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Analysis of the structural, spectroscopic, and molecular electrostatic potential (MESP) of (amino)carbonothionyl (nitro)benzamide derivatives

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ABSTRACT

This study examined the structural and spectroscopic properties of ten synthesized derivatives of carbonothionylbenzamide. These nitro group based molecules are five *meta*- (named M) and five *para*- (named P) compounds. These compounds showed no significant difference in their IR spectra from each other despite the positions of their nitro-substituent. The amino substituent has a long-range effect on the atomic and bond properties associated with C = O and C = S of the carbonothionylamide moiety supported by the ¹³C NMR shielding, IR wavenumber, and bond strength. The *meta*-molecules were more thermodynamically stable than the *para*-molecules, though with lower band gap difference, they are of higher HOMO and LUMO energy levels. Total stability energy of the fragment interaction from the *meta*- to *para*-molecule was relatively small. The *meta*-derivatives have a more electron-rich center than the *para*-compounds with lower molecular electrostatic potential values associated with V_{min} , V_{max} and V_s . Therefore, the order of the electron-rich center, V_{min} in the *meta*-molecules were: 2M > 5M > 4M > 1M > 3M and were found close to the C = O group of the carbonothionylamide unit of the fragment 2. The diethylnitro groups in molecules 3M or 3P have shown to be more susceptible at fragment 2 to nucleophilic attack to enhance their bidentate bonding behavior.

GRAPHICAL ABSTRACT



Introduction

Carbonothionylbenzamide derivatives have been much researched due to their versatility in different fields such as biology, medicine,^[1] and agriculture.^[2] These compounds, through their donor atoms and the electron density, inhibit microbial agents, regulate plant growth,^[2] and catalyze reactions.^[3]

Compounds with additional substituents have been reported with higher activity. The effect of substituents such

as halogens causes a shift in the electron distribution of the compounds, which have enhanced the activity of these compounds.^[4] Theoretical calculations of these compounds have helped in an understanding of the structural–activity relationship to develop methods for better molecular design. Carbonothionylbenzamide derivatives coordinate with metal atoms to form stable metal complexes.^[5–10] Most times, carbonothionylbenzamide derivatives chelate with the metal atom as bidentate compounds via their donor sites.^[11]

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Figure 2. Schematic representation of the synthesis of 3P.

These metal complexes are widely applied as antifungal,^[12] antibacterial,^[13] and herbicidal^[14] agents.

Considering these activities, this work focuses on the synthesis, characterization, and computational studies of five *meta* (M)-nitro and five *para* (P)-nitro carbonothionylbenzamide molecules which will provide insight into their structures. The interest is to analyze the changes in the spectroscopic, structural, molecular electrostatic potential (MESP), and fragment interaction of the molecules as results of the changes in the type of the substituents and the position of the NO₂ group (metal or para).

Results and discussion

Synthesis and characterization of the compounds

The synthesis and characterization of 1P, 1M, 2M, and 2P have been reported earlier by Fayomi.^[15] The reaction which involved condensation of the nitro-benzoylchloride followed by the addition of an amine is described in Figure 1.

However, the synthesis of 3M–5M and 3P–5P had some modifications as shown in Figure 2. Both 5P and 5M have their synthetic and spectroscopic studies reported in previous work.^[16]

It is imperative to note that these compounds were included in this work to study some other properties using computational methods.

The experimental results of the ¹³C NMR showed that the *para* or *meta* position of the NO₂ has a long-range shielding effect of the carbon atoms of C=O and C=S on fragment 2 of the molecules (Figure 3). The *para* position of NO₂ resulted in high shielding effect of the two C atoms, shielding tensors of 162.66 (C=O) and 179.65 (C=S) were obtained for 3P, and 165.78 (C=O) and 183.67 (C=S) obtained for 4P. The respective *meta*-structure were less shielded as found for 3M [161.87 (C = O) and 178.60 (C = S)] and 4M [160.52 (C = O) and 181.46 (C = S)].^[17] A stronger long-range effect on the shielding tensor was obtained by the nature of the substituents on the N(R¹)R² that defined the derivatives compared to the effect of the *para* and *meta* position of the NO₂ as molecule 3P and 3M had lower shielding compared to 4P and 4M. Also, the substituent effects of the N(R¹)R² strongly affect the IR vibrations position as the C=O and C=S vibrations of the 3P [1686 (C=O), 1347 (C=S)] and 3M [1682 (C=O), 1346 (C=S)] was lower in wavenumber compared to that of 4P [1721 (C=O), 1348 (C=S)] and 4M [1702 (C=O), 1354 (C=S)].^[18]

The geometrical and spectroscopic properties of the derivatives of carbonothionylbenzamide

To gain better insight into the spectroscopic and structural properties of the ten derivatives of carbonothionylbenzamide, computational modeling was used and the structures of the optimized geometries of the molecules are shown in Figure 4.

