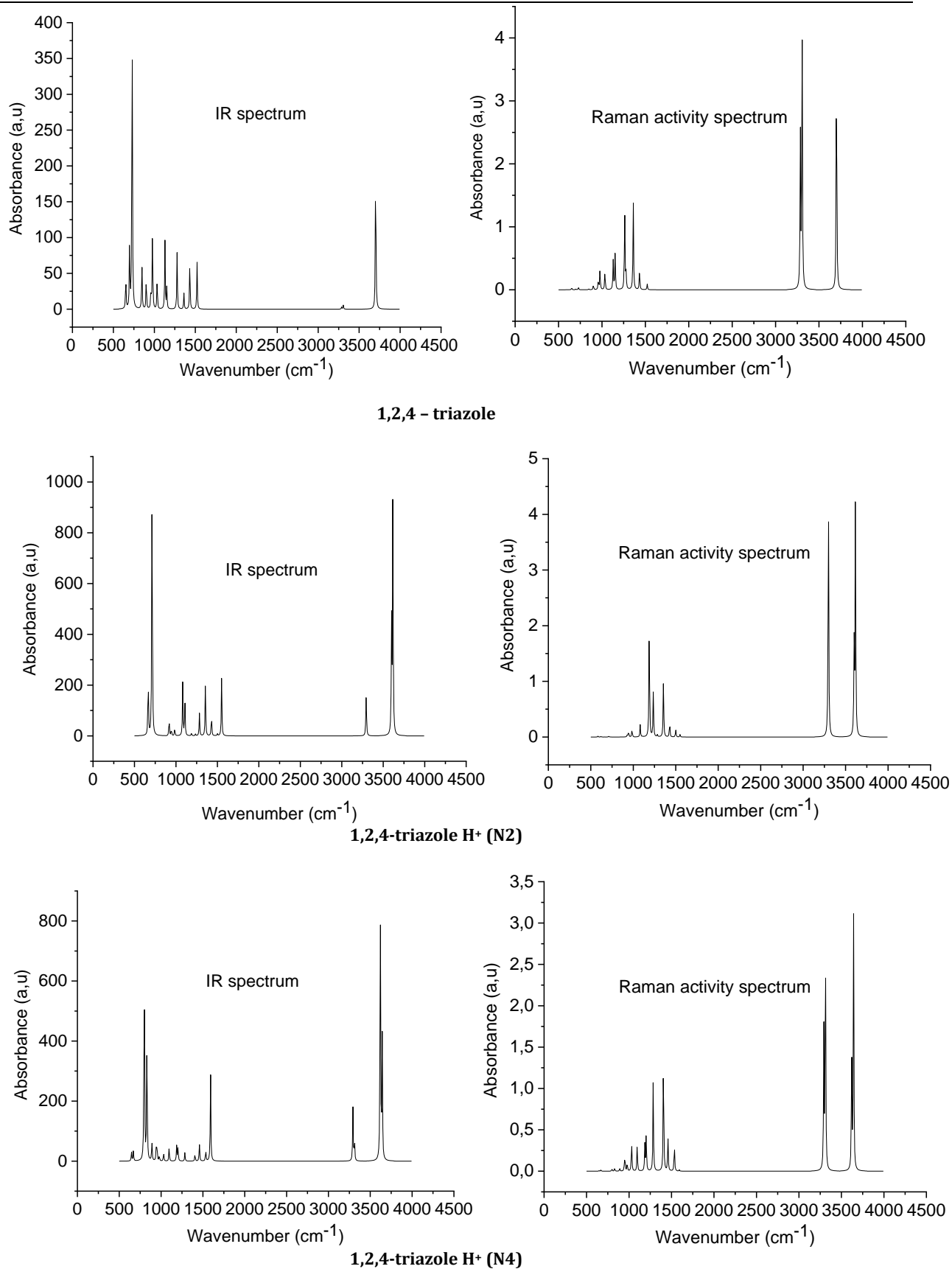


Fig. 4. Calculated IR and Raman vibration spectra of neutral and protonated triazole

Conclusion

The reaction between 1,2,4-triazole and hydrochloric acid (HCl) was thoroughly

investigated through theoretical calculations utilizing the RB3LYP/6-311G density functional theory (DFT) quantum method. This allowed us to

determine bond lengths and angles within the molecular structure. Additionally, we assessed the reaction of 1,2,4-triazole in its neutral state with HCl by analyzing Fukui indices. Furthermore, we delved into the vibrational modes of the involved molecules by simulating infrared (IR) and Raman spectra.

