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A DFT-Based Study of Cyclic Trithiocarbonate Linkage on the Structural Reactivities of Biologically Potent Substituted Cyclic Trithiocarbonates

Suresh Kumar Arya^a, Rahul Verma^b, Pankaj Kumar Kushwaha^b, Amit K. Chaturvedi,^c Devdutt Chaturvedi^{a*}
Sunil Kumar Srivastava^b

^aDepartment of Chemistry, School of Physical Sciences, Mahatma Gandhi Central University, Motihari -845401 (East Champaran) Bihar, India.

^bDepartment of Physics, School of Physical Sciences, Mahatma Gandhi Central University, Motihari -845401 (East Champaran) Bihar, India.

^cDepartment of Chemistry, Faculty of Science, J S University, Shikohabad, U P, India.

*Corresponding Author: devduttchaturvedi@mgcub.ac.in

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Abstract: This study presents a comprehensive theoretical investigation of cyclic trithiocarbonate derivatives using Density Functional Theory (DFT). The calculations employed the 6-311++G (d, p) basis set to explore structural, electronic, and thermodynamic properties. Key electronic properties of the cyclic trithiocarbamate derivatives were analyzed, including the Highest Occupied Molecular Orbital (HOMO) and Lowest Unoccupied Molecular Orbital (LUMO), which provide insights into the compound's stability and reactivity. Additionally, the molecular electrostatic potential (MEP) was also mapped to identify electrophilic and nucleophilic attack regions. Further thermodynamic properties were calculated, offering insights into the stability and behaviour of these derivatives. Chemical reactivity parameters were also determined, including chemical potential (μ), electronegativity (χ), chemical softness (s), electrophilicity index (ω), and chemical hardness (η). These parameters are crucial for understanding the chemical behavior and potential biological activity of the compounds. The primary objective of this study is to elucidate the role of the cyclic trithiocarbonate linkage in influencing the structural reactivities of substituted cyclic trithiocarbonates. The findings contribute to understanding the influence of ring substitution on the reactivity and electronic structure of cyclic trithiocarbonates, providing a theoretical foundation for future applications in materials science and medicinal chemistry.

Keywords: Cyclic trithiocarbonate, Structural Reactivities, Molecular Electrostatic Potential, Chemical Reactivity Parameters, DFT

1. Introduction:

Cyclic trithiocarbonates are an important class of organic compounds characterized by three sulfur atoms bonded to a

carbon atom along with a cyclic ring, typically represented by the general formula $(CH_2)_nCS_3$, where n is 2,3,4,5,6..... an organic group. Like organic carbonates, 1, 2, trithiocarbonates are also important

synthetic intermediates in a number of reactions³. They are characterized by presenting a thiocarbonyl group flanked by two sulfur atoms and may be linear or cyclic. Cyclic trithiocarbonates, attract much attention due to their variety of useful properties⁴.

They are used as a building blocks in the synthesis of new antibiotics, and as versatile ligands and polymers^{5, 6}. Trithiocarbonates are also of commercial importance in a wide variety of applications, for example as rubber stabilizers, ore flotation agents, and additives for lubricants and fuels⁷. Besides, they exhibit a remarkably high liver disorder-suppressing effect, and hypocholesterolemic, hypotriglyceridemic, radioprotective, and insecticidal activity.

Much attention has been paid to the synthesis of cyclic trithiocarbonates, which are very important intermediates for the preparation of insecticides, biologically active compounds, and the donor of a superconductor. Trithiocarbonates including ethylene trithiocarbonate (ETTC) have received much attention due to their biological activity and utilization as raw materials in many organic syntheses and pharmaceuticals. Recently, there has also been an increasing demand for ETTC in lithium batteries as an electrolyte additive for the formation of a solid electrolyte interface (SEI) layer on the electrode, thereby improving the cycle performance and the stability of the batteries. One of the most efficient methods for synthesizing cyclic trithiocarbonates reported in the literature is based on the reaction of epoxides with carbon disulfide (CS₂) in the presence of a base and/or a catalyst.

However, these procedures often suffer from low yields and poor selectivity. Depending on the catalyst and reaction conditions, a variety of products can be formed. In addition, use of the volatile, inflammable and toxic carbon disulfide is definitely a serious disadvantage. Our research group has synthesized and designed biologically potent sulfur compounds for two decades.⁸⁻¹⁰ The primary objective of this study is to investigate how the trithiocarbonate linkage affects the structural reactivities of various substituted cyclic trithiocarbonates.

To achieve this, Density Functional Theory (DFT) calculations were employed due to their advantageous balance between computational cost and accuracy, particularly for analyzing the structures of large molecular systems. By integrating DFT calculations with experimental observations, a more comprehensive understanding of the molecular characterization is attained. DFT provides precise insights into several key molecular properties, including vibrational frequencies, thermodynamic stability, and electronic characteristics, making it a valuable tool for the detailed analysis of polyatomic molecules.”

2. Computational Methods

All theoretical calculations were done using Gaussian 16 software.¹¹ All theoretical calculations are executed at the density functional theory (DFT) level with the B3LYP hybrid function involving the gradient correction of the exchange functional by Becke¹² and the correlation functional by Lee, Yang, and Parr¹³ with 6-311++G (d, p) basis set. Usually, B3LYP and DFT calculations are widely used and show better results with experimental values.

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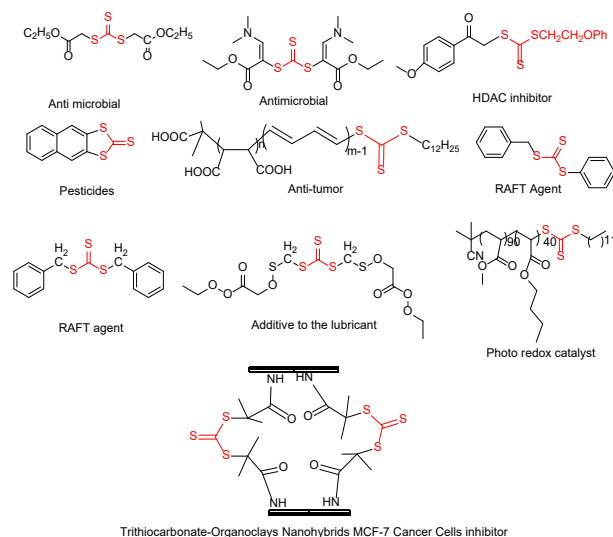


Figure 1: Structurally diverse biologically potent trithiocarbonates derivatives.