The electronic effects of the different chemical units around the carbonothionylamide unit are presented by fragmentation of each of the molecules into three different units as indicated in Figure 3 and Supplemental Material Figure S1. The chemistry of the carbonothionylamide unit (fragment 2) is very significant in determining its stability and coordination with metal atom when acting as a bidentate ligand.^[19] All the optimized geometries were characterized with zero imaginary frequency indicating their local minimum. The molecule 5P had the lowest carbonothionyl





Figure 3. Schematic molecular structures of molecules 3P, 4P, 3M, and 4M. The plane represented by dotted lines divides each carbonothionylamide molecule into fragments and allows interactions. The numbering is for the explanation of their C-NMR.

(C=S) bond distance indicating a stronger bond strength because of the effect of the dipyridyl-amino group (fragment 1) while 3P and its *meta* derivative, 3M had the longest bond distance indicating a weaker strength (Figure 4) as the effect of diethyl-amino group of its fragment 1.^[20,21]

In all the molecules, the *meta*-substituted (M) as a result of the para position of the nitro group on the benzyl unit of fragment 3 was found to be relatively more thermodynamically stable than their corresponding *para*-substituted (P) as evidenced from the lower energy and Gibbs free energy (Supplemental Material Table S1). However, the para derivatives had lower HOMO and LUMO energy level with a longer bandgap compared to the *meta*-substituted.

The selected bond distances and the bond order of the optimized geometries for those that involved the N, O, and S atoms are listed in Supplemental Material Table S2. A higher twist in the dihedral angle that defined the plane $O = C \dots S = O$ in fragment 2 over their linking nitrogen atom in each molecule (as shown in Figure 2 for 1P) was noticed in 3P, followed by 3M, while the smallest was found in 5M then 5P. Generally, there was a relatively greater twist of this angle in the *meta*-substituted (M) than in the *para*-substituted (P) except for the 2P. The single bonds (-) have bond orders that are relatively close to the expected value of 1.00 but the double bonds especially the conjugated ones are significantly lower than the expected value of 2.00. The C = O bond of fragment 2 had the highest bond order of approximately 2.00, the highest among the groups with

double bonds. The two N = O of the nitro group of fragment 3 had the lowest bond order among all the expected double bonds besides the imidazoyl N = C bond as a peculiar feature of the 2M and 2P. All the molecules were characterized with some two-bond distance interactions and the O...O interaction of the nitro group of fragment 3 observed to be the strongest. The sulfur atom of fragment 2 is also found to have significant hydrogen bond interaction with the nitrogen atom of fragment 1 (S...N). The strong resonance effect at N-C bond linking fragment 1 to fragment 2 was observed as this bond order increased by 1.10 in all the molecules to the stronger two bond distance electron coupling of S...N interaction.

The IR spectra of the derivatives of carbonothionylbenzamide

The computed IR spectra showed a significant correlation with the experimental IR (Figure 5 and Supplemental Material Figure S5) as a further confirmation of the experimental structure of the molecules. Both experimental and theoretical IR clearly showed no significant difference between the *meta* nitro (M) and *para* nitro (P) molecules (Supplemental Material Figure S5). The details of the types of all the prominent IR and RAMAN vibrations (\geq 20.00) are described in the supplementary Material Table S3. The assigned spectra with the negative percentage contribution in Supplemental Material Table S3 were characterized with



Figure 4. The optimized geometries of the ten derivatives of carbonothionylbenzamide molecules and the selected bonds distances and dihedral angle (fragment 2) in the plane as indicated with arrow lines in molecule 1P.

opposite vibrations that reduced the observed frequencies obtained at the wavelength. The stretching vibration of C = S in fragment 2 in many of the molecules were not found to be prominent. The IR and RAMAN wavelengths (in cm^{-1}) for the C = S bonds were observed for the molecules 1M, 2M, 3M, 4M, 5M, 1P, 2P, 3P, 4P and 5P at 803.36, 1145.03, 878.24, 875.03, 804.30, 799.93(781.10), 872.98(429.35), 871.61, 879.83 and 805.64, respectively, where the values in parentheses are the second wavelength of C = S vibration in the same molecule. The bending vibrational angle C-N-C in the fragment 2 appeared at the wavelength (cm⁻¹) of 184.34(156.83), 173.52, 181.03, 177.76, 193.13, 158.96, 190.36, 173.11, 176.63, 158.96 in the molecule 1M, 2M, 3M, 4M, 5M, 1P, 2P, 3P, 4P, and 5P, respectively. The frequency of C-N-C bending vibration appeared at 0.20-5.10 in all the molecules. The stretching vibrations of the N-H in the fragment 2 in all the molecules appeared at 3538 to 3640 $\rm cm^{-1}$ having stronger RAMAN peak than IR except in both 2P and 2M with three N-H vibrations because of the presence of imidazole group.^[22] Unlike the stretching vibration of N-H, the stretching vibration of C=O appeared stronger in IR spectra than RAMAN and within the range $1837-1910 \text{ cm}^{-1}$ in the molecules.