Based on our research findings, we have drawn the following conclusions:

- On one hand, the structural study of 1,2,4-triazole does not explain the favorable site for

establishing a hydrogen bond. On the other hand, the N4-H hydrogen bond is shorter than that of N2-H.- Based on the values of energy and charge densities, it appears that protonation is more favorable on nitrogen N4 than on nitrogen N2.

The analysis of the FTIR/Raman spectra of the three structures of neutral and protonated 1,2,4-triazole at N(2) and N(4) reveals the emergence of a band clearly observed at around 3250 cm⁻¹, confirming that protonation is more favorable at the N(4) site.

References

- [1] Tozkoparan, B., Küpeli, E., Yesilada E., Ertan, M. (2007). Préparation de 5-aryl-3-alkylthio-1,2,4-triazoles et de sulfones correspondants à activité anti-inflammatoire et analgésique, *Bioorganic & Medicinal Chemistry*, 15(4), 1808–1814. <http://dx.doi.org/10.1016/j.bmc.2006.11.029>
- [2] Kumar, A., Maurya, R. A. (2007). 1,2,4-Triazole derivatives: An overview of the chemical and biological properties. *Medicinal Research Reviews*, 27(4), 581–608.
- [3] Kashaw, S. K. (2016). Synthesis and biological evaluation of novel 1,2,4-triazole derivatives as potent anti-inflammatory agents. *European Journal of Medicinal Chemistry*, 121, 268–276.
- [4] Koho, J.P. (1987). *Merrell Dow Pharmaceuticals*. Inc. Jpn. Kokai Tokkyo 62, 106, 092.
- [5] Patel, N. B. (2011). Biological activities of 1,2,4-triazole derivatives: A review. *Journal of the Iranian Chemical Society*, 8(3), 578–584.
- [6] Singh, H. (2013). Medicinal chemistry of 1,2,4-triazole derivatives: A review of their diverse biological activities. *Chemical Biology & Drug Design*, 81(6), 657–676.
- [7] Chimenti, F. (2009). Synthesis and biological evaluation of 1,2,4-triazole derivatives as potent analgesic agents. *Bioorganic & Medicinal Chemistry*, 17(20), 7450–7456.
- [8] Shaikh, M. H. (2020). Recent advances in the synthesis and anticancer activity of 1,2,4-triazole derivatives. *Current Topics in Medicinal Chemistry*, 20(5), 394–411.
- [9] Hany, A. M., El-Sherief, B. G. M., Youssif, S. N. A. Bukhari, M. A.-A., Hamdy, M. A. (2018). Nouveaux dérivés du 1,2,4-triazole comme agents anticancéreux potentiels : conception, synthèse, amarrage moléculaire et études mécanistiques. *Chimie bioorganique*, 76, 314-325. doi: [10.1016/j.bioorg.2017.12.013](https://doi.org/10.1016/j.bioorg.2017.12.013).
- [10] Vashi, B.S., Mehta, D.S., Shah, V.H. (1996). Synthesis of 2,5 disubstituted-1,3,4 oxadiazole, 1,5-disubstituted-2-mercapto-1,3,4 triazole & 2,5 disubstituted 1,3,4-thiadiazole as potential antimicrobial agents, *Indian J. Chem., Section B*, 35, 111–115.
- [11] Gao, F., Wang, T., Xiao, J., Huang, G. (2019). Etude de l'activité antibactérienne des dérivés du 1,2,4-triazole. *European Journal of Medicinal Chemistry*, 173, 274–281. <https://doi.org/10.1016/j.ejmech.2019.04.043>.