Gauss View 6.0,14 the program was used for geometry visualization of the synthesis compounds. The vibrational analysis study used theoretically calculated FT-IR spectra and thermodynamic properties at the same level as the theory. The Chem Draw15 software is used to draw the chemical structure of compounds TTC1-6, TTCR1-6 & TTCW1-6, as shown in Figure 2. The optimized structure of all the compounds of the HOMO and LUMO energy values are used to compute the chemical reactivity of the compounds, including; chemical potential (μ), electronegativity (χ), chemical softness (s), electrophilicity index (ω), chemical hardness (η) can be evaluated as following equations.¹⁶⁻¹⁸

$$\text{Chemical potential } (\mu) = (IP + EA)/2 \quad (1)$$

$$\text{Chemical hardness } (\eta) = (IP - EA)/2 \quad (2)$$

$$\text{Chemical softness } (S) = 1/2\eta \quad (3)$$

$$\text{Electrophilicity index } (\omega) = \mu^2/2\eta$$

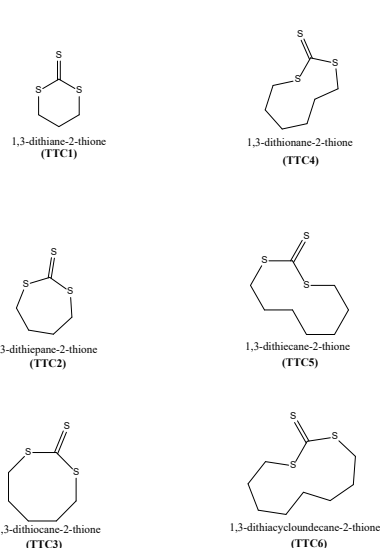


Figure (2a)

Figure (2b)

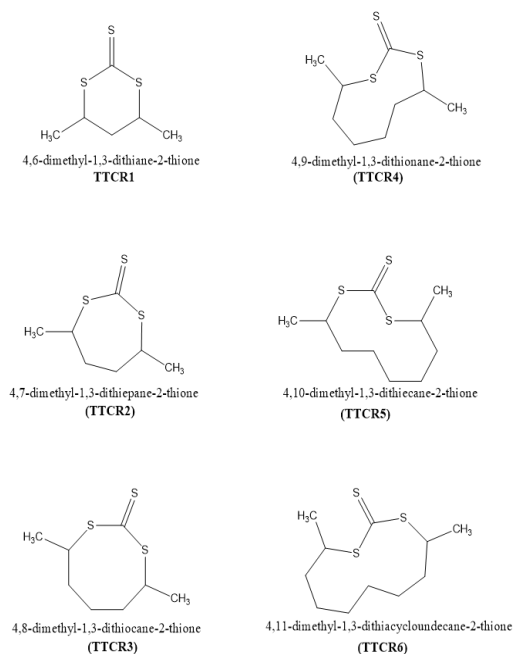


Figure (2c)

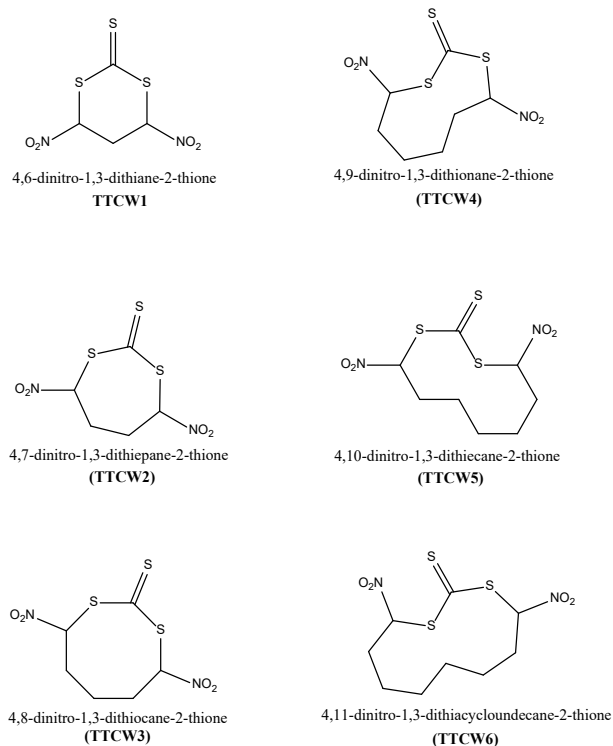


Figure 2. The chemical structures of cyclic trithiocarbonates cTTC1-6, TTCR1-6 & TTCW1-6.

3. RESULTS AND DISCUSSIONS

3.1 Optimization and structural analysis

The optimized structure of cyclic trithiocarbonates derivatives using the DFT method B3LYP/6-311++G (d,p) are presented in Figure 3. Table 1 shows the computed bond angle and distance between the carbon and sulfur atoms. The C=S bond length shows slight variations with changes in the number of carbon atoms in the cyclic trithiocarbonates, while a significant change occurs due to the presence of substituents- electron releasing/withdrawing groups on the cyclic ring of TTC compounds. This effect becomes even more pronounced when an

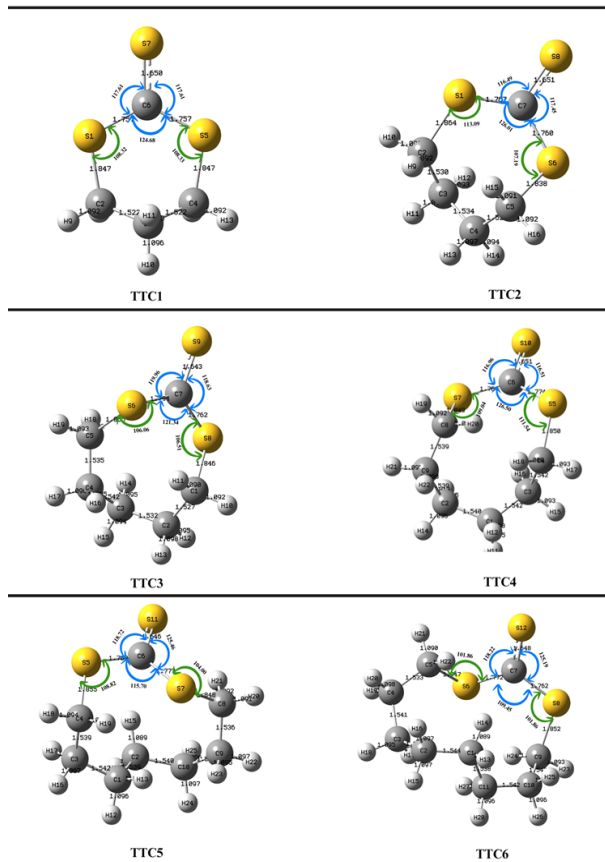


Figure (3a)