The UV spectra of the derivatives of carbonothionylbenzamide

The computed UV data agreed with the experimental UV data. However, the computed absorption peaks appeared at relatively lower wavelength (Figure 6 and Supplemental Material Figure S6). A significant difference in the excitation frequency and wavelength was observed between the *meta* nitro (M) and *para* nitro (P) molecules in both the experimental and computational methods.

The experimental absorbance depended mostly on the concentration of the molecules, and can only be explained



Figure 5. The experimental and theoretical IR with the theoretical Raman spectra for molecules 1M, 1P, 2M, and 2P.



Figure 6. The experimental and theoretical UV spectra for molecules 1M, 1P, 2M, and 2P.

in terms of the theoretical absorbance values. The hyperchromic shift to higher molar absorptivity (higher absorbance) occurred in the *meta* molecules of 1M and 2M than corresponding *para*-isomers 1P and 2P, possibly because of the carbonyl group or mono substitution on the nitro. The opposite was observed in the molecules with di-substituents of the nitro as the molar absorptivity of the *meta* isomers 3M, 4M, and 5M reduced than the *para*-substituted 3P, 4P, and 5P (Supplemental Material Figure S6). The experimental λ_{max} for the *meta*-molecules and *para*-molecules are not significantly different and are found around 300, 430, 360, 350, and 350 nm for molecules 1–5, respectively. The calculated λ_{max} significantly varied, the values for the 1M, 2M, 3M, 4M, and 5M were 441; 416; 452; 477; and 422 whereas that of the *para* molecules 1P, 2P, 4P, 5P, and 5P appeared at 467; 420; 476; 433; 410 nm, respectively. Both experimental and theoretical clearly showed that 3P or 3M had the lowest values of λ_{max} while 4P or 4M had the highest. The observed experimental order of the λ_{max} of P followed the same order as that of M (4M > 2M > 1M > 5M > 3M). This transition in most of the molecules was from fragment 2 to fragment 3 but different in 4M, and its *para* 4P, from fragment 2 to fragment 1 (Supplemental Material Table S4). It was also different in 5M and its *para* 5P where it was from fragment 1 to fragment 3. The λ_{max} is mostly characterized with the transition from a lower HOMO or HOMO – 1 which are predominantly around the S-atom π -bonds (as shown supplementary Material Table S5) to either LUMO or LUMO +

Table	1. T	he contribution	of the	electrostatic	(ES),	polarizability	(POL),	electrical (E	L = ES + PO	L + SE),	, and	charge	transfer	(CT) to	the	total	stability	interaction
energy	(E_{to})	_{tal}) in kcal/mol.																

Molecule	Total SCF energy	Energy change	Energy of deletion	ES	POL	EL	СТ	E _{Total}
1M	-1316.82	-1319.00	2.18	-945.37	36.57	-891.83	-1368.57	-758.91
1P	-1316.82	-1319.00	2.18	-941.66	36.39	-888.06	-1366.80	-754.92
2M	-1579.49	-1581.70	2.22	-952.53	-1.31	-913.32	-1392.01	-774.00
2P	-1579.49	-1581.70	2.21	-938.51	-19.62	-906.02	-1386.42	-764.58
3M	-1246.14	-1248.49	2.35	-955.66	-44.01	-924.41	-1476.20	-788.99
3P	-1246.14	-1248.49	2.35	-951.13	-45.46	-920.12	-1474.71	-785.17
4M	-1549.29	-1551.43	2.14	-871.03	-50.97	-851.27	-1341.76	-721.06
4P	-1549.29	-1551.43	2.14	-867.33	-52.30	-847.99	-1341.77	-717.20
5M	-1581.35	-1583.42	2.07	-856.09	-52.16	-840.71	-1298.69	-702.35
5P	-1581.36	-1583.42	2.06	-851.95	-45.85	-834.17	-1289.59	-698.30

1 that are also predominantly π -bonds. Therefore, this λ_{\max} absorption transition can be defined as $\pi \to \pi^*$ transition in the ligands.^[23]

