RASĀYAN *J. Chem.*
Vol. 19 | No. 4 | 2268-2275 | October-December | 2026
ISSN: 0974-1496 | e-ISSN: 0976-0083 | CODEN: RJCABP
http://www.rasayanjournal.com
http://www.rasayanjournal.co.in

SYNTHESIS, SPECTROSCOPIC CHARACTERIZATION AND ENHANCED ANTIMICROBIAL ACTIVITY OF Sb(III) AND Bi(III) CARBOHYDRAZONE COMPLEXES

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ABSTRACT

Two new series of metallo-organic complexes of Antimony (III) and Bismuth (III) having general formulas $[M(N\frown O)_2Cl]$ (where M= Sb and Bi) were synthesised by the reaction of sodium salts of carbohydrazones with $SbCl_3$ and $BiCl_3$ in THF in a 2:1 molar ratio, respectively. The present investigation was undertaken to explore the coordination behaviour of carbohydrazone ligands towards antimony(III) and bismuth(III) ions and to examine the influence of metal coordination on their antimicrobial properties.Elemental analysis, molecular weight measurements and spectroscopic [UV, IR and NMR (^{1}H and ^{13}C)] studies suggested a plausible penta-coordinated environment of metallo-organic complexes of Antimony (III) and Bismuth (III). These newly synthesised complexes of Antimony (III) and Bismuth (III) were screened against bacteria [Bacillus subtilis, Staphylococcus aureus (Gram-positive) and Escherichia coli (Gram-negative)] and found to be more active than their corresponding ligands. These complexes were also screened for their antifungal activity against various fungi (Fusarium oxysporum, Trichoderma reesei and Penicillium funiculosum), where enhanced antifungal activity was observed following coordination with the metal ions. By advancing metal-based systems with improved antimicrobial performance, the present study contributes to ongoing efforts aimed at addressing microbial infections and the growing challenge of antimicrobial resistance, contributing to the United Nations Sustainable Development Goal 3 (SDG-3: Good Health and Well-being).

Keywords: Carbohydrazones, Metallo-Organic Complexes of Antimony (III) and Bismuth (III), Antimicrobial Activity

RASĀYAN*J. Chem.*, Vol. 19, No.4, 2026

INTRODUCTION

The relationship between molecular features and biological response is an important consideration in chemistry and pharmaceutical science.[1,2]The biological response of a compound is influenced by its molecular framework and the nature of its interactions with biological targets.[3,4] Carbohydrazones are attractive ligands because they are easy to prepare and contain donor atoms capable of forming stable metal complexes.[5-7] They are also known for a wide range of biological properties, including antimicrobial, antioxidant, therapeutic, anticonvulsant, and cytotoxic activities.[8]Metal complexes often show better biological activity than their corresponding free ligands. This improvement is usually linked to chelation, which can change the electronic distribution of the molecule, increase lipophilicity, and help the complex pass more easily through microbial membranes.[9] Several studies on metal-hydrazone and Schiff-base complexes have shown stronger antibacterial and antifungal activities after coordination, supporting the idea that metal binding can improve the biological performance of the ligand.[10,11] Other reports have also discussed how coordination can stabilise the ligand framework and influence its interaction with biological systems.[12]The emergence of drug-resistant microorganisms has provided a constant demand for new antimicrobial compounds.[13] These systems have been attractive for further study because coordination of biologically active ligands with metal ions has been shown to enhance their biological performance. The development of such compounds is also consistent with the objectives of the United Nations Sustainable Development Goal-3 (SDG-3: Good Health and Well-being), which aims to promote better health and combat infectious diseases.

In coordination systems, information about metal-ligand bonding and the coordination environment is commonly inferred from spectroscopic techniques.[14] These methods provide reliable evidence for donor