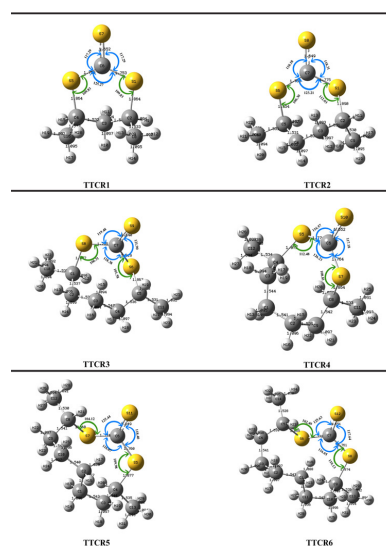


Figure (3b)

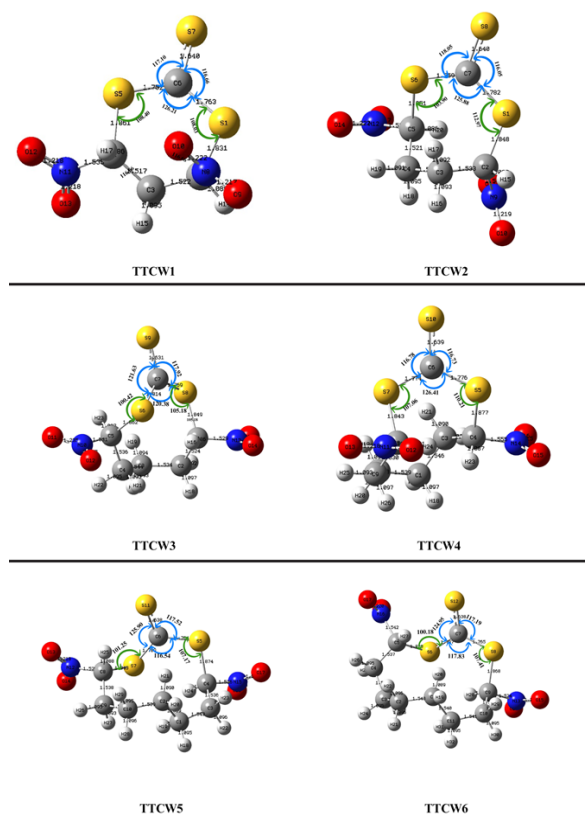


Figure 3(c)

Figure 3. The geometrical optimization parameters include the bond length and bond angle of a compound (TTC1-6, TTCR1-6 & TTCW1-6) in the ground state.

electronegative atom is attached to the cyclic ring in cyclic trithiocarbonates. In compound number TTCR1 & 4, the bond length of C=S is the largest (1.652 Å), while in compound number TTCW3, the bond length of C=S is the lowest (1.631 Å). When examining a compound's C-S bond, the bond length increases slightly with the expansion of ring size except TTC6, TTCr6 & TTCW6. The bond lengths and angles for all optimized cyclic trithiocarbonate derivatives are presented in Table 1. The compounds' inner bond angle S-C-S observed range from

115.7 to 126.5°. Specifically, TTC5 has the smallest bond angle at 115.7°, while TTC4 has the largest bond angle at 126.5°. The angular strain decreases as the ring size increases because the larger rings have more conformational flexibility, allowing them to accommodate the ideal bond angles better.

3.2 Frontier Molecular Orbitals Analysis

Molecular orbitals (Mos), both the Highest Occupied Molecular Orbital (HOMO) and Lowest Unoccupied Molecular Orbital (LUMO), and their energy gap (Eg) are very useful parameters in quantum chemistry. We can determine how the molecule interacts with other species; hence, they are called the Frontier molecular orbitals (FMOs). To explain several types of reactions and to predict the most reactive position in conjugated systems, molecular orbital, and their properties are used. The Frontier molecular orbital (HOMO and LUMO) affords information about the electrical and optical properties, as well as in UV-Visible spectra and quantum chemistry; it is used to explain various types of reactions in conjugated systems. Frontier Molecular Orbital (FMO) theory also associates molecular orbital energies and orbital coefficients with the reactivity of compounds. They also predict the stability and reactivity of the reacting molecules. A molecule having a small band gap is more polarizable and is generally associated with a high chemical reactivity and low kinetic stability. The HOMO and LUMO orbitals¹⁹ have been plotted using the DFT method B3LYP/6-311++G (d, p), as depicted in Figure 4. The subsequent charge transfer interactions within the molecules caused the decreased value of the HOMO and

LUMO energy gap.²⁰ The more rigid, more stable, and less reactive molecule has a higher energy band gap between its HOMO and LUMO.

According to the data given in Table 2, for all the studied compounds, EHOMO fell within the range of 5.21 to 7.27 eV, while ELUMO fell within the range of 1.99 to 3.67 eV. Among the studied substances, the highest Eg value of 3.91 eV, was observed for TTCW6, which indicated the Highest stability among the studied substances. The lowest Eg value (2.34 eV) was observed for TTCR4, which will be the least stable.

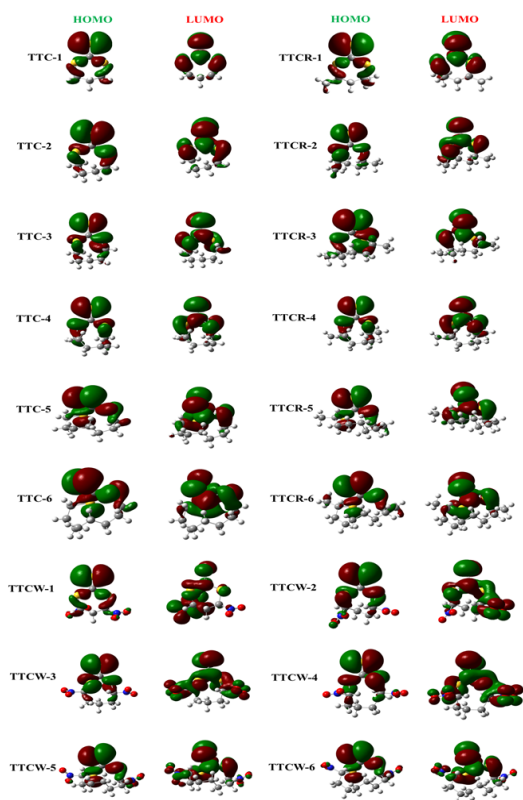


Figure 4. Optimized structures of the (TTC1-6, TTCR1-6 & TTCW1-6) compounds through B3LYP/6-311++G (d,p) level of theory.