The highest wavelength toward the visible region in each of the ligands was characterized mostly with HOMO to LUMO except in 2M (HOMO \rightarrow L+1), 5M (H - $1 \rightarrow LUMO$) and 2P (H - $1 \rightarrow LUMO$). The highest wavelength absorption was the predominant transfer of an electron from fragment 2 to fragment 3 in all the M and P molecules except for the 5M and para form, 5P that was predominantly from fragment 1 to fragment 3. The HOMO and H+1 were predominantly from fragment 2 except in 5M and 5P where the H+1 is fragment 1 while LUMO in all the molecules was fragment 3 as shown in Supplemental Material Table S6. The explanation agreed with the highest wavelength transition in 5M and 5P because of their significant transition from fragments 1 through to 3, contrary to other molecules of which their transition is from fragment 2 to 3. Details of each fragment contribution to the first six HOMO and LUMO energy levels are presented in Supplemental Material Table S6. The HOMO to LUMO transition from the table had the smallest absorptivity and can therefore be assigned as the $n \rightarrow \pi^*$ electron transition. This is presented from the features of the orbitals in the Supplemental Material Table S5, where the HOMO predominantly is present around the S atom lone pair and the LUMO at the fragment 3 benzene π -bonds.

Fragment interactions

The natural energy decomposition analysis (NEDA) analysis was used to compute the contribution of each of the fragments to the stability of the molecules and natural bond order $(NBO)^{[24]}$ method was used for the nature of the intramolecular charge transfer. The data generated for each of the fragment energy and dipole in the absence of the other fragments (def), in the presence of other fragments (cp), and the difference between the two states (ind) for each of the molecules are shown in Supplemental Material Table S6. The contribution of the electrostatic (ES), polarizability (POL), electrical (EL = ES + POL + SE), and charge transfer (CT) to the total stability energy (E_{total}) of the intra-fragment interaction within each of the molecules are shown in Table 1.

The induced dipole of each fragment in Supplemental Material Table S7 shows the level of its predisposition to nucleophilic attack or electrophilic attack depending on the nature of the fragment. A higher dipole moment of a fragment will have higher polarizability that will allow significant penetration of the electron from donor or acceptor depending on whether it is positively or negatively charged. The higher the value of induced dipole moment of a fragment that is negatively charged, the higher its level of is being available for to make a nucleophilic attack. In all the molecules (both P and M molecules), the fragment 2 became more available for nucleophilic attack than other fragments except in the para-molecule of imidazoyl derivative (2P) where the induced dipole of the fragment 1 significantly increased more than other fragments. This provided further insight into the reason for exaltation frequency of the π - π ^{*} transition (to 257.45 nm) in 2P which significantly got higher than the 2M and other molecules. The availability of fragment 2 for a nucleophilic attack made it important for metal coordination with the expected reaction for these kinds of bidentate ligands. The values of the induced dipole for fragment 2 were relatively in a close range in all the molecules but that of the molecule 3M and 3P have the highest tendency for the nucleophilic attack and the highest induced energy besides the fragment of the para imidazoyl molecule 2P. No significant changes were observed in the induced dipole of the fragments in each molecule from its meta- to para-substituted compounds except only in 2P as previously explained. The predicted positive sign on fragment 2 showed that it acted as the strong electrophilic center and well predisposed to strong nucleophilic attack in all the ligands.

The total stability energy of intra-fragment interaction and the contribution of the electrostatic (ES), polarizability (POL), electrical, and charge transfer (CT) are shown in Table 1. The level of contributions of different factors to the stability of the intra-fragment interactions is in the order of CT > ES > EL > POL. In all the molecules, there is a relatively small decrease in the total stability energy of the fragment interaction from the *meta*-substituted (M) to *para*substituted compounds (MOF) which furthers the insight into the reason. Whereas, the M compounds appeared thermodynamically more stable. Both the 3M and 3P, which had the highest values of the induced dipole for fragment 2, were relatively stable for inter-fragment interactions compared to other molecules.

The MESP analysis

The only possible existence of V_{max} is those associated with the nuclei as it has been pointed out that V_{max} does not



Figure 7. The change in the computed MESP values of ΔV_{min} , ΔV_{max} , and lowest value of the ΔV_{atom} of the molecules from that of the 1M (all in kcal/mol).

Table 2. The computed MESP values of V_{min} , V_{max} and that of the sulfur atom, $V_{\rm S}$ of the molecules.

