



Article

Polynuclear Cu(I) and Ag(I) Complexes of 1,3-Diisobutyl Thiourea, Synthesis, Crystal Structure and Antioxidant Potentials

Awal Noor ^{1,*}, Adnan Shahzad ^{2,3}, Ezzat Khan ^{2,4,*}, Muhammad Nawaz Tahir ⁵, Gul Shahzada Khan ⁴, Amin ur Rashid ⁶ and Muhammad Said ²

¹ Department of Basic Sciences, Preparatory Year Deanship, King Faisal University, Al Hofuf 31982, Al-Hassa, Saudi Arabia

² Department of Chemistry, University of Malakand, Chakdara 18800, Pakistan

³ Institute of Chemical Sciences, University of Swat, Swat 19120, Pakistan

⁴ Department of Chemistry, College of Science, University of Bahrain, Sakhir 32038, Bahrain

⁵ Department of Physics, University of Sargodah, Sargodah 40100, Pakistan

⁶ Department of Applied Physical & Material Sciences, University of Swat, Swat 19120, Pakistan

* Correspondence: anoor@kfu.edu.sa (A.N.); ekhan@uom.edu.pk (E.K.)

Abstract: Reaction of the 1,3-diisobutyl thiourea (L) with MX [M = Cu, Ag and X = Cl, NO₃] provide polynuclear heteroleptic complexes [Cu₃L₃Cl₃] (1), [Ag₂L₆](NO₃)₂ (2) and [Ag₆L₈Cl₄] (3). All complexes were characterized by single crystal X-ray diffraction. The solid-state crystal of these complexes (1–3) were determined by single crystal XRD. Which shows that complex (1) is tri-nuclear with trigonal planer arrangement, complex (2) is binuclear with four membered metalacyclic ring and complex (3) is hexa-nuclear. Complexes (1–3) are tested for their free radical scavenging activity by using 2,2-diphenyl-1-picrylhydrazyl free radical (DPPH) showing moderate potential.

Keywords: 1,3-diisobutyl thiourea; polynuclear complexes; Cu(I)/Ag(I) complexes; X-ray diffraction; antioxidant potential



Citation: Noor, A.; Shahzad, A.; Khan, E.; Tahir, M.N.; Khan, G.S.; Rashid, A.u.; Said, M. Polynuclear Cu(I) and Ag(I) Complexes of 1,3-Diisobutyl Thiourea, Synthesis, Crystal Structure and Antioxidant Potentials. *Inorganics* **2022**, *10*, 185. <https://doi.org/10.3390/inorganics10110185>

Academic Editors: Marius Andruh and Wolfgang Linert

Received: 7 September 2022

Accepted: 25 October 2022

Published: 27 October 2022

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Thiourea derivatives are active molecules acting as ligands in the development of coordination, bioorganic and bioinorganic chemistry [1]. Their complexes have been found to be potent antioxidant agents and enzyme inhibitors [2–4]. Generally, thiourea ligands are monodentate in nature, however, additional coordination sites at appropriate positions may afford chelates which exhibit extra stability [5] while bulk of the ligand saturates the coordination sphere of the central metal ion [6]. The chemistry of high nuclearity of polynuclear complexes of copper and silver has engrossed a great consideration from scientists in the last decade due to their role in catalysis [7–9], luminescence [10], nanoparticles [11–13], medicines [14,15], gas storage [16,17] and molecular magnet [18]. Thiourea based polynuclear complexes of copper(I) and silver(I) have been of particular interest due to their structures [19,20]. Studies reveal that in addition to the bonding mode of the ligand, metal to ligand ratio, solvent and temperature [21,22] and the steric bulk of the ligand plays the most significant role in determining the nuclearity of the cluster [23–26]. Sulfur atom of thiourea could provide bridges between metal ions due to its flexible coordination mode [27–31]. Thus, thiourea derivatives are among the most suitable ligands for integrating many metals ions in small molecular crystals [28–30,32–34].

In this study, keeping in mind the above mentioned advantages and exciting chemistry of thiourea derivatives, 1,3-diisobutyl thiourea (L) having low steric bulk was used for the synthesis of high nuclearity metallic clusters of copper(I) and silver(I) complexes, [Cu₃L₃Cl₃] (1), [Ag₂L₆](NO₃)₂ (2) and [Ag₆L₈Cl₄] (3). The choice of the title ligand, 1,3-diisobutyl thiourea (L) is based on flexible coordination behavior of sulfur atom of thiourea.

The structure of polynuclear metal complexes was determined by X-ray diffraction and all the complexes were tested for their antioxidant potentials. Hirshfeld surface analyses were used to get insights of the strength of the intermolecular interactions.

2. Experimental

2.1. General

All solvents and chemicals were acquired from commercial sources and were used as received without further purification. Solution of carbon disulphide (CS_2) in pet. ether (ca. 100 mL) was cooled to 0°C in an ice bath. A two equivalent excess amount of isobutylamine was added over a period of 10 min, with constant stirring. The reaction mixture was stirred for 12 h, after completion of the reaction all readily volatile material were removed under reduced pressure. Pure crystals of the compound were obtained and structurally confirmed as described in literature [35].

2.2. X-ray Diffraction Crystallography

Single crystals X-ray diffraction data (Mo-K α , $\lambda = 0.71073 \text{ \AA}$) of **1** and **2** were collected using a Bruker kappa APEXII CCD diffractometer and of for **3** the data were collected using STOE-IPDS II diffractometer fitted with low temperature unit. Crystal structures were refined with the help of SIR97 [36], SHELXL97 [37], WinGX [38], SAINT [39] and PLATON [40]. Crystallographic data of selected structural features and refinement details for the new complexes **1–3** presented in this study are summarized in Tables 1 and 2.

2.3. Syntheses of Complexes

[Cu₃L₃Cl₃] (1): $\text{CuCl}_2 \cdot 2\text{H}_2\text{O}$ (0.2 g, 1.1 mmol) was treated with 1,3-diisobutyl thiourea (0.44 g, 2.2 mmol) in methanol and the reaction mixture was stirred overnight. The reaction mixture was kept for slow evaporation at room temperature. After several days colorless block-like crystals of **1** (shown in Figure 1) were obtained and were accordingly characterized by EIMS, infrared spectroscopy and X-ray diffraction. Yield: 77%; MS(EI): m/z (%): 188 (99) tu, 253 (8) Cu-tu; IR (KBr) 3203 cm^{-1} (w) N-H, 2956 cm^{-1} (s) C-H, 2869 cm^{-1} (s) 1653 cm^{-1} (s) C = S 207 cm^{-1} (s) Cu-S.

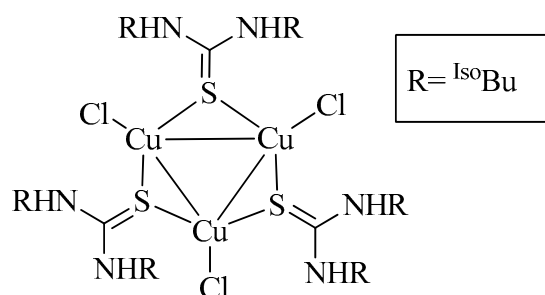


Figure 1. Trimeric copper complex, **1**.

[Ag₂L₆](NO₃)₂ (2): AgNO_3 (0.1 g, 0.588 mmol) in water was mixed with 1,3-diisobutyl thiourea (0.2 g, 1.06 mmol) in ethanol and the reaction mixture was stirred overnight at room temperature. Slow evaporation of the reaction mixture resulted in colorless crystals after 3 days and were characterized by X-ray structure analysis (Figure 2). Yield: 72%.

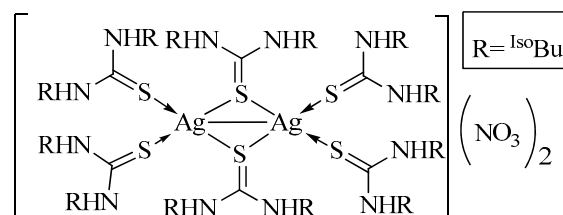


Figure 2. Dimeric silver complex, **2**.

[Ag₆L₈Cl₄] (3): A solution of AgCl (0.1 g, 0.7 mmol) was mixed with 1,3-diisobutyl thiourea (0.15 g, 0.79 mmol) in acetonitrile. After overnight stirring, the solvent was allowed to evaporate at room temperature. The colorless needle-like crystals of **3** (Figure 3) appeared in the solution after 3 days, they were separated from the mother liquor and the structure of the complex was determined by X-ray diffraction.

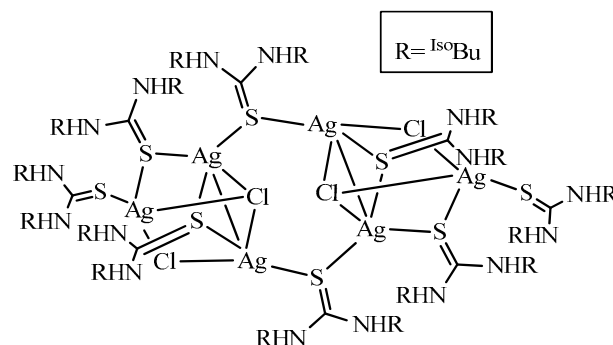


Figure 3. Silver cluster, **3**.