http://doi.org/10.31788/RJC.2026.1949712
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atom involvement, coordination number, and changes in the electronic environment of the metal centre. For p-block metal ions such as Sb(III) and Bi(III), the presence of a stereochemically active lone pair often leads to deviations from ideal geometry, and therefore distorted coordination environments are frequently proposed based on consistent spectroscopic observations. Recent publications further highlight the relationship between coordination and biological activity. For example, metal–ligand systems have been shown to display different activity patterns after coordination, indicating the role of the metal centre in modifying ligand behavior.[15] Structural studies on coordinated systems also suggest that the chemical environment around the ligand changes upon coordination, which may influence its reactivity and biological properties.[16] Work on Schiff-base complexes has reported enhanced antimicrobial effects when the ligand is bound to a metal ion. A related study further highlights how coordination affects the performance of hydrazone-based systems and supports the trend of improved microbial activity.[17] Complexes of antimony(III) and bismuth(III) have long been of interest because of their known medicinal relevance, including antimicrobial and other biological applications. These observations provide a strong basis for studying the coordination chemistry and biological properties of carbohydrazone complexes of antimony and bismuth. Despite their biological importance, comparatively few studies have examined antimony(III) and bismuth(III) carbohydrazone complexes in a systematic manner. This work was therefore undertaken to investigate their coordination behaviour and evaluate how metal coordination influences their antimicrobial activity. Based on these considerations, the present work describes the synthesis, spectroscopic characterisation, and antimicrobial evaluation of two series of antimony(III) and bismuth(III) carbohydrazone complexes.

EXPERIMENTAL

Materials

Solvents were dried by general methods before use. $SbCl_3$ and $BiCl_3$ (Aldrich) were used as supplied, while the ligands employed herein were prepared in the laboratory according to the general method reported earlier.[18]

Physical Measurements

Melting points were determined with a Gallen-Kamp melting point apparatus; infrared (IR) spectra were collected in the range of 4000-200 cm^{-1} on a BrukerTensor 27 FT-IR Spectrophotometer as KBr pellets. Magnetic Resonance spectra were recorded at room temperature using $CDCl_3$ solution (TMS internal reference) with a JEOL-FT A1 300 MegaHertz spectrometer, while elemental analyses for C, H, and N were determined by combustion analysis on a Coleman 5612 analyser. The UV-vis spectra of the carbohydrazones and their M(III) complexes are reported in the range of 200-800 nm, which was recorded on a Shimadzu 1800 UV spectrophotometer. Molecular weights were determined by the Rast method. The conductivity measurements were performed on dry DMF solutions of these coordination compounds using a Systronics conductivity bridge (Model 305) with a cell having a constant of 0.5 $cm^{-1.}$ The synthetic and analytical data for all prepared complexes are summarised in Table-1.

Table-1: Physical Data of Sb(III) and Bi(III) Complexes of Carbohydrazones.

Cmpd.	Yield (%)	M.P (^oC)	Color	Elemental analysis (%)				Mol. Wt. Found (Calcd.)
				C Found (Calcd.)	H Found (Calcd.)	N Found (Calcd.)	Sb Found (Calcd.)	
Sb-L1H	67	90	Gray	49.39 (49.15)	4.66 (4.64)	18.00 (17.91)	15.65 (15.57)	778.18 (781.89)
Sb-L2H	71	105	Brown	53.65 (53.44)	4.27 (4.25)	16.47 (16.40)	14.31 (14.26)	850.69 (853.95)
Sb-L3H	63	195	Dark brown	46.52 (46.33)	3.90 (3.88)	19.38 (19.30)	16.84 (16.78)	722.89 (725.79)
Sb-L4H	69	110	Dark green	52.52 (52.35)	3.92 (3.91)	17.02 (16.96)	14.79 (14.74)	823.20 (825.90)
Sb-L5H	74	103	Green	47.97 (47.80)	4.29 (4.28)	18.65 (18.58)	16.21 (16.15)	751.15 (753.84)

Bi-L1H	65	95	Reddish	44.30 (44.22)	4.18 (4.18)	16.15 (16.12)	24.09 (24.05)	867.45 (869.11)
Bi-L2H	72	110	Gray	48.57 (48.49)	3.86 (3.86)	14.91 (14.88)	22.24 (22.20)	939.60 (941.17)
Bi-L3H	69	98	Dark green	41.50 (41.36)	3.48 (3.47)	17.29 (17.23)	25.79 (25.70)	810.35 (813.01)
Bi-L4H	83	114	Dark brown	47.45 (47.35)	3.54 (3.53)	15.37 (15.34)	22.94 (22.89)	911.15 (913.12)
Bi-L5H	74	102	Greenish	42.93 (42.84)	3.83 (3.83)	16.69 (16.65)	24.90 (24.85)	839.30 (841.06)