Molecules	V _{min}	V _{max}	Vs
1M	-42.04	58.50	-37202.05
1P	-41.00	60.99	-37200.34
2M	-49.44	58.29	-37212.71
2P	-47.47	59.62	-37209.24
3M	-28.67	39.94	-37209.64
3P	-28.88	42.50	-37208.25
4M	-43.92	43.32	-37206.68
4P	-42.65	46.44	-37204.84
5M	-46.78	42.60	-37204.10
5P	-43.59	46.50	-37199.03

All the values in kcal/mol.

exist in the three dimensions of the MESP surface.^[25–28] Therefore, the V_{max} reported in this work represent only the most positive or highest values of the MESP surface.^[29–31] The importance of application of MESP for the analysis of the effect of *para*-substitution on benzene has been reported in the literature.^[32]

The significance of the $V_{\rm min}$ and $V_{\rm max}$ was that a more negative value of $V_{\rm min}$ indicated a higher electron density whereas more positive values of $V_{\rm max}$ implied a more electron-deficient positions in the molecule. The change in the computed MESP analysis: $\Delta V_{\rm min}$, $\Delta V_{\rm max}$, and lowest value of the $\Delta V_{\rm atom}$, were obtained by subtracting the values obtained for 1M from each of the other molecules as shown in Figure 7. The respective values of $V_{\rm min}$, $V_{\rm max}$, and $V_{\rm atom}$ for each of the molecules are itemized in Table 2. The values of the reported $V_{\rm atom}$ are the highest magnitude obtained among all the atoms which were found to correspond to that of the sulfur atom.

All the *meta* derivatives had more electron-rich centers compared to their *para* molecules as evident from the lower energy values of V_{min} , V_{max} , and V_S (Figure 7, Table 2). The molecules with di-substituent on the nitro unit (3P–5P or 3M–5M derivative) had less electron-deficient center than the mono-substituted or carboxylic containing nitro unit (1P–2P or 1M–2M derivatives) as evident from their V_{max} values. The order of the electron-rich center V_{min} in the molecules using the *meta*-substituted derivatives was 2M > 5M > 4M >1M > 3M. Though 3M or 3P were found to have less electronrich center V_{min} , yet had a very significant atomic potential of the sulfur atom V_S in comparison to 4M, 5M, and 1M. The position V_{min} was found closely positioned to the C=O group of the carbonothionylamide unit of the fragment 2 and V_{max} directly on top of the hydrogen atom of the N-H group of the amide unit of fragment 2 as depicted for 1P in the MESP surface plot (Figure 8).

Atomic electron susceptibility

The relative ability of each of the atoms in a molecule to act as electrophilic (–ve), nucleophilic (+ve), and radical attack site can best be understood using Fukui indices. The expression for the Fukui indices usually is derived from the electronic density v(r) for the change in the number of the electrons (*N*) under a constant external potential v(r):^[33]

$$F(r) = \left(\frac{\delta\rho}{\delta N}\right)_{\nu}$$

The highly nucleophilic or electrophilic or radical sites are expected to have a higher value of Fukui function (f_j) .^[34] The condensed expression of the atomic Fukui functions for *j*th atom site can be calculated from the atomic charges q(N)for the electrophilic (f_j^-) or nucleophilic (f_j^+) or radical (f_j^0) as follows:

$$f_j^- = q_j(N) - q_j(N-1)$$

$$f_j^+ = q_j(N+1) - q_j(N)$$

$$f_j^0 = \frac{1}{2} \left[q_j(N+1) - q_j(N-1)\% \right]$$

The values of the electrophilic (f_j^-) , nucleophilic (f_j^+) , and radical (f_j^0) Fukui indices for the sulfur, oxygen, nitrogen, and carbon atoms in each of the molecules are presented in the supplementary Material Table S8 while their MESP surfaces (MEPS) mapping showing the atomic sites for electrophilic, nucleophilic, and radical reactions are shown in Figure 9 and Supplemental Material Figure S7.

The atomic charges from the natural population analysis (NPA) were used to compute all the Fukui indices because of the ability to differentiate the reactive site^[35] and its insensitive to basis set because of the use of the occupancy-weighted symmetric orthogonalization procedure to transform the nonorthogonal atomic orbitals into an orthonormal set.^[36] Therefore, the orbitals of highest occupancy were strongly preserved while those of negligible occupancy can be distorted freely to achieve orthogonality.^[35] However, NPA tends to overestimating the ionicity.^[37] All the negative values of Fukui indices are usually disregarded and the site with the highest value of Fukui indices indicates a high reactivity but in some cases does not necessarily be the most reactive site.^[35,38,39]

As clearly shown in both Figure 9 and Supplemental Material Figure S7, the strongest mapped area as the electrophilic site is fragment 1 while fragments 2 and 3 act as the strong nucleophilic sites. A closer look at the atomic contributions according to their Fukui indices (Supplemental Material Table S8) shows that the main electrophilic center happened to be the nitro group (NO₂) while the S atom, the most significant nucleophilic center. An agreement with the predominance of the HOMO in the S atom of fragment 2,



Figure 8. The MESP surface, showing the position of the potential of the sulfur atom (V_s), minimum (V_{min}), maximum (V_{max}) potential of molecule 1M and 1P. The values are in kcal/mol.