2.4. Hirshfeld Surface Analysis

The Hirshfeld surfaces and 2D fingerprint plots were generated using Crystal Explorer 17.50 [41]. The X-ray single-crystal crystallographic information files were used as input files. The default setting used for Hirshfeld Surface/fingerprint generation in Crystal Explorer is: property: none; resolution: High (standard). For fingerprint generation (di vs. de plot) we used; range: standard, filter: by elements and fingerprint filter options is both inside-outside elements including reciprocal contacts. The interactions with normalized contact distance in crystal structure shorter than the sum of the corresponding van der Waals radii of the atoms, are highlighted by red spots and the longer contacts with the positive d_{norm} value are represented in blue color.

2.5. Antioxidant Assay

Complexes **1–3** have been tested for their antioxidant activity. The DPPH free radical scavenging method has been employed to investigate representative compounds as antioxidant agents. When compounds donate hydrogen or electrons to the free DPPH radical, the initial absorbance of the corresponding solution decreases. These observations are taken as a key to measure radical scavenging activity. A solution of DPPH was prepared (39 mg/100 mL), absorbance was measured under normal conditions at 517 nm for blank (A_0). Specific amount of complex solution was mixed with DPPH, solutions were incubated in dark for 30 min at room temperature. The absorbance of each sample was measured at the same wavelength, 517 nm (A_{sample}). Percent inhibition (I) % of DPPH radical was calculated for the various concentrations of compounds as given below [42].

$$\text{Percent Inhibition I\%} = \frac{A_0 - A}{A_0} \times 100$$

3. Results and Discussion

In our previous study, we treated acetonitrile solution of the ligand with CuCl salt under normal conditions. In reaction, mononuclear complex was exclusively obtained and the reactions worked in the same way with other metal salts, namely CuI, ZnCl₂ and HgCl₂ [3]. When the reaction of Cu(II) salt with the identical ligand in ethanolic medium was carried out, reduction of the metal ion was observed and the trinuclear Cu(I) complex was obtained. The metal salt in repeated experiments under identical conditions with two equivalents of the ligand did not give expected mononuclear complex of general formula [CuL₂Cl₂]. The same ligand with AgNO₃ salt in a 2:1 molar ratio, respectively, did not afford [AgL₂]NO₃ as an expected precursor, rather reduction of Ag(I) ion (as evident from

development of black coloration in the solution) afforded binuclear complex **2**, bearing general formula $[\text{Ag}_2\text{L}_6](\text{NO}_3)_2$. The reaction solution contained trace amounts of some unknown impurities which did not allow for collection of other data to determine exact purity of the reaction. However, crystals of suitable dimensions were selected under microscope for structure determination. The effect of Cl^- radical in Ag salt was totally different and following the same procedure gave a cluster containing six Ag ions, in a 6:8 molar ratio, metal to ligand, respectively. The cluster $[\text{Ag}_6\text{L}_8\text{Cl}_4]\text{Cl}_2$ stabilization was achieved as a result of partial reduction of Ag(I) ion as was observed in complex **2**. The role of both Cl^- and thiourea ligand as bridging ligands was found prominent in cluster formation. The work described hereunder indicates that the presence of anion and reaction medium is crucial in describing coordination chemistry around Cu and Ag metal ions. The reactions of Ag salts in the presence UV radiation can also lead to unexpected products.

3.1. Description of Crystal Structure of $[\text{Cu}_3\text{L}_3\text{Cl}_3]$ (**1**)

The crystal structures of complexes **1**, **2** and **3** are elucidated by single crystal X-ray diffraction. The molecular crystal structure of complex **1** is given in Figure 4. Selected bond lengths and bond angles are enlisted in Table 1 and the crystallographic refinement data are given in Table 2. The tri-nuclear copper cluster crystallizes in triclinic crystal system with a space group P-1. The unit cell reveals non superimposable conformers of complex **1**. According to X-ray analysis the complex **1** is trimeric having two daughter diastereomers in unit cell of the said complex, the same has also been reported in other similar complexes [17]. The monomeric portion (L-M-Cl) of the complex is connected through bridging bond via sulfur atom of $\text{C}=\text{S}$ moiety of thiourea, providing Cu_3S_3 six membered metalacyclic ring adopting chair conformation. Chlorine atom is coordinated to Cu at axial position. The geometry around each Cu ion is distorted trigonal planar with varying angles around Cu center (in the range of 116.61° – 124.36°). The bond distance between Cu-S is $2.258 \text{ \AA}$ and is comparable to the analogous compounds [17,43]. The Cu-Cl bond distance of $2.182 \text{ \AA}$ is shorter than that of the mononuclear metal complex [$2.272(3) \text{ \AA}$] with the identical ligand². The trigonal arrangement of Cu-Cu in tri-nuclear unit is stabilized by Cu—Cu interaction with distance of $2.850 \text{ \AA}$ [44,45]. The supramolecular structure is stabilized via regular pattern of intra- and intermolecular hydrogen bonding N—H—Cl interactions as shown in Figure 5. The intermolecular N—H—Cl interactions [3.122 and $3.210 \text{ \AA}$] are shorter than the intramolecular interactions [3.256 and $3.291 \text{ \AA}$], which are in turn shorter than those for recently reported mononuclear copper complexes [$3.349 \text{ \AA}$]⁶. Attempts to get more insight into the strength of intermolecular interactions using Hirshfeld surface analyses were unsuccessful due to the disordered structure.

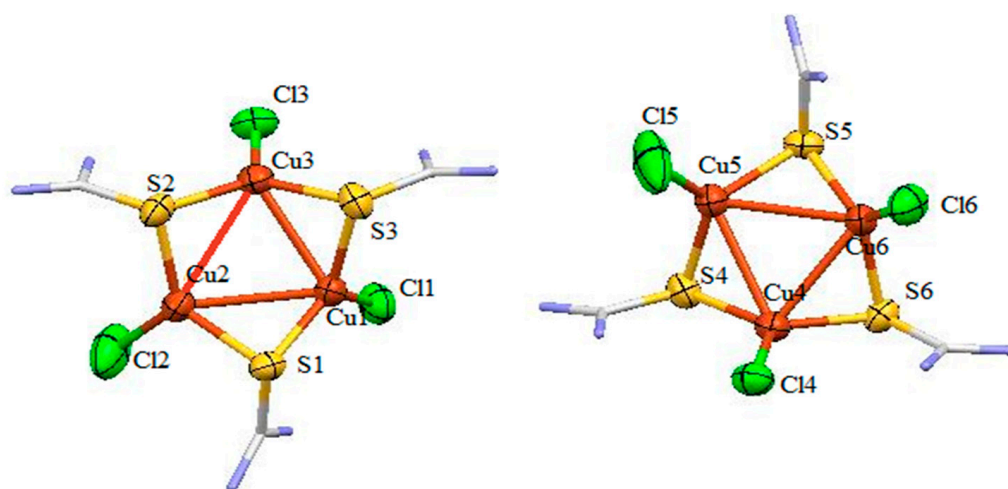


Figure 4. The molecular structure of compound **1**, only non-carbon atoms are numbered. Ellipsoids are drawn at 50% probability level; hydrogen atoms are omitted and carbons are represented by capped sticks.