Synthesis of carbohydrazones

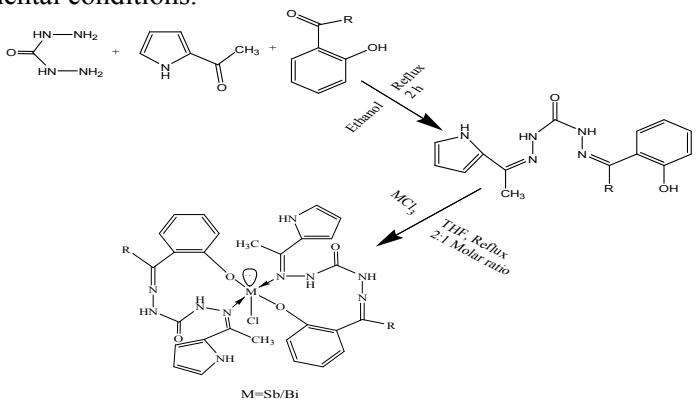
The carbohydrazones were prepared by heating an equimolar mixture of a hot ethanolic solution of carbohydrazide and a suitable carbonyl compound, such as 2-hydroxy-1-nephthaldehyde, o-hydroxy acetophenone, 2-hydroxy-1-acetonaphthone, salicylaldehyde, o-hydroxy propiophenone or 2-acetylpyrrole, in a refluxing mixture of ethanol for 2 h. The crude products were filtered and recrystallised from hot ethanolic solution.

Synthesis of Metal Complexes

A reaction between sodium salt ligand (2 molar equivalents) and Antimony trichloride, Bismuth trichloride (1 molar equivalent) in THF at 50 °C under reflux on a fractionating column for 8-10 h afforded a coloured viscous liquid (yield 62-74 %). It was purified by n-hexane/benzene mixture.

RESULTS AND DISCUSSION

Carbohydrazones are formed by the condensation reaction of carbohydrazide with appropriate carbonyls in a 1:1 molar ratio. The ligands employed in this work have been documented. The reaction of antimony trichloride and bismuth trichloride with the sodium salt of ligands in a 1:2 molar ratio in refluxing THF yielded corresponding coordination complexes of M(III). Crystals suitable for X-ray analysis could not be obtained under experimental conditions.



Scheme-1: Synthetic Route for the Preparation of M(III) Complexes

When the solvent was removed under reduced pressure, coloured viscous compounds were formed, which were found to be monomeric by molecular weight determinations.

UV-Visible Spectral Studies

The UV-Visible spectra of the ligands and their antimony(III) and bismuth(III) complexes were recorded in ethanol at room temperature, and the absorption bands are listed in Table-2. The ligands displayed two absorption bands in the 230–285 nm and 335–405 nm regions, corresponding to the $\pi \rightarrow \pi^*$ and $n \rightarrow \pi$ transitions, respectively. The $\pi \rightarrow \pi^*$ band did not change upon complexation, whereas the $n \rightarrow \pi^*$ band shifted to a lower wavelength, consistent with the azomethine nitrogen atom coordinating to the metal ion.

Infrared Spectroscopic Studies

The coordination sites were identified by the FTIR spectra of the ligands and their antimony(III) and bismuth(III) complexes, and the significant absorption bands are listed in Table-3. The ligands showed a

broad absorption band around 3410–3450 cm^{-1} for the phenolic –OH group and a strong band in the region 1668–1675 cm^{-1} assigned to the azomethine ν(C=N) stretching vibration, which shifted to a lower frequency upon complexation, indicating the coordination of the azomethine nitrogen atom.

Table-2: UV-Vis Spectra of (HL) and their Metal Complexes

Cmpds.	UV-Vis bands (nm)	Complexes	UV-Vis bands (nm)	Complexes	UV-Vis bands (nm)
L1H	230, 335	Sb-L1H	225, 320	Bi-L1H	220, 315
L2H	235, 385	Sb-L2H	232, 350	Bi-L2H	230, 355
L3H	265, 345	Sb-L3H	262, 325	Bi-L3H	261, 335
L4H	255, 400	Sb-L4H	253, 360	Bi-L4H	253, 350
L5H	285,405	Sb-L5H	280, 370	Bi-L5H	278, 380

The disappearance of the phenolic –OH band together with the appearance of new metal–oxygen and metal–nitrogen vibrations in the low-frequency region[20] confirms coordination through the deprotonated phenolic oxygen and azomethine nitrogen atoms. Small shifts observed for the ν(C–O) and ν(N–N) stretching vibrations further support the bidentate nature of the ligands in the synthesised complexes.