Figure 9. The MESP surfaces (MEPS) of the molecules in their neutral, electrophilic (-) and nucleophilic (+) states for molecules 1M, 2P, 2M, and 2P.

and the LUMO predominantly in the nitro group of fragment 3. The S atom in all the molecules also had a high tendency of acting as a point for a radical attack in addition to its properties as the nucleophilic center.

Synthetic and computational methods

Experimental materials

Analytical grade reagents were used for synthesis. 3-Nitro benzoyl chloride, 4-nitro benzoyl chloride glycine, and

histidine were purchased from Sigma-Aldrich. Diethylamine, diphenylamine, 2,2-dipyridylamine, and ammonium thiocyanate were obtained and used as supplied.

Ethanol was distilled with Mg ribbon/iodine (which remove the impurities), and stored with molecular sieve 3 Å. Other solvents, such as methanol, ethyl acetate, *n*-hexane, acetone, diethyl ether, and dichloromethane, were stored undistilled with molecular sieve 3 Å. Chloroform, and distilled water were used without further purification. Besides, dimethyl sulfoxide and deuterated chloroform (CDCl₃) were

purchased from Sigma-Aldrich and deuterated dimethyl sulfoxide (DMSO- d_6) was purchased from Merck Chemical Limited.

Experimental equipment and methods

StuartTM Scientific apparatus SMP 3 was used without correction to determine the melting point of the compounds. Waters Micromass LCT Premier MS instrument equipped with an electrospray ionization (ESI) source and a time-of-flight (TOF) mass analyzer was for mass of the molecular ions and fragments. The infrared spectroscopy was measured by ATR Perkin Elmer Spectrum 100 spectrometer. Likewise, both ¹H and ¹³C NMR were recorded on BRUKER 400 MHz spectrometer (AVANCE^{III} 400) in DMSO-*d*₆ and CDCl₃ with TMS as an internal standard. NMR data were expressed in ppm. The UV/visible spectra were taken on a Shimadzu NIS-3600 containing quartz cuvettes having a path length of 1 cm in the range 200–400 nm for UV and 400–900 nm for the visible region.

Experimental structural elucidation

We analyzed five *meta* nitro (M) and five *para* nitro (P) benzamide carbonothionyl derivatives (see Supplementary Material Figure S1). All the ten ligands tagged 1P, 1M, 2P, 2M, 3P, 3M, 4P, 4M, 5P, and 5M were synthesized and characterized experimentally. Only the experimental characterization of 3P, 3M, 4P, and 4M were reported in this work while the rest were already reported by some of the authors in the literature.^[15,16] The ¹H NMR, ¹³C NMR, and the mass spectra for the molecule 3P, 3M, 4P, and 4M were part of the supplementary (Supplemental Material Figures S2–S4) and the characterization data are presented in the following sections.

3P: N,N-(diethyl-2-thiocarbamoyl)-4-(4-nitro phenyl carboxamide)

Appearance: Yellow solid. Yield: 2.22 g (39.50%); Melting point (147–149 °C). ¹H NMR, 400 MHz (DMSO- d_6), ppm: δ 10.95 (s, 1H, 7-NHCO), 8.32 (d, 1H, H-2), 8.32 (d, 1H, H-4), 8.12 (d, 1H, H-1), 8.12 (d, 1H, H-5), 3.57 (m, 2H, H-11), 3.57 (m, 2H, H-9), 1.21 (s, 3H, H-10), 1.21 (s, 3H, H-12). ¹³C NMR (DMSO- d_6), ppm: δ 179.65 (C-8), 162.66 (C-7), 149.47 (C-3), 136.64 (C-6), 129.50 (C-1), 129.50 (C-5), 129.41 (C-4), 123.41 (C-2), 47.22 (C-9), 47.22 (C-11), 13.30 (C-10), 13.30 (C-12). IR, ν (cm⁻¹): 3279 (N-H), 1686 (C=O), 1347 (C=S), 1645 (C=C). (TOF-ESI MS) m/z (%): Calcld 280.0834. Found [M-H]⁻ 280.0965 (100).