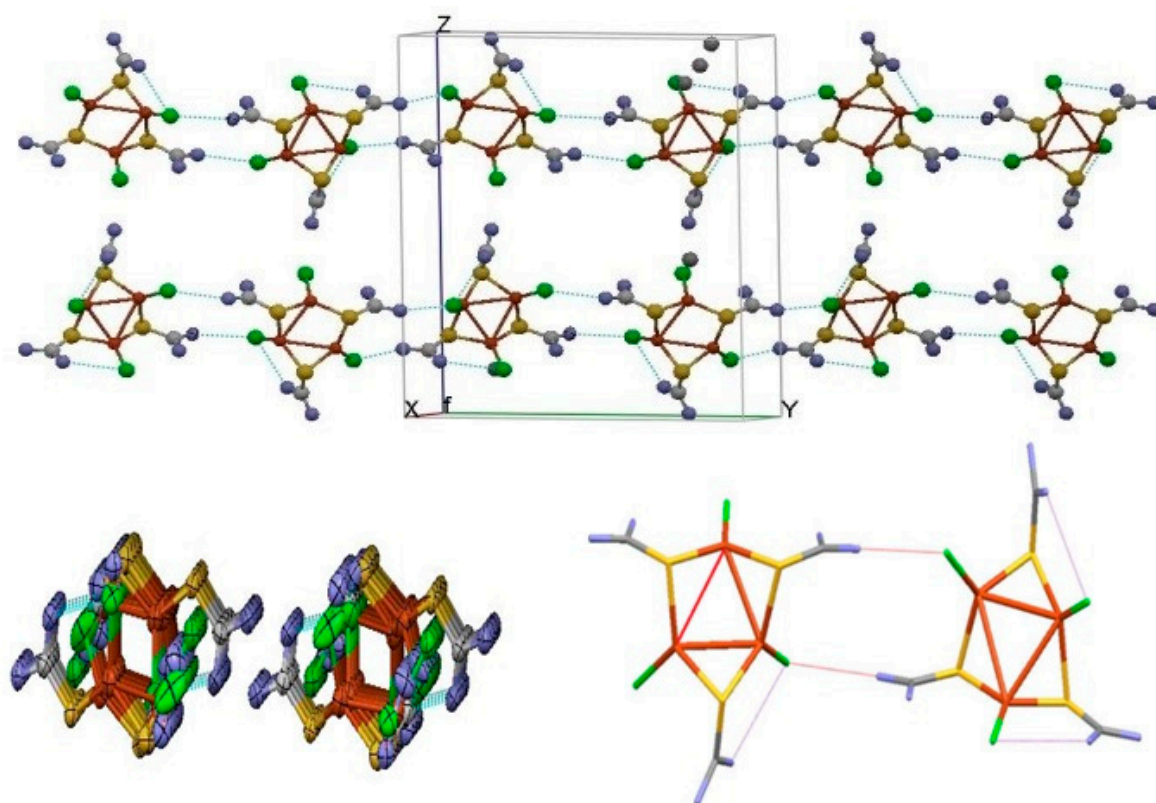


Figure 5. 2D representation of 1, the network is stabilized by intermolecular and intramolecular N—H—Cl type interactions.

3.2. Description of Crystal Structure of $[Ag_2L_6](NO_3)_2$ (2)

The molecular crystal structure of complex 2 is shown in Figure 6 and the selected bond lengths and bond angles are enlisted in Table 1. The binuclear silver complex crystallizes in triclinic crystal system with space group P-1. The binuclear complex 2 consists of two Ag(I) ions and six thiourea ligands. Both silver ions are bridged by S-atom of the two 1,3-diisobutyl thiourea ligands, forming four-membered Ag-S-Ag-S ring. Thiourea derivatives have different coordination mode for silver(I) ions. Two thiourea ligands are linked in terminal fashion to each metal ions and the remaining two thiourea ligands bridged both metal ions together. In this binuclear complex each silver atom is tetrahedrally coordinated through S-atom of the two terminal thiourea and two bridging thiourea molecules. The interatomic distance between Ag and S(bridged) is 2.622 Å. As expected, this distance is longer than the respective Ag-S (terminal) bond (2.491 Å) and is because of the electron deficient bond characters between Ag and bridging thiourea ligand [46–48]. The plane of Ag-S (terminal) and Ag-S (bridged) are mutually twisted by 83.88°. In a crystalline state, the molecules of the complex are stabilized by regular intermolecular hydrogen bonding i.e., N—O—H—N making a supramolecular structure. Different units are interlinked through nitrate ions as shown in Figure 7.

Hirshfeld surface analyses were used to get insights into the detailed information about the strength of intermolecular interactions. The interactions with normalized contact distance in crystal structure shorter than the sum of the corresponding van der Waals radii of the atoms, are highlighted by red spots and the longer contacts with the positive d_{norm} value are represented in blue color (Figure 8). The significant intermolecular interactions are mapped in Figure 9. On the Hirshfeld surfaces, the H...H interactions appear as the largest region (76.1%) of the fingerprint plot. The O...H/H...O contacts with a contribution of 18.8% due to the intermolecular N—H...O [2.037, 2.307 and 2.404 Å] and C—H...O [2.554 and 2.574 Å] hydrogen bonding give rise to a pair of characteristic wings in the fingerprint plot. The pair of

segregated sharp spikes represents the $S\cdots H/H\cdots S$ contacts with a contribution of 4.3%. The $N\cdots H$ and $C\cdots H$ interactions are found to be negligible (0.3 and 0.1%, respectively).

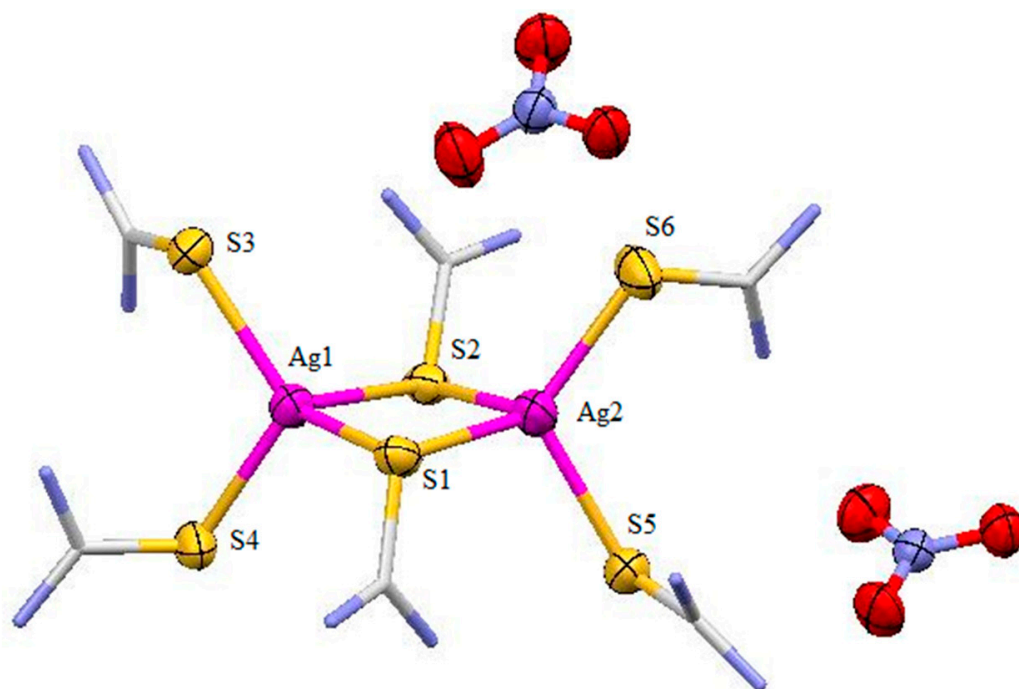


Figure 6. The molecular structure of compound **2**, only non-carbon atoms are numbered. Ellipsoids are drawn at 50% probability level, hydrogen atoms are omitted and carbons are represented by capped sticks.

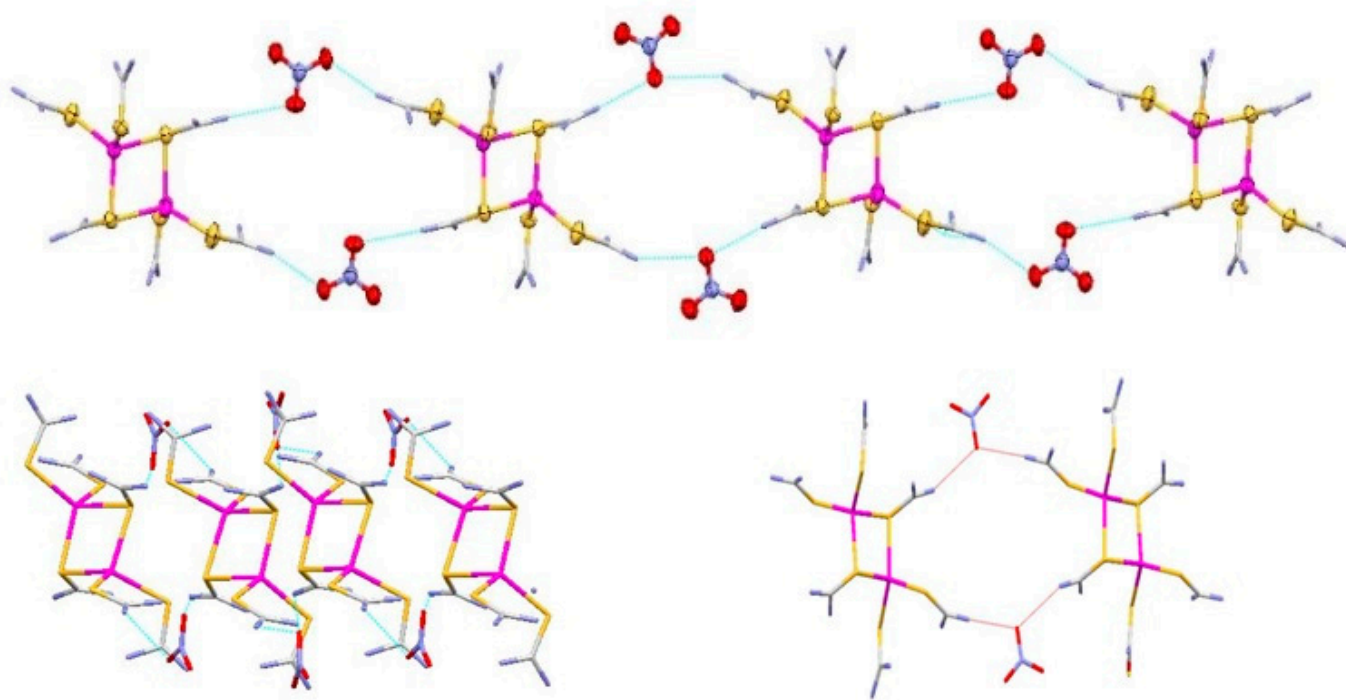


Figure 7. 2D representation of **2**, the network is stabilized by intramolecular N—H—O hydrogen bonding.