Table-3: Characteristic Stretching Vibration Frequencies (cm^{-1}) for Ligands (LH) and their Metal Complexes.

Compd.	$\nu_{C=N}$	ν_{Bi-O}	ν_{Bi-N}	ν_{Sb-O}	ν_{Sb-N}	ν_{M-Cl}	ν_{N-N}	ν_{C-O}	ν_{OH}/ ν_{N-H}
L1H	1672	-	-	-	-	-	-	1575	3410
L2H	1675	-	-	-	-	-	-	1585	3415
L3H	1668	-	-	-	-	-	-	1580	3413
L4H	1670	-	-	-	-	-	-	1590	3410
L5H	1670	-	-	-	-	-	-	1585	3418
Sb-L1H	1650	-	-	525	410	286	999	1607	3375
Sb-L2H	1652	-	-	530	410	288	1010	1622	3378
Sb-L3H	1646	-	-	526	412	280	1015	1613	3372
Sb-L4H	1645	-	-	529	414	315	1008	1609	3370
Sb-L5H	1655	-	-	528	411	303	1002	1608	3375
Bi-L1H	1652	435	405	-	-	242	997	1604	3372
Bi-L2H	1650	450	415	-	-	245	1007	1613	3375
Bi-L3H	1653	430	410	-	-	250	1003	1607	3374
Bi-L4H	1655	450	420	-	-	271	1015	1613	3372
Bi-L5H	1650	440	407	-	-	265	1005	1609	3370

^{1}H NMR Studies

The ligands and their M(III) complexes' 1H NMR data were recorded in $CDCl_3$ (Table-4). The signal at δ ~11.25 ppm (s) that is assigned to the -NH proton [21] of the ligands, remains unaltered, showing this is not engaged in complexation in the complex spectra. The ligands' OH proton signal can be seen at δ ~11.20-12.55 ppm (s) in the 1H NMR spectra of the ligands and disappears in the spectra of the corresponding M(III) complexes, possibly indicating deprotonation of the functional group and chelation of the ligand moiety through the phenolic oxygen with the antimony and bismuth atoms in the complexes.

For the ligands, the downfield deshielding of the proton signal for the methyl protons [-C(CH_3)=N] and azomethine protons [-CH=N] by δ ~ 1.80-1.85 ppm (s) and δ ~7.50-7.85 ppm, respectively. The resonance of this azomethine nitrogen would be deshielded (in comparison to its position in an isolated compound), due to lone pair electron donation to Sb/Bi centre, and appears downfield in the spectra of the corresponding Sb/Bi complexes; however, it remains unchanged at δ ~ 6.10-7.55 ppm for aromatic protons in ligands that are not perturbed by M(III) centres.

Table-4: ^{1}H NMR Data for the Ligands and for Their Corresponding Complexes

Compound	-HCN	-OH	-CH_3CN	Aromatic protons
L1H	7.50	11.20	1.80	6.15-7.20
L2H	7.81	12.25	1.85	6.10-7.15
L3H	7.62	11.50	1.81	6.65-7.34
L4H	7.85	12.55	1.84	6.10-7.55

L5H	7.58	11.55	1.82	6.78-7.35
Sb-L1H	8.1	-	1.90	7.25-7.40
Sb-L2H	8.17	-	1.92	7.35-7.50
Sb-L3H	8.40	-	2.02	7.30-7.50
Sb-L4H	8.30	-	1.97	7.40-7.55
Sb-L5H	8.25	-	1.98	7.30-7.55
Bi-L1H	8.70	-	1.89	7.15-7.50
Bi-L2H	8.45	-	1.90	7.35-7.50
Bi-L3H	8.30	-	2.00	7.40-7.55
Bi-L4H	8.21	-	1.97	7.30-7.40
Bi-L5H	8.34	-	1.99	7.40-7.50

Antimicrobial Studies

It was estimated how susceptible the bacterial strain was to various compounds through measurement of inhibition zone diameter (diameter of the clear area), ligands, and their complexes were screened for antifungal activity against three strains of fungus using the well diffusion method[22] involving ketoconazole as a reference, and they showed some potential activity. The results are listed in Table-5.