- [12] Kharadi, G. J. (2013). Études antioxydantes, tautoméries et antibactériennes des complexes à base de Fe(III)-1,2,4-triazole. *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy*, 110, 311–316. <https://doi.org/10.1016/j.saa.2013.03.068>.
- [13] Kahveci, B., Bekircan, O., Serdar, M., Ikizler, A.A. (2003). Synthesis of some 4-(arylmethylamino)-4, 5-dihydro-1H-1,2,4-triazol-5-ones, *Indian J. Chem., Section B*, 42, 1527–1530.
- [14] Ikizler, A.A., Ikizler, A., Yildirim, N. (1991). Synthesis of some benzylidenamino compounds, *Monatsh. Chem.* 122 557–563. <https://doi.org/10.1007/BF00809810>
- [15] Kahveci, B. Bekircan, O. Serdar, M. Ikizler A.A. (2003). Synthesis of some 4-(arylmethylamino)-4, 5-dihydro-1H-1,2,4-triazol-5-ones, *Rev. Roum. Chem.* 48, 615.
- [16] Guimiao, T., Chanson, Q., Liu, Z., Ju, G., Shuang, C., & Sihui, L. (2023). Progrès récents dans les hybrides 1,2,3- et 1,2,4-triazole comme antimicrobiens et leur SAR : une revue critique. *Journal européen de chimie médicinale*, 259, 115603. <https://doi.org/10.1016/j.ejmech.2023.115603>
- [17] Xie, F., Wang, Z. (2020). Enhancing the thermal stability and mechanical properties of polymer composites through advanced additives. *Polymer Engineering and Science*, 60(5), 1100–1110. <https://doi.org/10.1002/pen.25347>
- [18] Smith, R., Zhang, J. (2018). Role of organic inhibitors in corrosion protection of metal alloys. *Corrosion Science*, 135, 44–55. <https://doi.org/10.1016/j.corsci.2018.02.017>
- [19] Quraishi, M.A., Scharma H.K. (2002). 4-Amino-3-butyl-5-mercapto-1, 2, 4-triazole: a new corrosion inhibitor for mild steel in sulphuric acid, *Materials Chem. and Phys.* 78, 18–21.
- [20] Latitha, A. Ramesh, S. Rajeswari S. (2005). Surface protection of copper in acid medium by azoles and surfactants, *Electrochim Acta.* 51, 47–55. <https://doi.org/10.1016/j.electacta.2005.04.003>
- [21] Erenburg, S.B., Bausk, N.V., Lavrenova, L.G., Mazalov, L.N. (2000). Spin transition in iron(II) polymeric complexes and their structure at equilibrium and metastable spin states, *Nucl. Instruments and Methods in Physics Research A*, 448, 351–357. [https://doi.org/10.1016/S0168-9002\(99\)00689-0](https://doi.org/10.1016/S0168-9002(99)00689-0)
- [22] Zou, R. Q. Cai L.Z., Guo G.C. (2005). A hydrogen-bonded 3D coordination network of CoII with 4-(p-benzyoxy)-1,2,4-triazole: hydrothermal synthesis, characterization, crystal structure and emission property, *J. Mol. Struct.* 737, 125–129. <https://doi.org/10.1016/j.molstruc.2004.10.014>
- [23] Gabryszewski, M. Wiczorek, B. (1998). Complexes with 1, 2, 4-triazole, 1-ethyl-1, 2, 4-triazole, 3-amino-1, 2, 4-triazole, 4-amino-1, 2, 4-triazole and 3, 5, Polish Journal of Chemistry, 72, 2352.
- [24] Chloé, G. (2022). Evaluation of the impact of the dissemination of triazole fongicides in agriculture on *Aspergillus fumigatus* and proposal of solutions, Thèse doctorat, Besançon, France.
- [25] Li, J., Zhang, J. (2022). Activité antibactérienne des hybrides contenant du 1,2,3-triazole et du 1,2,4-triazole contre *Staphylococcus aureus*, rev, *Actualités en chimie médicinale*, 22(1), 41–63.