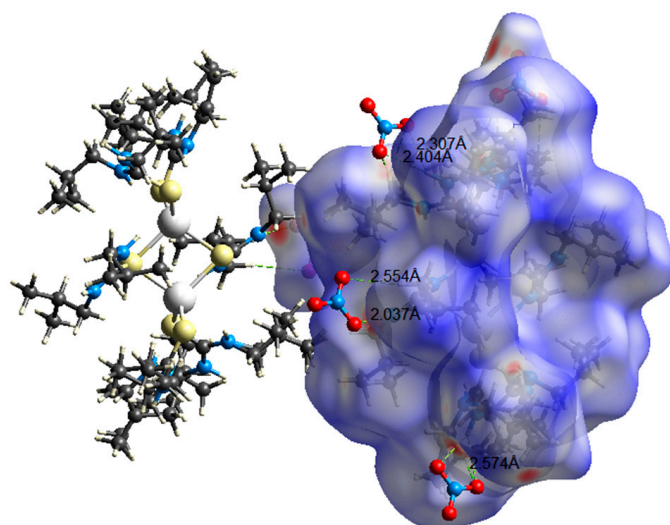


Figure 8. View of the three-dimensional Hirshfeld surface of **2** plotted over d_{norm} in the range -0.4382 to 1.6504 .

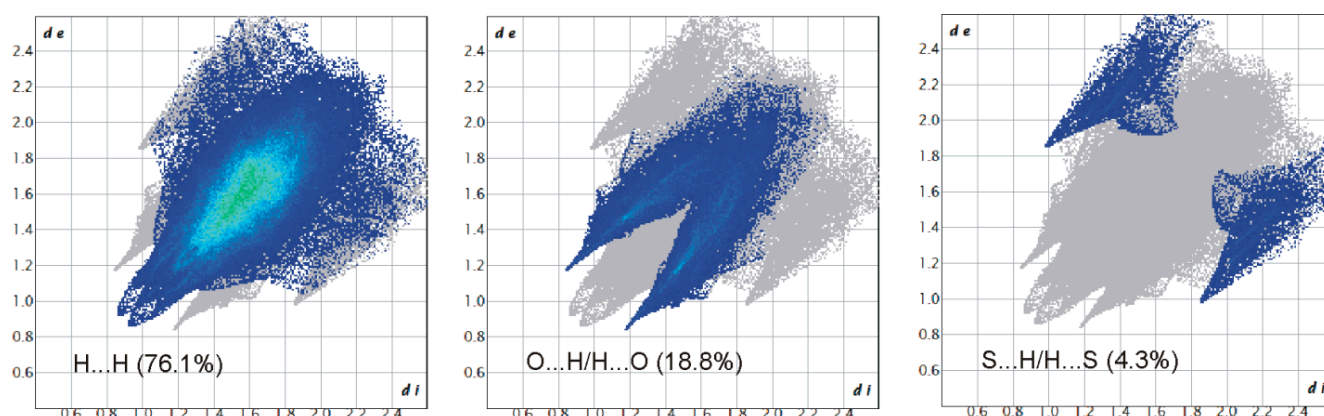


Figure 9. Two-dimensional fingerprint plots for all intermolecular contacts in **2**. The percentage of contribution is specified for each contact.

3.3. Description of Crystal Structure of $[Ag_6L_8Cl_4]$ (**3**)

The molecular structure of polynuclear silver complex **3** was confirmed by X-ray diffraction analysis as shown in Figure 10. The complex crystallizes in monoclinic crystal system with space group $P 2_1/c$. The single crystal analysis reveals that there are two types of silver ions, one is 5-coordinated and the other is 4-coordinated. The thiourea ligands are either terminal or bridged as discussed for complex **2**. The cluster structure is composed of six silver ions, four chlorine ligands and eight thiourea ligands. The chlorine ligands also show variable coordination modes, one of them bridges three silver ions and the other one is bridged to two silver ions (μ^3 - and μ^2 -Cl, respectively). The overall charge on the complex is +2 and every individual silver is present as +1 ion. Four Cl^- ions present in the molecule neutralize +4 charge internally leaving +2 as overall charge on the complex. The geometry around one of the silver ions is distorted tetrahedral. The complex can be regarded as dimer of the two tri-nuclear cationic clusters bridged together with the help of two thiourea ligands. The coordination environments around all silver ions (Ag1, Ag2 and Ag3) in asymmetric unit are different but geometry around silver atoms is distorted tetrahedral.

Ag1 is coordinated to one bridging thiourea (μ -S), one terminal thiourea and two bridging Cl ligands in which one chlorine is present as μ^2 and the other one is μ^3 . Ag2 is surrounded by three bridging thiourea and a chlorine ligand (μ^3 -Cl) in the same manner as for Ag1. The Ag3 is coordinated to two bridging thiourea (μ -S) and two bridging Cl

ligands, μ^2 and μ^3 . The structural parameters of the complex are summarized for selected atoms in Table 1. The Ag-S bond distance around the tetrahedrally coordinated Ag1 atom is 2.446 Å for terminal thiourea and 2.602 Å for bridged thiourea ligand, respectively. The slight elongation in the later bond may be traced by the electron delocalization of a single electron pair among the three nuclei. Such bonds are also called electron deficient bonds. Ag1-Cl1 and Ag1-Cl2 bond distances are 2.644 Å and 2.642 Å, respectively. Ag2-S1, Ag2-S3 and Ag2-S4 bond distances are 2.543 Å, 2.507 Å and 2.642 Å, respectively, and Ag2-Cl1 bond distance is 2.682 Å. Similarly, the Ag3-S4 and Ag3-S3 bond distances are 2.505 and 2.529 Å. Ag3-Cl1 and Ag3-Cl2 bond distances are 2.862 and 2.711 Å, respectively. The data show that Ag3 has relatively weak interaction with Cl[−] ligands as compared to Ag1 and Ag2 [49–51].

The angles around Ag1 center S2-Ag1-Cl1, S1-Ag1-Cl1, S2-Ag1-Cl2, S1-Ag1-Cl2 and S1-Ag1-S2 are 113.13°, 107.23°, 119.42°, 100.30° and 107.23°, respectively. The two asymmetric units are interconnected by bridging thiourea forming six-member ring. The crystallographic data show that the complex has Ag–Ag interactions with an average distance of 3.120 Å and the cluster is stabilized by argentophilicity. The complex formation is an unexpected result, but the data set obtained for the complex is in close agreement with the reported silver complexes bearing Ag-S and Ag-Cl ligands [29,52].

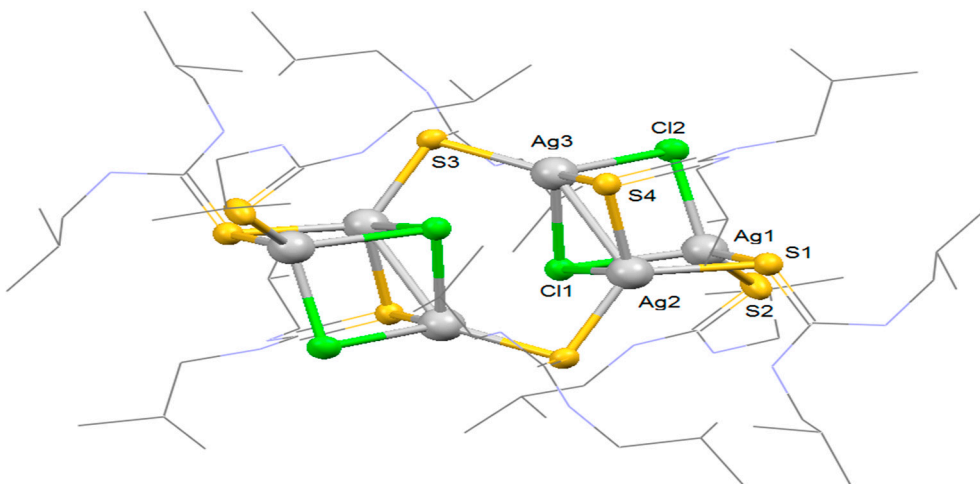


Figure 10. Molecular structure of silver cluster, complex 3. Only Ag, S and Cl atoms are labeled for an asymmetric unit, thermal ellipsoids are drawn at 40% probability level, hydrogen atoms are omitted and bonds connecting N and C are represented by wireframes for simplicity.