Table-5: Antimicrobial Activity Comparison for Ligands and Metal Complexes at varying Concentrations

Compound	Bacterial strain	20	40	60	80	Fungal strain	20	40	60	80
		Conc.(µg/mL)					Conc.(µg/mL)			
L1H	*B. subtilis*	7	9	9	10	*F. oxysporum*	8	8	10	11
	S. aureus	7	9	9	11	*T. reesei*	7	9	10	10
	E. coli	7	9	10	11	*P. funiculosum*	7	8	10	10
L2H	*B.subtilis*	10	11	12	12	*F. oxysporum*	10	10	12	12
	S. aureus	9	10	12	13	*T. reesei*	10	11	11	13
	E. coli	10	10	11	13	*P. funiculosum*	9	10	12	13
L3H	*B.subtilis*	5	6	7	8	*F. oxysporum*	6	7	8	9
	S. aureus	5	7	8	8	*T. reesei*	5	6	7	8
	E. coli	6	6	8	9	*P. funiculosum*	5	7	8	8
L4H	*B.subtilis*	9	9	11	11	*F. oxysporum*	8	9	11	12
	S. aureus	9	10	11	11	*T. reesei*	9	10	10	12
	E. coli	9	9	10	11	*P. funiculosum*	9	9	10	12
L5H	*B.subtilis*	6	7	9	9	*F. oxysporum*	6	8	8	9
	S. aureus	7	8	8	10	*T. reesei*	7	8	8	10
	E. coli	6	8	9	10	*P. funiculosum*	7	7	9	10
Sb-L1H	*B.subtilis*	11	12	12	13	*F. oxysporum*	11	11	13	13
	S. aureus	11	12	12	14	*T. reesei*	10	12	12	14
	E. coli	10	12	13	14	*P. funiculosum*	11	12	12	13
Sb-L2H	*B.subtilis*	15	16	16	17	*F. oxysporum*	15	15	17	17
	S. aureus	15	16	16	18	*T. reesei*	14	16	16	18
	E. coli	14	16	17	18	*P. funiculosum*	15	16	16	17
Sb-L3H	*B.subtilis*	7	8	8	9	*F. oxysporum*	7	7	9	9
	S. aureus	7	8	8	10	*T. reesei*	6	8	8	10
	E. coli	6	8	9	10	*P. funiculosum*	7	8	8	9
Sb-L4H	*B.subtilis*	13	14	14	15	*F. oxysporum*	13	13	15	15
	S. aureus	13	14	14	16	*T. reesei*	12	14	14	16
	E. coli	12	14	15	16	*P. funiculosum*	13	14	14	15
Sb-L5H	*B.subtilis*	9	10	10	11	*F. oxysporum*	9	9	11	11
	S. aureus	9	10	10	12	*T. reesei*	8	10	10	12
	E. coli	8	10	11	12	*P. funiculosum*	9	10	10	11
Bi-L1H	*B.subtilis*	12	13	13	14	*F. oxysporum*	12	12	14	14
	S. aureus	12	13	13	15	*T. reesei*	11	13	13	15
	E. coli	11	13	14	15	*P. funiculosum*	12	13	13	14
Bi-L2H	*B.subtilis*	16	17	17	18	*F. oxysporum*	16	16	18	18

	S. aureus	16	17	17	19	*T. reesei*	15	17	17	19
	E. coli	15	17	18	19	*P. funiculosum*	16	17	17	18
Bi-L3H	*B.subtilis*	8	9	9	10	*F. oxysporum*	8	8	10	10
	S. aureus	8	9	9	11	*T. reesei*	7	9	9	11
	E. coli	7	9	10	11	*P. funiculosum*	8	9	9	10
Bi-L4H	*B.subtilis*	14	15	15	16	*F. oxysporum*	14	14	16	16
	S. aureus	14	15	15	17	*T. reesei*	13	15	15	17
	E. coli	13	15	16	16	*P. funiculosum*	14	15	15	16
Bi-L5H	*B. subtilis*	10	11	11	12	*F. oxysporum*	10	10	12	12
	S. aureus	10	11	11	13	*T. reesei*	9	11	11	13
	E. coli	9	11	12	12	*P. funiculosum*	10	11	11	12