Table 1. The compound's calculated

bond lengths and bond angles (TTC1-6, TTCR1-6, and TTCW1-6) in the ground state.

Compounds Bond Length (Å) Bond Angle (°)

Compounds	Bond Length (Å)		Bond Angle (°)	
TTC1	C6-S7	1.650	S1-C6-S7	117.61
	C6-S5	1.757	S5-C6-S7	117.61
	C6-S1	1.757	S1-C6-S5	124.68
	S1-C2	1.847	C6-S1-C2	108.32
	S5-C4	1.847	C6-S5-C4	108.33
TTC2	C7-S8	1.651	S1-C7-S8	116.49
	C7-S6	1.760	S6-C7-S8	117.45
	C7-S1	1.767	S1-C7-S6	126.01
	S1-C2	1.864	C7-S1-C2	113.09
	S6-C5	1.838	C7-S6-C5	107.19
TTC3	C7-S9	1.643	S9-C7-S6	119.96
	C7-S8	1.762	S9-C7-S8	118.63
	C7-S6	1.794	S6-C7-S8	121.34
	S6-C5	1.855	C7-S6-C5	106.06
	S8-C1	1.846	C7-S8-C1	106.51
TTC4	C6-S10	1.651	S10-C6-S5	116.51
	C6-S7	1.764	S10-C6-S7	116.96
	C6-S5	1.774	S7-C6-S5	126.50
	S5-C4	1.850	C6-S7-C8	109.04
TTC5	S7-C8	1.849	C6-S5-C4	111.54
TTC6	C6-S11	1.646	S11-C6-S5	118.72
	C6-S7	1.777	S11-C6-S7	125.46
	C6-S5	1.763	S5-C6-S7	115.70
	S5-C4	1.855	C6-S5-C4	108.82
TTCR1	S7-C8	1.848	C6-S7-C8	104.00
TTCR2	C7-S12	1.648	S12-C7-S6	125.19
	C7-S8	1.762	S12-C7-S8	118.22
	C7-S6	1.772	S6-C7-S8	116.52
	S6-C5	1.847	C7-S6-C5	101.86
TTCW1	S8-C9	1.852	C7-S8-C9	109.45
TTCW2	C6-S7	1.652	S7-C6-S5	117.29
	C6-S5	1.756	S7-C6-S1	117.29
	C6-S1	1.754	S5-C6-S1	125.27
	S1-C2	1.860	C6-S5-C4	109.83
TTCW3	S5-C4	1.864	C6-S1-C2	109.83
TTCW4	C7-S8	1.649	S8-C7-S1	118.31
	C7-S6	1.760	S8-C7-S6	118.18
	C7-S1	1.775	S6-C7-S1	123.21
	S1-C2	1.890	C7-S6-C5	106.30
TTCW5	S6-C5	1.854	C7-S1-C2	112.03

TTCR3	C7-S9	1.640	S9-C7-S8	119.48
	C7-S8	1.755	S9-C7-S6	121.90
	C7-S6	1.819	S8-C7-S6	118.38
	S6-C5	1.867	C7-S8-C1	106.31
	S8-C1	1.857	C7-S6-C5	101.58
TTCR4	C6-S10	1.652	S10-C6-S5	116.57
	C6-S7	1.764	S10-C6-S7	117.18
	C6-S5	1.774	S5-C6-S7	126.23
	S5-C4	1.872	C6-S5-C4	112.48
	S7-C8	1.864	C6-S7-C8	108.81
TTCR5	C6-S11	1.649	S11-C6-S5	118.40
	C6-S7	1.774	S11-C6-S7	125.44
	C6-S5	1.760	S7-C6-S5	116.07
	S5-C4	1.877	C6-S7-C8	104.12
	S7-C8	1.868	C6-S5-C4	109.98
TTCR6	C7-S12	1.651	S12-C7-S6	125.63
	C7-S8	1.761	S12-C7-S8	117.64
	C7-S6	1.772	S6-C7-S8	116.65
	S6-C5	1.865	C7-S6-C5	102.49
	S8-C9	1.874	C7-S8-C9	110.13
TTCW1	C6-S7	1.640	S7-C6-S5	116.66
	C6-S7	1.755	S7-C6-S1	126.21
	S1-C4	1.831	C6-S5-C4	108.40
	C7-S8	1.861	C6-S7-C8	108.03
	C7-S6	1.640	S8-C7-S6	116.03
TTCW2	C7-S8	1.759	S7-C7-S6	118.03
	S6-C5	1.848	C7-S1-C2	12.97
	C7-S8	1.851	C7-S6-C5	103.90
	C7-S8	1.631*	S9-C7-S6	121.63
	C7-S8	1.769	S8-C7-S6	120.38
TTCW3	S6-C5	1.864	C7-S6-C5	100.32
	S8-C9	1.845	C7-S8-C9	105.18
	C6-S10	1.639	S10-	116.78
	C6-S7	1.774	C6-S7	116.73
	C6-S5	1.776	C6-S5	126.41
TTCW5	S7-C8	1.877*	S7-C6-S5	107.06
	C6-S11	1.843	C4-S7-C6	110.21
	C6-S7	1.638	S11-	125.90
	C6-S7	1.789	C6-S7	117.52
	C6-S5	1.764	C6-S5	116.54
TTCW6	S7-C8	1.844	S7-C6-S5	101.25
	C7-S12	1.638	C6-S5-C4	107.17
	C7-S8	1.765	S12-	124.95
	C7-S6	1.787	C7-S6	117.19
	S8-C9	1.823	C7-S8	117.83
		1.868	S6-C7-S8	100.18*
			C7-S8-C9	107.41

According to Koopmans²¹ and Kohn–Sham theorem²², suggest by using HOMO and LUMO energy values of a molecule, the global chemical reactivity descriptor of molecules such as hardness, chemical potential, softness, electronegativity, and electrophilicity index as well as local reactivity have been defined. HOMO signifies the ability to donate an electron (nucleophile), and the energy of HOMO is directly connected to the ionization potential (IP), and LUMO value implies the tendency to gain an electron (electrophile), and LUMO energy is associated directly with electron affinity (EA). The quantum chemical parameters, including HOMO, LUMO, energy gap, ground state energy, chemical potential (μ), global hardness (η), softness (S), and global electrophilicity (ω), have been computed by DFT method B3LYP/6-311++G(d,p) are given in Table 2. The electronegativity is (χ)[−] negative of the chemical potential (μ), which is a tendency for an atom of a given chemical element to attract shared electrons (or electron density) when forming a chemical bond. The chemical potential provides a global reactivity index and is related to charge transfer from a system of higher chemical potential to lower chemical potential. The chemical potential (μ) of all studies compounds TTCR6 -3.82 shows lowest value while TTCW3 -5.38* has the highest chemical potential value as a strong electron-acceptor molecule.