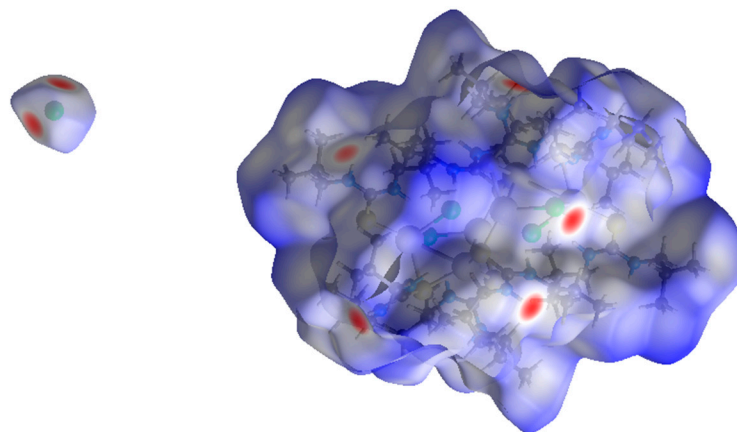


Figure 11. View of the three-dimensional Hirshfeld surface of 3 plotted over d_{norm} in the range -0.4772 to 2.1283 .

Hirshfeld surface analyses (Figure 11) show that the fingerprint profiles are dominated by H...H contacts (85.1%). The contributions due to the Cl...H/H...Cl interactions are the maximum (11.1%) that have been observed as segregated sharp spikes (Figure 12). Other contributions are due to S...H/H...S and N...H/H...N interactions (1.8 and 1%, respectively).

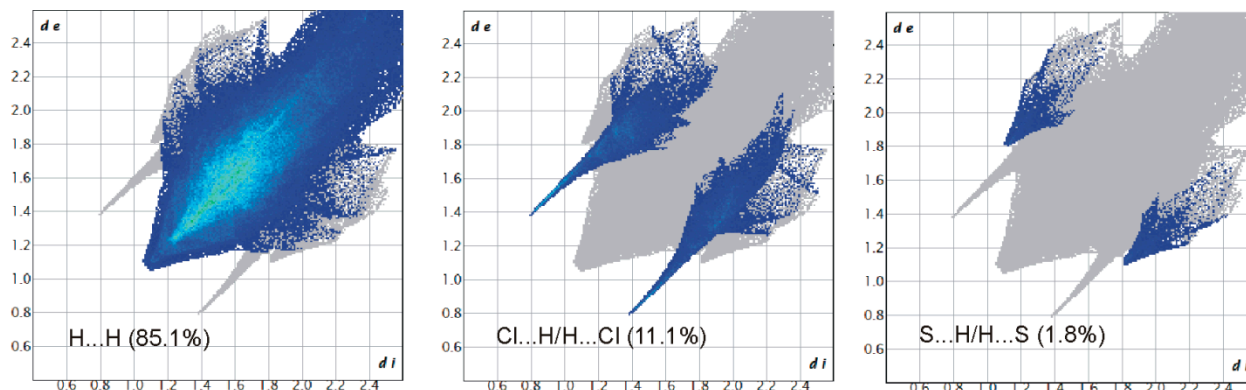


Figure 12. Two-dimensional fingerprint plots for all intermolecular contacts in **2**. The percentage of contribution is specified for each contact.

Table 1. List of selected bond lengths (Å) and bond angles (°) of compound **1–3**.

Compound	Atoms	Bond Length	Atoms	Bond Angle
1	Cu1-S1	2.221(17)	S1-Cu1-Cl1	123.17(7)
	Cu1-Cl1	2.233(19)	S1-Cu1-S3	117.41(6)
	Cu1-S3	2.2697(18)	S3-Cu1-Cl1	119.21(7)
	Cu1-Cu2	2.889(10)	Cu1-Cu2-Cu3	54.87(3)
2	Ag1-S4	2.5329(15)	S4-Ag1-S3	113.30(5)
	Ag1-S3	2.5568(14)	S4-Ag1-S1	113.51(5)
	Ag1-S1	2.5941(14)	S3-Ag1-S1	115.49(5)
	Ag1-S2	2.6451(10)	S4-Ag1-S2	100.16(5)
	Ag1-Ag2	3.3539(6)	S3-Ag1-S2	112.00(5)
3	Ag1-S1	2.602(15)	S2-Ag1-Cl1	113.13(5)
	Ag1-S2	2.446(14)	Cl1-Ag1-S1	107.23(6)
	Ag1-Cl1	2.462(13)	S2-Ag1-Cl2	119.42(5)
	Ag1-Ag2	3.120(6)	S1-Ag1-Cl2	100.30(7)
	Ag2-S1	2.543(11)	S1-Ag1-S2	107.23(5)
	Ag2-S4	2.642(10)	Ag2-S3-Ag3	93.88(5)
	Ag2-S3	2.507(14)	Ag3-Cl2-Ag1	89.43(6)
	Ag3-S4	2.505(15)	Ag1-Cl1-Ag2	72.01
	Ag3-S3	2.529(12)	Ag1-S1-Ag2	89.17

3.4. Determination of Antioxidant Activities by DPPH Radical Scavenging Test

The inhibitory effect of polynuclear thiourea complexes of copper and silver (**1–3**) has been studied using DPPH as free radical. Thiourea complexes with transition metals are known for their antioxidant potentials [2]. Thus, we were interested in studying the synthesized complexes for their antioxidant activities. We observed that these complexes upon addition to the DPPH solution show a habitual variation in absorbance (concentration range 00–100 ppm) in Table 3. On addition of compounds, the absorbance of DPPH decreases with increase in concentration in a regular expected pattern. The percent radical scavenging activity (DPPH) of compounds increases from top (zero concentration of tested compound) to bottom (maximum concentration of tested compound, 100 ppm). The DPPH free radical scavenging activity of compounds (**1–3**) at 100 ppm of the compounds in reaction mixture were determined to be 19.5%, 29.3% and 19.2%, respectively. The inhibition caused by complexes (**1–3**) are diagrammatically shown in Figures 13–15. In

these compounds, the antioxidant ability of compound **2** is higher (29.3%) than the other compounds, which was also reflected by the color change of the solution mixture during the course of the experiment (Figure 16).

Table 2. Crystal structure determination and structure refinements of compound 1–3.

	1	2	3
Empirical formula	C ₅₄ H ₁₂₀ N ₁₂ Cu ₆ Cl ₆ S ₆	C ₅₄ H ₁₂₀ N ₁₄ Ag ₂ O ₆ S ₆	C ₇₂ H ₁₆₀ N ₁₆ Ag ₆ Cl ₆ S ₈
Formula weight	1603.97	1479	2366.57
Temperature (K)	296	296	296
Wavelength (Å)	0.71073	0.71073	0.71073
Crystal system	Triclinic	Triclinic	Monoclinic
Space group	P-1	P-1	P 21/c
Aa	11.016(4)	11.611(6)	11.7020(11)
Bb	18.227(7)	15.499(8)	16.5310(14)
Ac	21.634(8)	24.149(13)	28.0730(3)
Aα	89.832(2)	99.159(3)	90
Bβ	86.125(2)	102.357(2)	99.096(5)
Γγ	81.288(2)	108.098(3)	90
Volume Å ³	4284.0(3)	3988.8(4)	5362.3(9)
μ (mm ^{−1})	1.83	0.70	1.422
Z	2	2	2
Density (Mg m ^{−3})	1.243	1.277	1.466
F (0, 0, 0)	1562	1624	2432
(h, k, l) min	(−13, −22, −27)	−14, −18, −30	(−13, −19, −33)
(h, k, l) max	(13, 22, 27)	14, 19, 30	(13, 19, 33)
Theta (max)	26.5	27.0	24.999
R (reflection)	0.069 (17650)	0.057 (17072)	0.0853 (5485)
wR ₂	0.236	0.180	0.1706

Table 3. DPPH radical scavenging activities (% RSA) of compound (1–3).

Concentration (ppm)	1	2	3
20	5.2	9.4	6.5
40	13.7	16.8	12.5
60	18.2	18.2	15.6
80	19.2	27.9	16.0
100	19.5	29.3	19.2

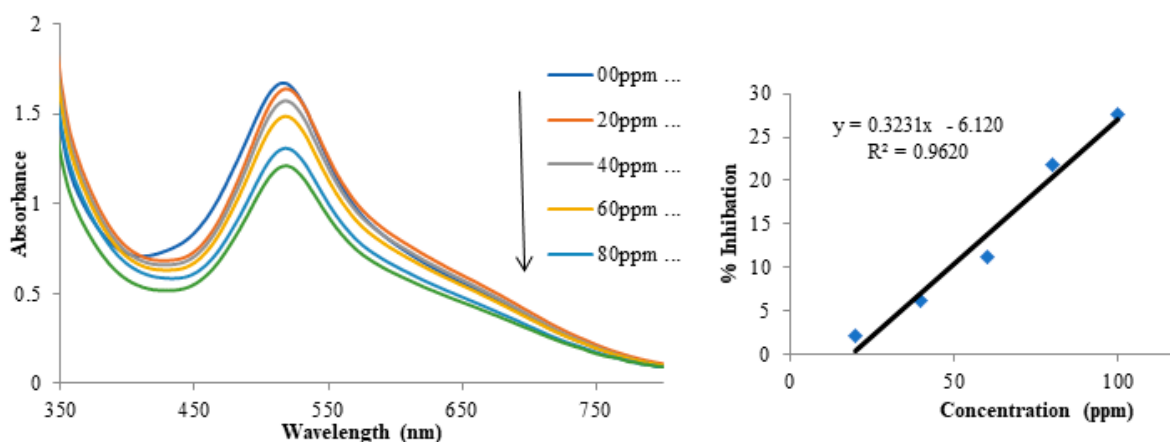


Figure 13. Absorption spectra of compound **1**. Arrow shows the decreasing change in absorption spectra of the compound/DPPH mixture on increasing concentration of the compound (left). Graphical representation of % Inhibition versus concentration of compound **1** for radical scavenging activity (right).