Streptomycin Inhibition zone: 20mm; Ketoconazole Inhibition zone – 22mm. *Standard

The synthesised antimony(III) and bismuth(III) complexes exhibited better antimicrobial activity than the corresponding ligands, showing that metal coordination enhances their biological behaviour. This enhancement may be attributed to chelation, which increases the lipophilic nature of the complexes, thereby facilitating their interaction with microbial cell membranes.[23] These findings support further biological evaluation of these complexes and are relevant to the development of new antimicrobial agents, in line with the objectives of the United Nations Sustainable Development Goal 3 (SDG 3: Good Health and Well-being).

Coordination Environment of M(III) Complexes

The above spectral analysis (UV, IR, and NMR) suggests the bidentate nature of ligands and the monomeric nature of these complexes. Antimony and bismuth are bound by a carbohydrazone ligand through a nitrogen and oxygen atom (Fig.-1). Taking into account the fact that two bidentate chelate rings and one chlorine atom are present, a penta-coordinated environment around the metal atom may be tentatively proposed for these synthesised compounds.

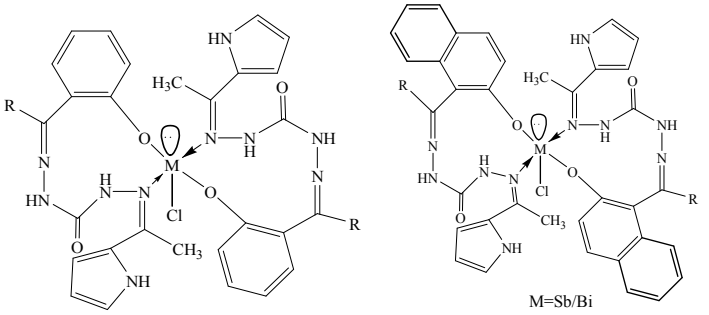


Fig.-1: Plausible Coordination Environment of the Metal Complexes.

CONCLUSION

Two series of carbohydrazone complexes of antimony(III) and bismuth(III) were synthesised and studied using elemental analysis and spectroscopic techniques. Infrared and NMR data possibly indicate coordination of the ligands through azomethine nitrogen and phenolic oxygen atoms in an anisobidentate (N, O) manner, showing effective metal-ligand binding. The above spectral analysis (UV, IR and NMR) and molecular weight measurements suggest the presence of a five-coordinate environment around the metal centres. The metal complexes demonstrated greater antibacterial efficacy than that of corresponding free ligands, with relatively better activity observed for bismuth(III) complexes. The improvement in biological activity is attributed to metal coordination, which facilitates interactions between the complexes and microbial cells, requiring further studies on toxicity, mechanism of action and in vivo activity; such investigations may support the development of new antimicrobial agents against drug-resistant microbial infections, in keeping with SDG-3: Good Health and Well-Being, the third Sustainable Development Goal of the United Nations.

ACKNOWLEDGEMENTS

The authors are thankful to the Head, Department of Chemistry, University of Rajasthan, Jaipur, for providing necessary laboratory facilities.

CONFLICT OF INTERESTS

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

The present work is related to *SDG-3: Good Health and Well-being*. All the authors contributed significantly to this manuscript, participated in reviewing/editing and approved the final draft for publication. The research profile of the authors can be verified from their ORCID ids, given below:

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Cite this article as: S. Choudhary and R. K. Gunsaria, *Rasayan J. Chem.*, 19(4), 2268-2275(2026), https://doi.org/10.31788/RJC.2026.1949712