3.3 Global Chemical Reactivity Analysis

Table 2. Calculated value of the global chemical reactivity indices of (TTC1-6, TTCR1-6 & TTCW1-6) compounds all in eV.

Compound	HOMO	LUMO	E_g	μ	η	S	ω	χ
TTC1	-6.04	-2.43	3.61	-4.23	1.80	0.28	4.97	4.23
TTC2	-5.64	-2.17	3.47	-3.91	1.73	0.29	4.41	3.91
TTC3	-5.58	-2.59	2.99	-4.09	1.49	0.33	5.59	4.09
TTC4	-5.33	-2.94	2.38	-4.13	1.19	0.42	7.17	4.13
TTC5	-5.74	-2.20	3.54	-3.97	1.77	0.28	4.46	3.97

TTC 6	-5.70	-2.04	3.67	-3.87	1.83	0.27	4.08*	3.87
TTCR1	-5.70	-2.04	3.67	-3.87	1.83	0.27	4.08	3.87
TTCR2	-5.69	-2.15	3.54	-3.92	1.77	0.28	4.33	3.92
TTCR3	-5.52	-2.57	2.95	-4.04	1.48	0.34	5.53	4.04
TTCR4	-5.21*	-2.88	2.34*	-4.04	1.17*	0.43*	7.00	4.04
TTCR5	-5.69	-2.15	3.54	-3.92	1.77	0.28	4.33	3.92
TTCR6	-5.65	-1.99*	3.67	-3.82*	1.83	0.27	3.98	3.82*
TTCW1	-7.27*	-3.40	3.87	-5.34	1.94	0.26*	7.35	5.34
TTCW2	-7.07	-3.31	3.76	-5.19	1.88	0.27	7.16	5.19
TTCW3	-7.09	-3.67*	3.42	-5.38*	1.71	0.29	8.46*	5.38*
TTCW4	-7.02	-3.44	3.58	-5.23	1.79	0.28	7.63	5.23
TTCW5	-7.14	-3.29	3.83	-5.21	1.93	0.26	7.05	5.21
TTCW6	-7.07	-3.17	3.91*	-5.12	1.95*	0.26	6.71	5.12

Chemical hardness (η) and softness (S) efficiently estimate organic moiety's reactivity and stability.²³ The molecules with less hardness (η) and greater softness values (S) have strong electron-acceptance and good electrophile species. Softness has an inverse relation with twice the value of hardness. The value of “ S ” should be larger, and the “ η ” value should be lower, indicating the increasing electron acceptance ability. However, compound TTCR4 values of the chemical hardness, softness, and electronegativity values are calculated as 1.17, 0.43, and 4.04 eV, respectively showing that the molecule is hard and stable. Thus, a good electrophile is a species characterized by a high S value and a low η value. The electrophilicity index (ω) scale allows the classification of organic compounds as strong electrophiles with $\omega > 1.5$ eV, moderate electrophiles with ranges $0.8 < \omega < 1.5$ eV, and very weaker electrophiles with $\omega < 0.8$ eV.²⁴ The electrophilicity (ω) index values range from 3.74 eV to 7.53 eV. Strong electrophiles presenting an electrophilicity (ω) index higher than 2.0 eV participate easily in polar Diels-Alder reactions.²⁵ The compound TTCW3, $\omega = 8.46^*$ eV, is the most electrophilic organic species, participating in ionic organic reactions.²⁶

The high reactivity species presenting an electrophilicity ω index higher than 4.00 eV are super electrophiles showing high reactivity in polar reactions.²⁷ Thus,

here, most of the studied compounds indicate the very high value of ω , so they are good as an electrophile.

3.4 Molecular Electrostatic Potential (MEP) Analysis

The net electrostatic effect produced by a molecule's overall charge distribution (electrons + nuclei) at a point in space around it is known as the molecular electrostatic potential. It relates the total charge distribution to dipole moments, partial charges, electronegativity, and the site of chemical activity of the molecule.²⁸ In Figure 5, different electrostatic potential values on the surface are represented by different colors: red represents the areas with the most negative electrostatic potential, blue represents the areas with the most positive electrostatic potential, and green represents areas with zero potential. The most positive and negative regions, represented by blue and red colors on the MEP map, are the preferred locations for nucleophilic and electrophilic attacks, respectively.²⁹ Such maps are very useful when studying molecular structure and physicochemical characteristics because they use color grading to represent areas of positive, negative, and neutral electrostatic potential.³⁰

Molecular Electrostatic Potential (MEP) is an essential tool³¹ for interpreting electrostatic (electron and nuclei) distribution potential and envisaging the reac-

tive site of wide ranges in

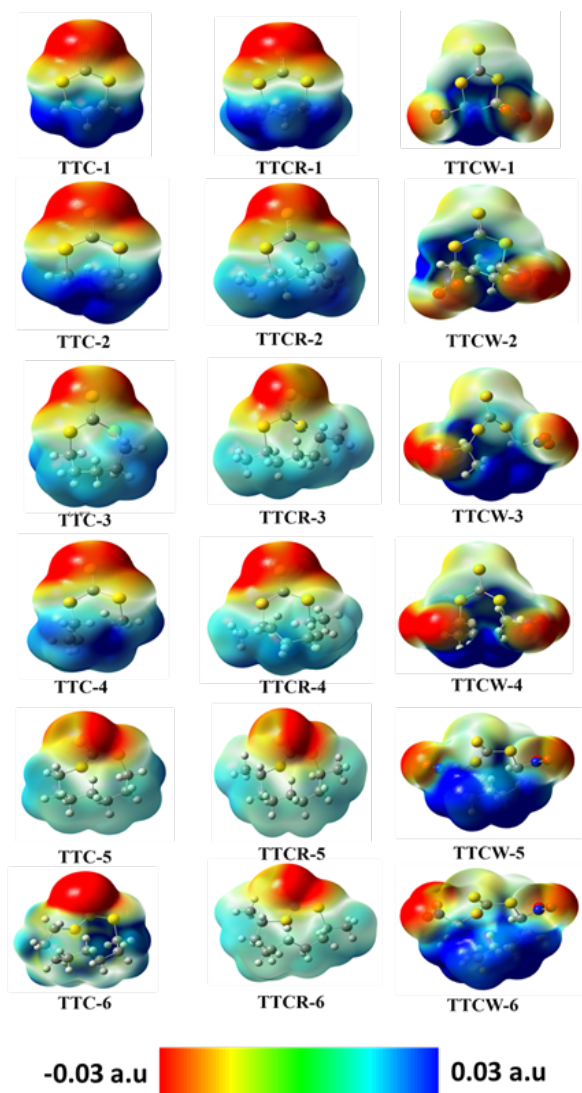


Figure 5. Molecular Electrostatic Potential (MEP) maps plot of (TTC1-6, TTCR1-6 & TTCW1-6) compounds.

both electrophilic and nucleophilic attacks in chemical reactions, hydrogen bonding interactions, and biological platforms.³² The MEP iso-surface plot provides a significant visual method to comprehend the compound's reactive sites and various polar regions. To identify suitable sites for nucleophilic and electrophilic attacks, the MEP and con-

tour diagram for all compounds were calculated at the B3LYP/6-311++G (d, p) level of theory, which is represented in **Figure 5**. The surface region is arranged hierarchically as red < orange < yellow < green < blue.