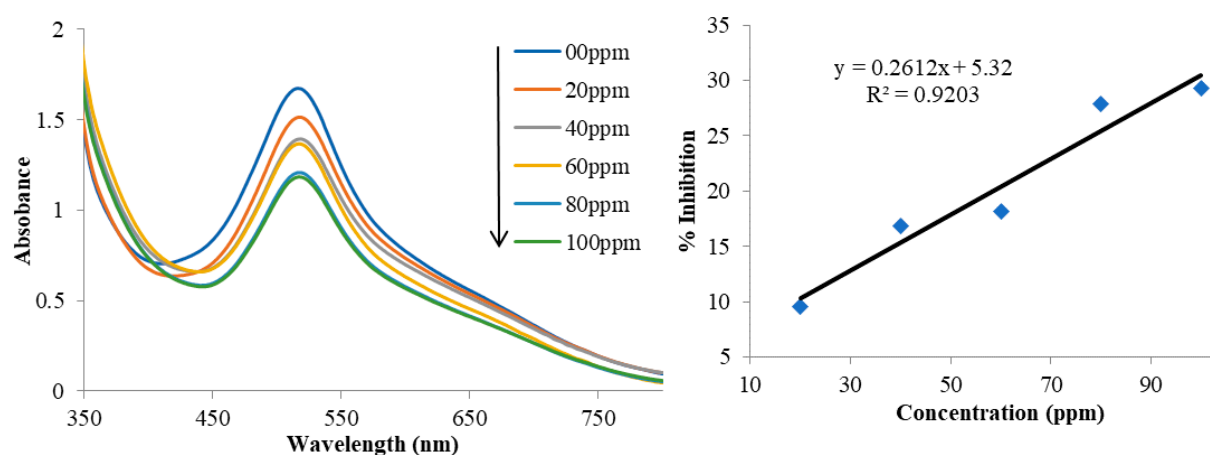


Figure 14. Absorption spectra of blank (DPPH, top) which alters by addition of compound 2 (left), graphical representation of % Inhibition versus concentration of compound 2 mixed with DPPH solution (right).

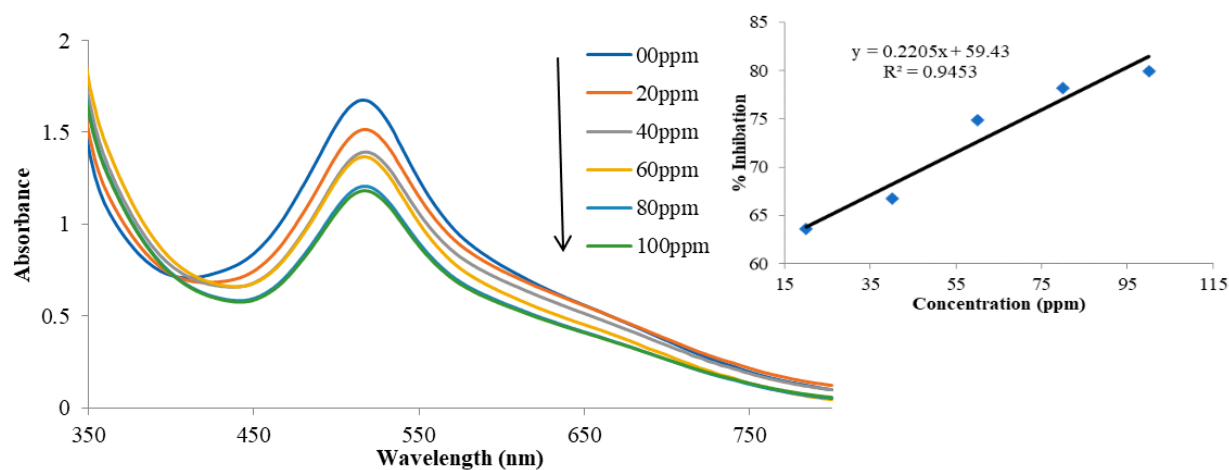


Figure 15. Absorption spectra of compound 3 and pure DPPH, the maximum absorbance was observed for the later one (left) and % Inhibition versus concentration of compound 3 for radical scavenging activity (right).



Figure 16. Naked eye detection of anti-DPPH radical scavenging activity shown by compound 2. The solution having purple color on right hand side is blank (without antioxidant agent) and that on left hand side contains 100 ppm of the antioxidant agent.

Graphical representation of the antioxidant potentials of complexes **1–3** reveals that the activity is dose dependent. With the increase in concentration of the complex in its solution, the scavenging activity increases. As a result of greater activity, a decrease in absorbance intensity was observed. Among the three complexes, complex **2** is comparatively more active at the concentration range of 100 ppm. The compound (**2**) is capable of showing naked-eye detection of the same activity, as made evident from the Figure 16. Solution without complex (blank/control) at the right is dark purple in color, there is almost no change in the color when 20 and 40 ppm complex solution is mixed. The color changes abruptly from purple to yellow with the addition of 60 and 80 ppm complex solution and to green at 100 ppm. The efficiency of the complex is predominantly because of the presence of nitrate ion out of the coordination sphere which makes the complex more soluble in the given solvent. The counter anion (chloride) in complexes **1** and **3** possesses a different coordination behavior and the activity is therefore poor.

4. Conclusion

The presence of anion in metal salts and reaction medium (solvent) plays a pivotal role in nuclearity of resultant complexes. Three new heteroleptic polynuclear complexes $[\text{Cu}_3\text{L}_3\text{Cl}_3]$ (**1**), $[\text{Ag}_2\text{L}_6](\text{NO}_3)_2$ (**2**) and $[\text{Ag}_6\text{L}_8\text{Cl}_4]$ (**3**) were successfully synthesized by treating 1,3-diisobutyl thiourea with CuCl_2 , AgNO_3 and AgCl , respectively. The formation of **1** was independent of applied reaction conditions (temperature and concentration) and metal to ligand molar ratio. All complexes were characterized by single crystal X-ray diffraction. Crystal analyses show that **1** has two non-super imposable diastereomers in trimeric form, while **2** is dimeric with two-fold axis of rotation and **3** is consisting of two asymmetric units $[\text{Ag}_3\text{L}_3\text{Cl}_2]$ bridged by two thiourea ligands with two-fold axis of rotation. These complexes show moderate antioxidant potential against DPPH.

Author Contributions: Conceptualization, methodology, software, A.S., E.K. and A.N.; validation, formal analysis, E.K., A.N. and M.N.T.; investigation, A.S. and E.K.; resources, E.K. and A.N.; data curation, A.N., A.N. and E.K.; writing—original draft preparation, A.S., A.N., E.K., G.S.K., A.u.R. and M.S.; writing—review and editing, visualization, A.S., E.K. and A.N.; supervision, project administration, funding acquisition, E.K. and A.N. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Deanship of Scientific Research, Vice Presidency for Graduate Studies and Scientific Research, King Faisal University, Saudi Arabia [Grant No. Grant1399].

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The crystallographic data have been deposited at the Cambridge Crystallographic Data Centre as supplementary publications under CCDC Nos. 2196016 (compound **1**), 2196017 (compound **2**) and 2204046 (compound **3**). These data can be obtained free of charge from the Cambridge Crystallographic Data Centre, www.ccdc.cam.ac.uk/datarequest/cif.

Acknowledgments: This work was supported by the Deanship of Scientific Research, Vice Presidency for Graduate Studies and Scientific Research, King Faisal University, Saudi Arabia [Grant No. Grant1399].

Conflicts of Interest: There are no conflict of interest to be declared.