REFERENCES

1. M. J. Keiser, J. J. Irwin and B. K. Shoichet, *Biochemistry*, **49**,10267(2010), https://doi.org/10.1021/bi101540g
2. Z. H. Cohen, H. Pervaz, K. M. Khan and C. T. Supuran, *Journal of Enzyme Inhibition and Medicinal Chemistry*, **20**, 81(2005), https://doi.org/10.1080/14756360410001733748
3. S. A. Amankrah, T. Salpadoru, K. Cotton, M. A. Patrauchan, K. L. Wozniak and N. Gerasimchuk, *Molecules*, **29**, 5779(2024), https://doi.org/10.3390/molecules29235779
4. J. R. Dimmock, P. Kumar, T. M. Allen, G. Y. Kao, S. Halleran, J. Balzarini and E. De Clercq, *Pharmazie*, **52**, 182(1997).
5. M. A. El-Helw, U. I. El-Ayaan, Y. G. Abou El-Reash, G. M. Abu El-Reash, *Applied Organometallic Chemistry*, **39**, e7830(2025), https://doi.org/10.1002/aoc.7830
6. T. Salpadoru, K. E. Pinks, J. A. Lieberman, K. Cotton, K. L. Wozniak, N. Gerasimchuk and M. A. Patrauchan, *Microbiology Spectrum*, **12**, e04234(2024), https://doi.org/10.1128/spectrum.04234-23
7. C. Bonaccorso, T. Marzo and D. La Mendola, *Pharmaceuticals*, **13**, 4(2019), https://doi.org/10.3390/ph13010004
8. C. Weng , *Angewandte Chemie International Edition*, **62**, e202310040(2023), https://doi.org/10.1002/anie.202310040
9. H. D. Yin, L. Quan and L. Li, *Inorganic Chemistry Communications*, **11**, 1121(2008), https://doi.org/10.1016/j.inoche.2008.06.017
10. P. Sharma, D. Perez, A. Cabrera, N. Rosas and J. L. Arias, *Acta Pharmacologica Sinica*, **29**, 881(2008), https://doi.org/10.1111/j.1745-7254.2008.00818.x
11. R. Agrawal, J. Sharma, D. Nandani, A. Batra and Y. Singh, *Journal of Coordination Chemistry*, **64**, 554 (2011), https://doi.org/10.1080/00958972.2010.550915
12. R. C. Liu, Y. Q. Ma, L. Yu, J. S. Li, J. R. Cui and R. Q. Wang, *Applied Organometallic Chemistry*, **17**, 662(2003), https://doi.org/10.1002/aoc.491
13. G. Muteeb, M. T. Rehman, M. Shahwan, M. Aatif, *Pharmaceuticals*, **16**, 1615(2023), https://doi.org/10.3390/ph16111615
14. D. Osypiuk, B. Cristóvão and A. Bartyzel, *Crystals*, **10**, 1004(2020), https://doi.org/10.3390/cryst10111004
15. J. R. Khusnutdinova and D. Milstein, *Angewandte Chemie International Edition*, **54**, 12236(2015), https://doi.org/10.1002/anie.201503873
16. M. A. Uvarova, M. V. Novikova, V. A. Eliseenkova, D. E. Baravikov, F. M. Dolgushin O. B. Bekker and I. A. Lutsenko, *Russian Journal of Coordination Chemistry*, **49**, 680(2023), https://doi.org/10.1134/S1070328423600419

17. M. A. Uvarova, F. M. Dolgushin, K. A. Babeshkin, N. N. Efimov, N. V. Gogoleva, D. N. Nebykov and I. L. Eremenko, *Inorganica Chimica Acta*, **575**, 122445(2025), https://doi.org/10.1016/j.ica.2024.122445
18. C. Perz, M. Paul and P. Bazerque, Biologia y Medicina Experimental, **15**, 113(1990).
19. J. E. Waters, L. Stevens-Cullinane, L. Siebenmann and J. Hess, *Current Opinion in Microbiology*, **75**, 102347(2023), https://doi.org/10.1016/j.mib.2023.102347
20. A. Kumari, R. V. Singh and J. P. Tandon, *Main Group Metal Chemistry*, **15**, 1(1992).
21. I. A. Mir, I. Singh, R. J. Butcher, R. Sharma, *Chemistry Select*, **10**, e05522(2025), https://doi.org/10.1002/slct.202405522
22. C. Erhonyota, G. I. Edo, F. O. Onoharigho, *Acta Ecologica Sinica*, **43**, 684(2023), https://doi.org/10.1016/j.chnaes.2022.08.006
23. M. Alhujaily, A. Shafie, M. S. Alhussaini, A. A. I. Alyahya, *Applied Biochemistry and Biotechnology*, **198**, 7272(2026), https://doi.org/10.1007/s12010-026-05800-z

[RJC-9712/2026]