The red regions (electron enrichment regions), which are countered around the regions of oxygen atoms, exhibit nucleophilic areas. In contrast, the blue color region (absence of electrons) is prone to the electrophilic areas. From Figure 5, the maximum positive region is localized on the C-H bonds. The average of two extremes represents zero potential as a green color, whereas the slightly electron-rich areas are defined as yellow in color, respectively. The color code of the map is in the range map between -0.03 a.u dark red and 0.03 a.u dark blue region, respectively.

The MEP plot in Fig.5 shows that TTC6 has a highly electron-rich region near the sulfur atom of the C=S bond, while other compounds like TTC1, TTC2, TTCR1, and TTCR2 have comparatively lower electron-rich region near the sulfur atom of the C=S bond. In these compounds, the sulfur atom is particularly susceptible to electrophilic attack, while in the other compounds, the susceptibility is moderate.

A nucleophilic region is also observed near the C-H bond of the ring where an electron-withdrawing NO₂ group is attached mainly in TTCW3, TTCW4, TTCW5, and TTCW6, which exhibits high reactivity, shows a strong electrophilic region near the oxygen atom of the nitro group and nucleophilic regions near the C-H bonds of the ring in the MEP plot.

3.5 Molecular planarity parameter (MPP) and deviation span from plane (SDP).

Planarity is a very important structural characteristic of molecules, which is closely related to many molecular properties. However, there is currently no simple, universal, and robust way to measure molecular planarity. In order to fill this evident gap, we propose two metrics of molecular planarity, namely molecular planarity parameter (MPP) and span of deviation from plane (SDP), to characterize the planarity of molecules quantitatively. MPP reflects the overall degree of deviation of the structure from a plane, while SDP represents the span of the structural deviation relative to the fitting plane; respectively, they are complementary to each other. The examples in this article demonstrate that these metrics have strong rationality and practicality. They can not only be used to investigate the planarity of the entire molecule but can also measure the planarity of local structures, and they can even be employed to study variation of molecular planarity during a dynamic process. In addition, we also propose a new representation, namely coloring atoms according to their signed deviation distance to the fitting plane.

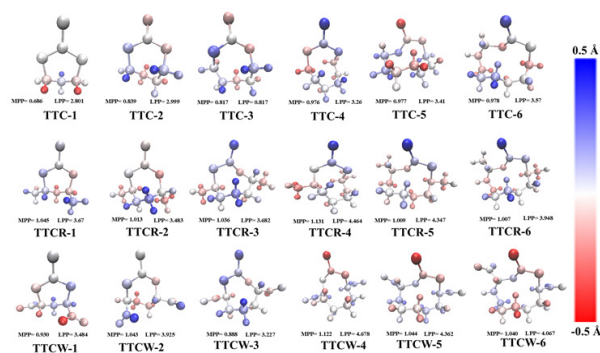


Figure 6. MPP and SDP (in Å) calculated for all Atoms of compounds (TTC1-6, TTCR1-6 & TTCW1-6) optimized at B3LYP/6-311++G (d, p) level. Atoms are coloured according to ds values using colour scale from + 0.5 Å (blue) to - 0.5 Å (red). The bluer (redder) the colour, the larger the distance of the atom below (above) the fitting plane.

3.5.1 Implementation of MPP and SDP in Multiwfn

Evaluation of MPP and SDP has been supported by our freely available code Multiwfn5 since version 3.8. Multiwfn accepts almost all known structure files of chemical systems for this kind of calculation, for example, xyz, pdb, pqr, mol, mol2, cif, gro, and so on. Executable files of Multiwfn for all platforms are directly available from its website, including Windows, Linux and MacOS. The process of using Multiwfn to calculate MPP and SDP is extremely simple. After booting up Multiwfn and load input file, user just needs to input “MPP” in the main menu, and input the indices of the atoms for which the MPP and SDP will be calculated, then intermediate information yielded during evaluation of MPP and SDP as well as the final result will be immediately printed as shown in Fig.6. It is worth to emphasize that MPP and SDP are not necessarily to be calculated for the whole system, one can evaluate them for any part of the system to study planarity of a local region by inputting corresponding atom indices in Multiwfn. Table 3. The calculated value of the Molecular planarity parameter (MPP) and span of deviation from the plane (SDP) (TTC1-6, TTCR1-6 & TTCW1-6) compounds.

COMPOUND	MPP (Å)	SDP (Å)
TTC-1	0.686*	2.801
TTC-2	0.839	2.999
TTC-3	0.817	0.817*
TTC-4	0.976	3.261
TTC-5	0.977	3.416
TTC-6	0.978	3.577
TTCR-1	1.045	3.679
TTCR-2	1.013	3.483
TTCR-3	1.036	3.682
TTCR-4	1.131	4.464
TTCR-5	1.009	4.347
TTCR-6	1.007	3.948
TTCW-1	0.930	3.484
TTCW-2	1.043	3.925
TTCW-3	0.888	3.227
TTCW-4	1.122*	4.678*
TTCW-5	1.044	4.362
TTCW-6	1.040	4.067

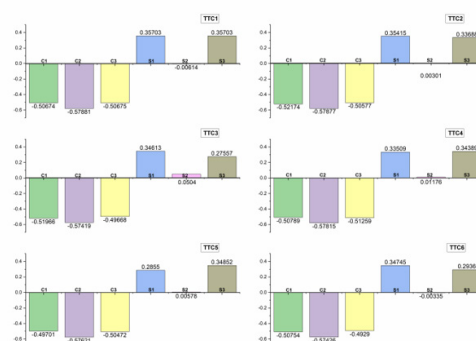
In observing Table 3, it was found that generally, the deviation from molecular planarity increases with an increase in ring size. We find that the compound TTC1 shows the least deviation from planarity with comparatively moderate deviation from the fitting plane, while TTCW4 shows the highest deviation of molecular planarity with the highest span of deviation from the fitting plane. The compound TTC3 has the least deviation from the fitting plane with comparatively moderate deviation from the molecular planarity.