References

1. Khan, E.; Khan, S.; Gul, Z.; Muhammad, M. Medicinal Importance, Coordination Chemistry with Selected Metals (Cu, Ag, Au) and Chemosensing of Thiourea Derivatives. A Review. *Crit. Rev. Anal. Chem.* **2021**, *51*, 812–834. [[CrossRef](#)] [[PubMed](#)]
2. Shahzad, A.; Khan, E.; Said, M.; Khan, G.S.; Syed, M.G.; Noor, A.; Zahoor, M.; Ullah, R.; Bari, A. Complexes of 1, 3-diisobutyl thiourea with copper (I), zinc (II) and mercury (II): Their antioxidant and antibacterial evaluation. *Crystals* **2021**, *11*, 989. [[CrossRef](#)]
3. Rahman, F.U.; Bibi, M.; Altaf, A.A.; Tahir, M.N.; Ullah, F.; Khan, E. Zn, Cd and Hg complexes with unsymmetric thiourea derivatives; syntheses, free radical scavenging and enzyme inhibition essay. *J. Mol. Struct.* **2020**, *1211*, 128096. [[CrossRef](#)]

4. Rahman, F.U.; Bibi, M.; Khan, E.; Shah, A.B.; Muhammad, M.; Tahir, M.N.; Shahzad, A.; Ullah, F.; Zahoor, M.; Alamery, S. Thiourea derivatives, simple in structure but efficient enzyme inhibitors and mercury sensors. *Molecules* **2021**, *26*, 4506. [[CrossRef](#)] [[PubMed](#)]
5. Khan, U.A.; Badshah, A.; Tahir, M.N.; Khan, E. Gold (I), silver (I) and copper (I) complexes of 2, 4, 6-trimethylphenyl-3-benzoylthiourea; synthesis and biological applications. *Polyhedron* **2020**, *181*, 114485. [[CrossRef](#)]
6. Noor, A.; Qayyum, S.; Jabeen, F.; Rehman, A.U. Mononuclear Tricoordinate Copper (I) and Silver (I) Halide Complexes of a Sterically Bulky Thiourea Ligand and a Computational Insight of Their Interaction with Human Insulin. *Molecules* **2022**, *27*, 4231. [[CrossRef](#)]
7. Mykhalichko, B.M.; Temkin, O.N.; Mys'kiv, M. Polynuclear complexes of copper(I) halides: Coordination chemistry and catalytic transformations of alkynes. *Russ. Chem. Rev.* **2000**, *69*, 957–984. [[CrossRef](#)]
8. Levitsky, M.M.; Bilyachenko, A.N.; Shul'pin, G.B. Oxidation of C-H compounds with peroxides catalyzed by polynuclear transition metal complexes in Si- or Ge-sesquioxane frameworks: A review. *J. Organomet. Chem.* **2017**, *849–850*, 201–218. [[CrossRef](#)]
9. Roy, P.; Dhara, K.; Manassero, M.; Banerjee, P. Di-, Tetra-, and Polynuclear Copper (II) Complexes: Active Catalysts for Oxidation of Toluene and Benzene. *Eur. J. Inorg. Chem.* **2008**, *2008*, 4404–4412. [[CrossRef](#)]
10. Musina, E.I.; Shamsieva, A.V.; Strel'nik, I.D.; Gerasimova, T.P.; Krivolapov, D.B.; Kolesnikov, I.E.; Grachova, E.V.; Tunik, S.P.; Bannwarth, C.; Grimme, S.; et al. Synthesis of novel pyridyl containing phospholanes and their polynuclear luminescent copper(i) complexes. *Dalton Trans.* **2016**, *45*, 2250–2260. [[CrossRef](#)]
11. Kobielska, P.A.; Telford, R.; Rowlandson, J.; Tian, M.; Shahin, Z.; Demessence, A.; Ting, V.P.; Nayak, S. Polynuclear Complexes as Precursor Templates for Hierarchical Microporous Graphitic Carbon: An Unusual Approach. *ACS Appl. Mater. Interfaces* **2018**, *10*, 25967–25971. [[CrossRef](#)] [[PubMed](#)]
12. Puyo, M.; Lebon, E.; Vendier, L.; Kahn, M.L.; Fau, P.; Fajewerg, K.; Lepetit, C. Topological Analysis of Ag–Ag and Ag–N Interactions in Silver Amidinate Precursor Complexes of Silver Nanoparticles. *Inorg. Chem.* **2020**, *59*, 4328–4339. [[CrossRef](#)] [[PubMed](#)]
13. Zhang, S.; Zhao, L. Macrocyclic-Encircled Polynuclear Metal Clusters: Controllable Synthesis, Reactivity Studies, and Applications. *Acc. Chem. Res.* **2018**, *51*, 2535–2545. [[CrossRef](#)] [[PubMed](#)]
14. Bergamini, F.R.G.; Nunes, J.H.B.; de Carvalho, M.A.; Ribeiro, M.A.; de Paiva, P.P.; Banzato, T.P.; Ruiz, A.L.T.G.; de Carvalho, J.E.; Lustri, W.R.; Martins, D.O.; et al. Polynuclear copper (II) complexes with nalidixic acid hydrazones: Antiproliferative activity and selectivity assessment over a panel of tumor cells. *Inorg. Chim. Acta* **2019**, *484*, 491–502. [[CrossRef](#)]
15. Sun, W.H.; Li, K.H.; Liu, H.; Gu, Y.T.; Zhang, Y.; You, Z.L.; Li, W. Synthesis, Characterization, Crystal Structures, and Antibacterial Activity of Polynuclear Nickel (II) and Copper (II) Complexes with Similar Tridentate Schiff Bases. *Russ. J. Coord. Chem.* **2017**, *43*, 693–699. [[CrossRef](#)]
16. Semerci, F.; Yeşilel, O.Z.; Soylu, M.S.; Keskin, S.; Büyükgüngör, O. A two-dimensional photoluminescent cadmium (II) coordination polymer containing a new coordination mode of pyridine-2,3-dicarboxylate: Synthesis, structure and molecular simulations for gas storage and separation applications. *Polyhedron* **2013**, *50*, 314–320. [[CrossRef](#)]
17. Mei, G.; Li, Z.; Zhang, H.; Li, G.; Meng, X. Synthesis, Structures, and Properties of Two Novel Zn (II) Polynuclear Complexes. *Synth. React. Inorg. Met. Org. Nano Met. Chem.* **2010**, *40*, 163–169. [[CrossRef](#)]
18. Roubeau, O.; Clérac, R. Rational Assembly of High-Spin Polynuclear Magnetic Complexes into Coordination Networks: The Case of a [Mn4] Single-Molecule Magnet Building Block. *Eur. J. Inorg. Chem.* **2008**, *2008*, 4325–4342. [[CrossRef](#)]
19. Papaefstathiou, G.S.; Perlepes, S.P. Families of Polynuclear Manganese, Cobalt, Nickel and Copper Complexes Stabilized by Various Forms of Di-2-pyridyl Ketone. *Comments Inorg. Chem.* **2002**, *23*, 249–274. [[CrossRef](#)]
20. Yao, L.; Niu, G.; Li, J.; Gao, L.; Luo, X.; Xia, B.; Liu, Y.; Du, P.; Li, D.; Chen, C.; et al. Circularly Polarized Luminescence from Chiral Tetranuclear Copper(I) Iodide Clusters. *J. Phys. Chem. Lett.* **2020**, *11*, 1255–1260. [[CrossRef](#)]
21. Haasnoot, J.G. Mononuclear, oligonuclear and polynuclear metal coordination compounds with 1,2,4-triazole derivatives as ligands. *Coord. Chem. Rev.* **2000**, *200–202*, 131–185. [[CrossRef](#)]
22. Bhowmik, P.; Chattopadhyay, S.; Drew, M.G.B.; Ghosh, A. A polynuclear helical and two dinuclear copper (II) complexes of a monocondensed N, N, O donor Schiff base with pseudohalides as co-ligand. *Inorg. Chim. Acta* **2013**, *395*, 24–32. [[CrossRef](#)]
23. Escuer, A.; Esteban, J.; Perlepes, S.P.; Stamatatos, T.C. The bridging azido ligand as a central “player” in high-nuclearity 3d-metal cluster chemistry. *Coord. Chem. Rev.* **2014**, *275*, 87–129. [[CrossRef](#)]
24. Marvaud, V.; Decroix, C.; Scuiller, A.; Tuyères, F.; Guyard-Duhayon, C.; Vaissermann, J.; Marrot, J.; Gonnet, F.; Verdager, M. Hexacyanometalate Molecular Chemistry: Di-, Tri-, Tetra-, Hexa- and Heptanuclear Heterobimetallic Complexes; Control of Nuclearity and Structural Anisotropy. *Chem. A Eur. J.* **2003**, *9*, 1692–1705. [[CrossRef](#)] [[PubMed](#)]
25. Wang, X.-L.; Qin, C.; Wang, E.-B.; Su, Z.-M. Metal Nuclearity Modulated Four-, Six-, and Eight-Connected Entangled Frameworks Based on Mono-, Bi-, and Trimetallic Cores as Nodes. *Chem. A Eur. J.* **2006**, *12*, 2680–2691. [[CrossRef](#)]
26. Papatriantafyllopoulou, C.; Manessi-Zoupa, E.; Escuer, A.; Perlepes, S.P. The sulfate ligand as a promising “player” in 3d-metal cluster chemistry. *Inorg. Chim. Acta* **2009**, *362*, 634–650. [[CrossRef](#)]
27. Ahmad, S.; Isab, A.A.; Perzanowski, H.P. Silver (I) complexes of thiourea. *Transit. Met. Chem.* **2002**, *27*, 782–785. [[CrossRef](#)]