3*M*: N,N-(diethyl-2-thiocarbamoyl)-4-(3-nitro phenyl carboxamide)

Appearance: Brown solid. Yield: 1.00 g (58%); Melting point (110–112 °C). ¹H NMR, 400 MHz (DMSO- d_6), ppm: δ 8.61 (d, 1H, J = 8.2 Hz, H-1), 8.37 (d, 1H, J = 7.4 Hz, H-3), 8.13 (d, 1H, J = 1.8 Hz, H-5), 7.63 (d, 1H, J = 8.0 Hz, H-4), 3.96 (m, 2H, J = 7.6 Hz, H-1), 3.96 (m, 2H, J = 7.6 Hz, H-1),

1.26 (s, 3H, J = 10.2 Hz, H-10), 1.26 (s, 3H, J = 7.0 Hz, H-12). ¹³C NMR (DMSO- d_6), ppm: δ 122.96 (C-1), 178.60 (C-8), 161.87 (C-7), 148.36 (C-2), 137.37 (C-6), 133.61 (C-5), 130.17 (C-4), 127.23 (C-3), 47.92 (C-9), 47.92 (C-11), 13.43 (C-10), 13.43 (C-12). IR, ν (cm⁻¹): 3275 (N-H), 1682 (C=O), 1346 (C=S), 1659 (C=C). (TOF-ESI MS) m/z(%): Calculated 280.0834. Found [M-H]⁻ 280.0846 (100).

4P: N,N-(diphenyl-2-thiocarbamoyl)-4-(4-nitro phenyl carboxamide)

Appearance: Yellow solid. Yield: 5.97 g (79%); Melting point $(144-146 \,^{\circ}\text{C})$. ¹H NMR, 400 MHz (DMSO- d_6), ppm: δ 10.15 (d, 1H, 2-NHCO), 8.25 (d, 1H, J = 8.8 Hz, H-5), 8.25 (d, 1H, J = 8.8 Hz, H-7), 8.15 (d, 1H, J = 5.0 Hz, H-4), 8.15 (d, 1H, J = 5.0 Hz, H-8), 7.73 (m, 1H, J = 8.5 Hz, H-11), 7.73 (m, 1H, J = 8.5 Hz, H-13), 7.73 (m, 1H, J = 7.8 Hz, H-17), 7.73 (m, 1H, J = 7.8 Hz, H-19), 7.60 (m, 1H, J = 8.5 Hz, H-12), 7.60 (m, 1H, J=8.5 Hz, H-18), 6.95 (d, 1H, H-10), 6.95 (d, 1H, H-14), 6.95 (d, 1H, H-16), 6.95 (d, 1H, H-20),. ¹³C NMR (DMSO- d_6), ppm: δ 183.67 (C-1), 165.78 (C-2), 149.48 (C-6), 143.36 (C-9), 143.36 (C-15), 139.20 (C-3), 130.02 (C-11), 130.02 (C-19), 130.02 (C-13), 130.02 (C-17), 128.87 (C-4), 128.87 (C-8), 123.24 (C-5), 123.24 (C-7), 119.60 (C-10), 119.60 (C-14), 119.60 (C-16), 119.60 (C-20), 116.67 (C-12), 116.67 (C-18). IR, ν (cm⁻¹): 3382 (N-H), 1721 (C = O), 1348 (C = S), 1697 (C = C). (TOF-ESI MS) m/z(%): Calculated 376.0834. Found [M-H]⁻ 376.1066 (6).

4*M*: N,N-(*diphenyl-2-thiocarbamoyl*)-4-(3-nitro phenyl carboxamide)

Appearance: Yellow solid. Yield: 2.25 g (29.70%); Melting point (110–112 °C). ¹H NMR, 400 MHz (DMSO- d_6), ppm: δ 8.67 (d, 1H, J = 2.0 Hz, H-4), 8.32 (d, 1H, J = 2.0 Hz, H-6), 7.91 (d, 1H, J = 2.0 Hz, H-8), 7.54 (d, 1H, J = 2.0 Hz, H-7), 7.31 (m, 1H, J = 7.7 Hz, H-13), 7.32 (m, 1H, J = 1.3 Hz, H-11), 7.29 (m, 1H, J=7.7 Hz, H-17), 7.28 (m, 1H, J=1.3 Hz, H-19), 7.23 (d, 1H, J=7.8 Hz, H-10), 7.21 (d, 1H, H-14), 7.19 (d, 1H, J=1.4 Hz, H-16), 7.17 (d, 1H, J=8.0 Hz, H-20), 7.01 (m, 1H, J = 7.3 Hz, H-18), 6.98 (m, 1H, J = 1.1 Hz, H-12). ¹³C NMR (DMSO- d_6), ppm: δ 181.46 (C-1), 160.52 (C-2), 148.22 (C-5), 143.13 (C-9), 143.13 (C-15), 134.44 (C-3), 133.57 (C-8), 130.12 (C-17), 130.28 (C-7), 130.12 (C-11), 130.12 (C-13), 130.12 (C-19), 128.02 (C-6), 122.47 (C-4), 120.99 (C-10), 120.99 (C-14), 120.99 (C-16), 120.99 (C-20), 117.81 (C-12), 117.81 (C-18). IR, ν (cm⁻¹): 3152 (N-H), 1702 (C = O), 1354 (C = S), 1591 (C = C). (TOF-ESI MS) Calculated 376.0834. Found m/z(%): [M-H]⁻ 376.0934 (100).