3.6 Natural population analysis

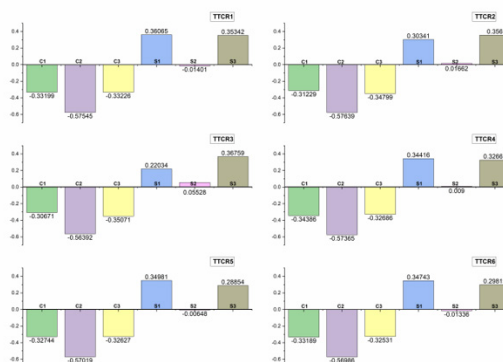
Natural Population Analysis (NPA) is employed to characterize electron density distribution for understanding charge transfer, electronic structure, and molecular bonding [33, 34]. This analysis provides natural atomic charges that offer numerical stability and a precise description of electron distribution within a molecule. NPA is based on the concept of Natural Bond Orbitals (NBO) [35], representing an optimized set of localized orbitals that illustrate the bonding framework. In this study, NPA was conducted using natural atomic orbital occupancy implemented in the Gaussian program to determine the natural charges on the

atoms of

(a)



(b)



(c)

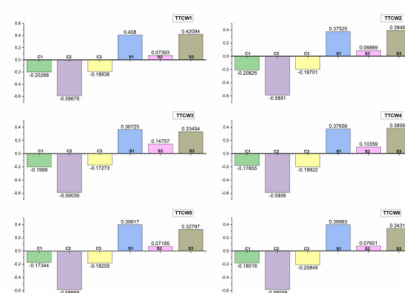


Figure 7. Histogram plot of natural atomic charge on the atoms of TTCs linkage group in (a) TTC-1-6 (b) TTCR-1-6 (c) TTCW-1-6

substituted

cyclictrithiocarbonates

were calculated using the B3LYP/6-311++G(d,p) method. Figure 7 presents the histogram plot of the natural atomic charge on the atoms of the TTCs linkage group. The plot illustrates the impact of different substitutions on the TTC group by analysing the charge distribution across its atoms. S1 and S3 are the terminal atoms of TTC through which the linkage with various substituted groups is attached. C1 and C3 belong to the atom on the other side of the linkage bond. C2 and S2 are the atoms involved in the C=S bond in the TTC group. The NPA shows that the charges on atoms C1, C2, and C3 are negative, while S1 and S3 carry positive charges. In TTC1, TTC6, TTCR, TTCR5, and TTCR6, the charge on atom S2 is negative and electrophilic, while the charge on S2 is positive in all other compounds, indicating that these compounds become nucleophilic.

The positive charge on S2 is more pronounced in all six molecules (TTCW1-TTCW6) having electron-withdrawing NO₂ groups as substituents. Molecule TTCW3 shows the highest positive charge on S2 and, therefore, is highly nucleophilic in nature. As shown in Table-1, the C=S of S2 with C2 is also shortest among all studied molecules.

3.7 ELF and LOL Analysis

Surface analysis based on covalent bonding was performed using an electron localization function (ELF) with a bump map and LOL maps. A bump map with a large or narrowed peak area describes the electronic environment of an atom. They offer a valuable opportunity to identify pairs of electrons on the molecular surface. ELF and LOL have similar chemical mapping because they depend

on the kinetic energy density. However, ELF arises from the electron pair density; LOL simply exhibits a gradient of localized orbitals and is used when localized orbitals overlap. Images of the studied substances in ELF and LOL formats are shown on the color tint map and contour maps of the hydrogen bond region in Figure 8. The ELF map was built in the range of 0.0–0.2; however, delocalized electrons are projected in a reduced range (0.5) [50,51].

Due to the presence of a covalent bond or nuclear layer, a high position of electrons is created in this region, as demonstrated by its high value in this region. The electron cloud was delocalized around some carbon atoms in the studied substances, which is represented by blue areas. Critical points and their trajectories, chemical bonding, and chemically significant regions (red and orange) are clearly shown on the ELF map, localized mainly around hydrogen atoms and present in all substances under study.

It should be noted that the central regions of some hydrogen atoms in all the studied substances were white, which indicates that the electron density exceeded the upper limit of the color scale.

3.8 Bond dissociation Enthalpies and Gibbs free energies of TTC linkage bond

The thermodynamic stability of TTC linkage bonds can be effectively evaluated by analyzing two critical parameters: Bond Dissociation Enthalpies (BDE) and Gibbs Free Energies (ΔG). These thermodynamic parameters provide insight into the strength of TTC linkages with various substituents. The calculat-

ed BDEs and Gibbs free energies for the TTC linkage bonds are summarized in Table 4, offering a quantitative measure of bond stability across different molecular configurations.

The high BDE value and Gibbs free energies for **TTCR4 & TTCW4** suggest a strong linkage with their substituents. In contrast, **TTCR3, TTCR5, TTCR6 & TTCW3, TTCW5, TTCW6** exhibit lower BDE values and Gibbs free energies, indicating a weaker linkage. The remaining

Compounds	BDE (kcal/mol)	ΔG (kcal/mol)	Compounds	BDE (kcal/mol)	ΔG (kcal/mol)
TTCR1	32.63	36.78	TTCW1	29.19	35.28
TTCR2	30.15	34.11	TTCW2	28.84	35.10
TTCR3	29.71	33.86	TTCW3	27.65	33.92
TTCR4	48.30	50.67	TTCW4	46.36	50.88
TTCR5	30.20	34.07	TTCW5	27.54	33.50
TTCR6	29.92	33.77	TTCW6	26.49	32.52

compounds show moderate linkage strength with their respective substituents. It is notable that the linkage is stronger when a substituent is attached to the cyclic structure.

3.9 Vibrational analysis

To examine the effect of the attached group on the vibrational features of cyclic trithiocarbonates, a vibrational analysis of substituted TTCs was conducted using the DFT method at the B3LYP/6-311++G(d,p) level of theory. Infrared spectroscopy is used to determine the functional groups present in organic compounds to identify the characteristic vibrations such as stretching, bending, and twisting [36, 37]. The appearance of C–S stretching, C=S stretching, and –S–C–S– in-plane bending vibrations in substituted TTCs are presented in Table 5 and their spectral graphs are shown in Figure 9. A strong absorption in the region 800–900 cm^{-1} corresponds to the –S–C–S– in-plane bending vibration of the TTC group. The band appeared in the region 1000–1100 cm^{-1} , corresponding to the stretching vibration of the carbon-sulfur double bond (C=S) present in the TTC group.