28. Safin, D.A.; Babashkina, M.G.; Bolte, M.; Pape, T.; Hahn, F.E.; Verizhnikov, M.L.; Bashirov, A.R.; Klein, A. Polynuclear and mixed-ligand mononuclear CuI complexes with N-thiophosphorylated thioureas and 1,10-phenanthroline or PPh₃. *Dalton Trans.* **2010**, *39*, 11577–11586. [\[CrossRef\]](#)
29. Safin, D.A.; Babashkina, M.G.; Bolte, M.; Garcia, Y. Homoleptic polynuclear CuI and AgI complexes of N-thiophosphorylated thioureas o-RO(O)CC₆H₄NHC(S)NHP(S)(OiPr)₂ (R = Me, Et). *CrystEngComm* **2012**, *14*, 774–778. [\[CrossRef\]](#)
30. Metlushka, K.E.; Sadkova, D.N.; Nikitina, K.A.; Pashagin, A.V.; Khrizanforov, M.N.; Budnikova, Y.H.; Morozov, V.I.; Islamov, D.R.; Latypov, S.K.; Kataeva, O.N.; et al. Synthesis of the first chiral polynuclear copper(I) complex based on (R)-1-(1-phenyl) ethyl-3-(O,O-diethylthiophosphoryl)thiourea and its characterization in the solid state and solution. *New J. Chem.* **2020**, *44*, 3224–3231. [\[CrossRef\]](#)
31. Li, G.; Che, D.-J.; Li, Z.-F.; Zhu, Y.; Zou, D.-P. Versatile coordination patterns in the reaction system of N-benzoyl-N'-(2-pyridyl) thiourea with CuCl₂. Their reaction conditions, systematic isolation and crystal structures. *New J. Chem.* **2002**, *26*, 1629–1633. [\[CrossRef\]](#)
32. Nguyen, H.H.; Thang, P.C.; Rodenstein, A.; Kirmse, R.; Abram, U. Bipodal Acylthiourea Ligands as Building Blocks for Bi-, Tetra-, and Polynuclear Oxorhenium (V) Complexes. *Inorg. Chem.* **2011**, *50*, 590–596. [\[CrossRef\]](#) [\[PubMed\]](#)
33. Vaidya, S.; Shukla, P.; Tripathi, S.; Rivière, E.; Mallah, T.; Rajaraman, G.; Shanmugam, M. Substituted versus Naked Thiourea Ligand Containing Pseudotetrahedral Cobalt (II) Complexes: A Comparative Study on Its Magnetization Relaxation Dynamics Phenomenon. *Inorg. Chem.* **2018**, *57*, 3371–3386. [\[CrossRef\]](#) [\[PubMed\]](#)
34. Luckay, R.C.; Sheng, X.; Strasser, C.E.; Raubenheimer, H.G.; Safin, D.A.; Babashkina, M.G.; Klein, A. Competitive bulk liquid membrane transport and solvent extraction of some metal ions using RC(S)NHP(X)(OiPr)₂ (X = O, S) as ionophores. Formation of the polynuclear complex of [Ag(N≡C–NP(S)(OiPr)₂)]_n. *Dalton Trans.* **2009**, *39*, 8227–8236. [\[CrossRef\]](#) [\[PubMed\]](#)
35. Altaf, A.A.; Shahzad, A.; Gul, Z.; Khan, S.A.; Badshah, A.; Tahir, M.N.; Zafar, Z.I.; Khan, E. Synthesis, crystal structure, and DFT calculations of 1, 3-diisobutyl thiourea. *J. Chem.* **2015**, *2015*, 913435. [\[CrossRef\]](#)
36. Altomare, A.; Burla, M.C.; Camalli, M.; Cascarano, G.L.; Giacovazzo, C.; Guagliardi, A.; Moliterni, A.G.G.; Polidori, G.; Spagna, R. SIR97: A new tool for crystal structure determination and refinement. *J. Appl. Crystallogr.* **1999**, *32*, 115–119. [\[CrossRef\]](#)
37. Herbst-Irmer, R.; Sheldrick, G.M. Refinement of Twinned Structures with SHELXL97. *Acta Crystallogr. Sect. B* **1998**, *54*, 443–449. [\[CrossRef\]](#)
38. Farrugia, L. WinGX and ORTEP for Windows: An update. *J. Appl. Crystallogr.* **2012**, *45*, 849–854. [\[CrossRef\]](#)
39. Kuhn, A.; Köhler, J.; Lotsch, B.V. Single-crystal X-ray structure analysis of the superionic conductor Li₁₀GeP₂S₁₂. *Phys. Chem. Chem. Phys.* **2013**, *15*, 11620–11622. [\[CrossRef\]](#)
40. Spek, A. Structure validation in chemical crystallography. *Acta Crystallogr. Sect. D* **2009**, *65*, 148–155. [\[CrossRef\]](#)
41. Turner, M.; McKinnon, J.J.; Wolff, S.; Grimwood, D.; Spackman, P.; Jayatilaka, D.; Spackman, M. *CrystalExplorer17*; University of Western Australia: Perth, Australia, 2017; Volume 108, p. 76730.
42. Yuan, C.; Du, L.; Jin, Z.; Xu, X. Storage stability and antioxidant activity of complex of astaxanthin with hydroxypropyl-β-cyclodextrin. *Carbohydr. Polym.* **2013**, *91*, 385–389. [\[CrossRef\]](#) [\[PubMed\]](#)
43. Bombicz, P.; Mutikainen, I.; Krunks, M.; Leskelä, T.; Madarász, J.; Niinistö, L. Synthesis, vibrational spectra and X-ray structures of copper(I) thiourea complexes. *Inorg. Chim. Acta* **2004**, *357*, 513–525. [\[CrossRef\]](#)
44. Battaini, G.; Granata, A.; Monzani, E.; Gullotti, M.; Casella, L. Biomimetic Oxidations by Dinuclear and Trinuclear Copper Complexes. In *Advances in Inorganic Chemistry*; van Eldik, R., Reedijk, J., Eds.; Academic Press: Cambridge, MA, USA, 2006; Volume 58, pp. 185–233.
45. Ahmad, S.; Altaf, M.; Stoeckli-Evans, H.; Rüffer, T.; Lang, H.; Mufakkar, M.; Waheed, A. Crystal Structures of Trinuclear Chlorido(N,N'-diethylthiourea)copper(I) and a Second Polymorph of Iodidotris(N,N'-diethylthiourea)copper(I). *J. Chem. Crystallogr.* **2010**, *40*, 639–645. [\[CrossRef\]](#)
46. Isab, A.A.; Nawaz, S.; Saleem, M.; Altaf, M.; Monim-ul-Mehboob, M.; Ahmad, S.; Evans, H.S. Synthesis, characterization and antimicrobial studies of mixed ligand silver(I) complexes of thioureas and triphenylphosphine; crystal structure of {[Ag(PPh₃)(thiourea)(NO₃)]₂·[Ag(PPh₃)(thiourea)]₂(NO₃)₂}. *Polyhedron* **2010**, *29*, 1251–1256. [\[CrossRef\]](#)
47. Mironov, I.; Tselodub, L. Stability of Mononuclear and Binuclear Silver (I) Complexes with Thiourea in Aqueous Solution. *Russ. J. Inorg. Chem.* **1996**, *41*, 228–232.
48. Samadov, A.S.; Mironov, I.V.; Gorichev, I.G.; Kovalchukova, O.V.; Stepnova, A.F. Study of Silver(I) Complex Formation with Some Thiourea Derivatives in Aqueous Solution. *Russ. J. Gen. Chem.* **2020**, *90*, 2111–2114. [\[CrossRef\]](#)
49. Pakawatchai, C.; Sivakumar, K.; Fun, H.-K. Bis(N,N'-dimethylthiourea-S)silver(I) Perchlorate and Tris(N,N'-dimethylthiourea-S)silver(I) Perchlorate. *Acta Crystallogr. Sect. C* **1996**, *52*, 1954–1957. [\[CrossRef\]](#)
50. Choudhary, M.A.; Ahmad, S.; Aslam, M.; Saleem, M.; Tahir, M.N.; Fettouhi, M.; Isab, A.A. Synthesis, crystal structure and antimicrobial activities of a dinuclear silver (I) complex of bis (diphenylphosphano) methane and thiourea. *Z. Nat. B* **2019**, *74*, 745–750.
51. Fernandes, J.A.; Segura, D.F.; Netto, A.V.G.; Frem, R.C.G.; Mauro, A.E.; Paz, F.A.A. A Tetranuclear Silver–Thiourea Cluster. *J. Chem. Crystallogr.* **2015**, *45*, 410–418. [\[CrossRef\]](#)
52. Bowmaker, G.A.; Pakawatchai, C.; Saithong, S.; Skelton, B.W.; White, A.H. 1:1 complexes of silver(I) thiocyanate with (substituted) thiourea ligands. *Dalton Trans.* **2009**, *14*, 2588–2598. [\[CrossRef\]](#)