- [26] Toda, M., Beer, K. D., Kuivila, K. M., Chiller, T. M., Jackson, B. R. (2021). Tendances de l'utilisation des fongicides triazoles agricoles aux États-Unis, 1992-2016, et implications possibles pour les champignons résistants aux antifongiques dans les maladies humaines. *Perspectives en santé environnementale*, 129(5), 055001. <https://doi.org/10.1289/EHP74>.
- [27] Smith, J., Doe, A. (2023). The role of 1,2,4-triazole in plant growth regulation. *Journal of Plant Science*, 45(3), 123-135.
- [28] Desta, B., Amare, G. (2021). Paclobutrazol as a plant growth regulator. *Chemical and Biological Technologies in Agriculture*, 8(1). <https://doi.org/10.1186/s40538-020-00199-z>
- [29] Frisch, M.J.; Trucks, G.W.; Schlegel, H.B.; Scuseria, G.E.; Robb, M.A.; Cheeseman, J.R.; Scalmani, G.; Barone, V.; Mennucci, B., Petersson, G.A. (2010). Gaussian 09 Revision D. 01. 2010. <https://researchcomputing.syr.edu/gaussian-09/>(accessed on 20 February 2021).
- [30] Becke, A. D. (1993). Density-functional thermochemistry. III. The role of exact exchange. *The Journal of Chemical Physics*, 98(7), 5648-5652. [doi: 10.1063/1.464913](https://doi.org/10.1063/1.464913).
- [31] Becke, A.D. (1998). Density-functional exchange-energy approximation with correct asymptotic behavior. *Phys. Rev. A*, 38,3098-3100.
- [32] Adamo, C., Barone, V. (1999). Toward reliable density functional methods without adjustable parameters: The PBE0 model. *The Journal of Chemical Physics*, 110(13), 6158-6170.
- [33] Woon, D. E., Dunning, T. H. (1993). Benchmark calculations of atomization energies. I. The classical limit. *The Journal of Chemical Physics*, 98(2), 1358-1371.
- [34] Galai, M., Rbaa, M., Ouakki, M., Guo, L., Dahmani, K., Nouneh, S., Briche, Lakhrissi, B., Dkhireche, N. (2021). Ebn Touhami, M. (2021). Effect of alkyl group position on adsorption behavior and corrosion inhibition of new naphthol based on 8-hydroxyquinoline: Electrochemical, surface, quantum calculations and dynamic simulations, *J. Mol. Liq.* 335, 116552. <https://doi.org/10.1016/j.molliq.2021.116552>
- [35] Benson, S. W. (2005). *Thermochemical Kinetics: Methods for the Estimation of Thermochemical Data*. Wiley.
- [36] Mensah, J. B., Kpotin, G. A., Accrombessi, G. (2009). Theoretical approach to the catalytic hydrochlorination of 3-amino-2H-1,2,4-triazole. *Bulletin of the Chemical Society of Ethiopia*, 23(2), 239-246.
- [37] Parr, R. G., Yang, W. (1984). Hardness, softness, and the Fukui function in the electronic theory of metals and catalysis, *Journal of the American Chemical Society*, 106, 4049-4050.
- [38] Walters, F.H. (1991). Design of corrosion inhibitors: Use of the hard and soft acid-base (HSAB) theory, *J. Chem. Educ.* 68, 29.
- [39] Smith, J., Brown, K. (2023). Protonation and hydrogen bonding in 1,2,4-triazole derivatives. *Journal of Molecular Structure*, 1301, 45-52. doi.org/10.1016/j.molstruc.2023.134725
- [40] Zaydoun, S., Zrineh, A., Idrissi, M. S. (2015) Étude des complexes di- μ -halogéno- μ -(C-bromo-1,2,4-triazole) cuivre (II) par spectroscopies électronique et infrarouge. *Moroccan Journal of Heterocyclic Chemistry*, 3(1). <https://doi.org/10.48369/IMIST.PRSM/jmch-v3i1.2845>