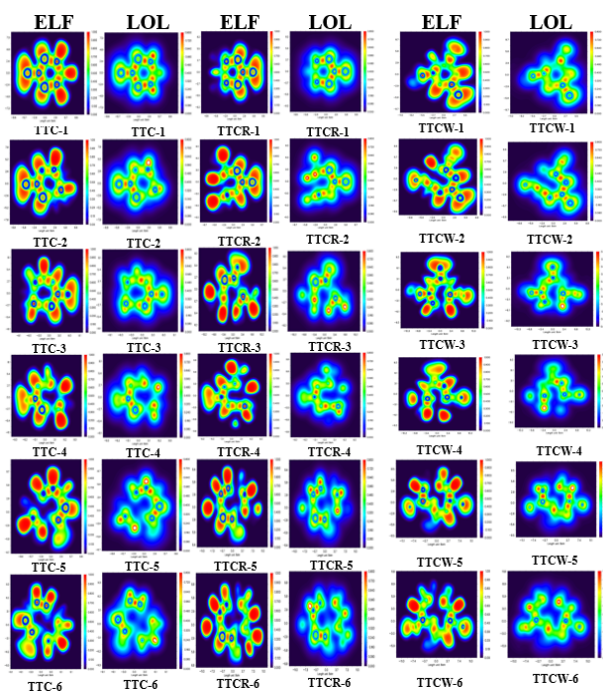


Figure 8. Electron localization function (ELF) maps (left) and localized orbital locator (LOL) maps (right) of the compounds TTC-1 To TTCW6

Table 4. Bond Dissociation Enthalpies and Gibbs Free Energies of TTC linkage bond calculated at B3LYP/6-311++G(d,p) level of theory.

Table 5. Calculated vibrational frequencies (cm⁻¹) of compounds (TTC1-6, TTCR1-6 & TTCW1-6).

Compounds	C=S str. (cm ⁻¹)	C-S (cm ⁻¹)	S-C-S (cm ⁻¹) (in-plane)	S-C-S (cm ⁻¹) (out-of-plane)
TTC1	1045.68	631.92	889.17	450.96
TTC2	1025.80	617.06	862.52	463.19
TTC3	1054.30	647.08	807.18	506.91
TTC4	1024.32	645.85	856.02	470.04
TTC5		636.41	850.99	465.39
TTC6	1044.38	608.43	859.09	470.23
TTCR1	1047.35	575.26	880.14	471.08
TTCR2	1028.75	567.31	863.55	464.77
TTCR3	1027.53	618.79	813.14	469.99
TTCR4	1051.03	660.75	860.17	470.16
TTCR5	1019.05	628.22	836.34	518.02
TTCR6	1038.99	629.35	843.67	467.32
TTCW1	1042.63	777.25	892.78	448.31
TTCW2	1053.20	652.86	843.69 829.12	457.57
TTCW3	1050.40 1065.99	645.39	859.28	475.50
TTCW4		597.48		597.48
	1037.50		834.76	
TTCW5		646.16		482.89
	1064.68		843.90	
TTCW6		645.17		479.40
	1062.19			

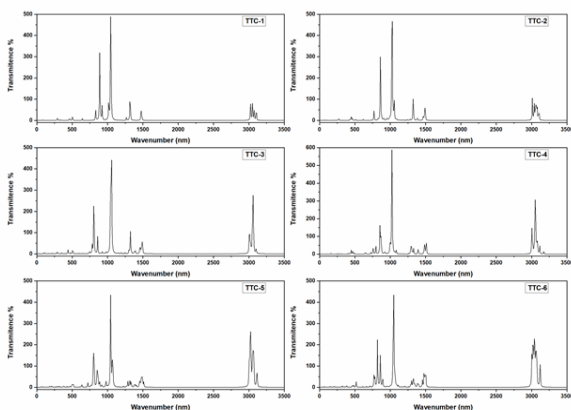


Figure (9a)

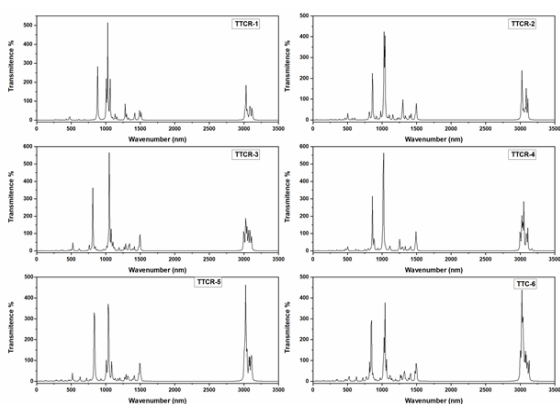


Figure (9b)

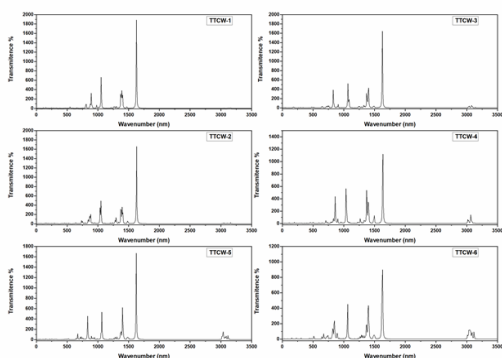


Figure (9c)

Figure 9. Infrared Graphical features of TTCs linkage group in cyclic trithiocarbonates (a) TTC-1-6 (b) TTCR-1-6 (c) TTCW-1-6

4. Conclusions

In conclusion, this study utilized density functional theory (DFT) to investigate the electronic and structural properties of the cyclic trithiocarbonate derivatives (TTC1-6, TTCR1-6 & TTCW1-6). The Frontier Molecular Orbital (FMO) analysis provided key insights into the Highest Occupied Molecular Orbital (HOMO), Lowest Unoccupied Molecular Orbital (LUMO), energy band gap, and ground state energy of these compounds. These findings highlight the chemical stability of the derivatives, as the energy band gap is a critical indicator of molecular stability and reactivity. Additionally, the Molecular Electrostatic Potential (MEP) map analysis identified the most reactive sites within the molecules. The MEP map revealed that the regions around the C-S bonds are prone to electrophilic attacks due to their electron-deficient nature, while the sulfur atoms serve as nucleophilic sites, being electron-rich. These results offer valuable insights into the reactivity patterns of cyclic trithiocarbonate derivatives, which can inform future studies on their potential applications in medicinal chemistry and other fields.

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