Computational methods

The optimization of the molecules was carried out using the hybrid DFT functional M062X that is known to be good for thermodynamic and kinetic calculations^[40] and basis set 6-311G(d,p) in the Gaussian 09 (G09) package.^[41] The associated properties with the natural bond orbital (NBO) analysis^[42] and natural energy decomposition analysis

(NEDA)^[43] were obtained using NBO 6.0G program^[44] as implemented in the FIREFLY 8.1.G^[45] which is partially based on the GAMESS (US)^[46] source code. The IR and RAMAN spectra assignments were carried out by the potential energy distribution (PED) analysis as implemented in VEDA package.^[47]

The MESP was computed from a standard equation at a point *r* as:

$$V(r) = \sum_{A}^{N} rac{Z_A}{|r-R_A|} - rac{
ho(r') d^3 r'}{|r-r'|}$$

where Z_A , R_A , $\rho(r')$, and N represent the charge of nucleus A, its position, electron density, and the total number of nuclei, respectively. The critical points (CP) corresponding to (3, +3) and by (3, -3) represent the MESP minima (V_{\min}) and MESP maxima (V_{\max}) on the MESP topology analysis while the saddle points are represented with (3, +1) and (3, -1).^[48]

The molecular rendering was achieved using programs: Chimera,^[49] MarvinSketch,^[50] Gnuplot,^[51] and VMD.^[52]

Conclusion

The experimental synthesis and computational study of five *meta* nitro and five *para* nitro with carbonothionylbenzamide unit were carried out. Each of the ten molecules was fragmented into three to gain better insight into the electronic communication, nucleophilicity, and stability. The chemistry of the carbonothionylamide unit (fragment 2) became very significant as it can determine its stability and coordination with metal when acting as a bidentate ligand.

No significant difference was observed between the IR spectra of meta-nitro (M) and *para* nitro (P) substituted molecules according to the result obtained from both experimental and theoretical methods.

The type of the substituent on the amino group of fragment 1 have a long-range effect on the ¹³C NMR shielding and IR wavenumber as it resulted in higher shielding tensor of the carbon atoms in C=O and C=S and also higher wavenumber for the vibration C=O and C=S in molecule 4P or 4M because of the presence of dibenzylamino group compared to that of 3P or 3M that have the lowest because of the presence of diethylamino group.

The presence of dipyridylamino group in 5P and 5M resulted in stronger carbonothionyl (C=S) bond while diethylamino group led to weaker bond as found in 3P and 3M.

The *meta* position of the nitro unit (M) resulted in more thermodynamically stable structures but has a higher HOMO and LUMO energy levels with lower band-gap compared to the *para* (P) compounds. There was a little relative reduction in the total stability energy of the fragment interaction from the *meta*- to *para*-substituted compounds.

All the meta derivatives had more electron-rich center than the para-substituted compounds as evident from the lower energy values of $V_{\rm min}$, $V_{\rm max}$, and $V_{\rm S}$. The order of the electron-rich center $V_{\rm min}$ in the molecules for the meta-substituted compounds was 2M > 5M > 4M > 1M > 3M, which was found close to the C = O group of the carbonothionylamide unit of the fragment 2.

The presence of carboxylic or the mono-substitution of the nitro group in the meta-substituted molecule 1M and 2M resulted in a hyperchromic shift to higher UV molar absorptivity compared to their *para*-substituted molecule in contrast to the di-substituted nitro compounds as the molar absorptivity of the *meta*-substituted – 3M, 4M, and 5M is lower than the *para*-substituted 3P, 4P, and 5P.

The longest wavelength toward the visible region in each of the ligands was characterized mostly with HOMO to LUMO.

The presence of the diethylnitro group in molecule 3M or 3P resulted in a more susceptible fragment 2 to nucleophilic attack which enhanced their bidentate properties as ligand and also resulted in better fragment interaction energy.

The results of the Fukui indices show that the main electrophilic center in the molecules was located on the nitro group (NO_2) while the S atom was the most significant nucleophilic center. This justified for the S atom predominantly to be HOMO and the LUMO was predominantly the nitro group.

Among all the atoms in the molecules, the sulfur atom had the lowest atomic potential energy (V_{atom}) and more pronounced in molecules 2M and 3M than other compounds.

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Ethical statement/conflict

This study does not require any ethical clearance and also there is no conflict of interest.

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