EUROPEAN JOURNAL OF BIOMEDICAL AND PHARMACEUTICAL SCIENCES
http://www.ejbps.com

ISSN 2349-8870
Volume: 6
Issue: 13
539-546
Year: 2019

SPECTRAL CHARACTERIZATION AND ANTIMICROBIAL EVALUATION OF NOVEL $Tl^{(I)}$-15C5 COMPLEXES

Rajeev Ranjan*

Univ. Department of Chemistry, DSPM University, Ranchi.

***Corresponding Author: Dr. Rajeev Ranjan**
Univ. Department of Chemistry, DSPM University, Ranchi.

Article Received on 20/10/2019 **Article Revised on 10/11/2019** **Article Accepted on 01/12/2019**

ABSTRACT
Crown ethers are being used in applications across the spectrum of science. Beyond their traditional place in chemistry their applications in biology include the ability to regulate enzyme activity, interact with and cleave DNA, and act as antimicrobial agents. Functionalized crowns have been synthetically designed to achieve these functions; however, the basic heterocycles themselves yield beneficial biological interactions as well. Simple crown compounds such as 15C5 and 18C6 have the ability to interact with enzymes. Remarkable complexation properties of cryptand have been found towards heavy metal cations like Tl^{+}, Cd^{2+}, Hg^{2+}, Pb^{2+} etc. The crown ether-metal ion binding is enhanced in the absence of non-coplanar donor oxygen atoms and electron withdrawing substituents in the crown ether skeleton. The present paper describes the preparation, spectral characterization, antibacterial and antifungal studies of novel $Tl^{(I)}$-15C5 complexes. The metal salts used for complexation were salts of nitrophenols. Products were isolated from thallium salts of all the three ligands, o-nitrophenol, 2,4-dinitrophenol and 2,4,6-trinitrophenol. The bonding patterns of complexes are suggested from the studies of elemental analysis, molar conductivity, IR, UV-Vis and ^{1}H-NMR spectral analysis. Antibacterial and antifungal activities of the synthesized complexes were measured by Kirby Bauer disc diffusion method.

KEYWORDS: 15C5, FTIR, NMR, ONPH, DNPH, TNPH.

INTRODUCTION
Crown ethers are macrocycles that, in their simplest form, are cyclic oligomers of dioxane. Macrocycles of the $(CH_2CH_2O-)n$ type in which $(n \geq 4)$ are generally referred to as crown ethers.[1-2] This is partly because they comprise a special group of heterocycles that bind cations.[3-4] Crown ethers form complexes with a host of cations, including alkali, alkaline earth, NH^{4+}, Tl^{+}, Ag^{+}, Au^{+}, Ra^{2+}, Pb^{2+}, Cd^{2+}, Zn^{2+}, Hg^{+}, Hg^{2+}, lanthanides, transition metals, etc.[5-15] Crown ethers[16-17] have many applications in catalysis, organic synthesis, biochemistry, microbiology, and material science. Their applications in biology include the ability to regulate enzyme activity, interact with DNA[18], and act as antimicrobial agents. Simple crown compounds such as 15-crown-5 and 18-crown-6 have the ability to interact with enzymes.[19] This interaction increases the activity of enzymes when used in organic solvents.[20] Numerous enzymes experience increased activity from the presence of crown ethers.[21-23] Crown ether compounds have been designed and synthesized to interact with DNA.[24] Crowns may be synthesized to inhibit cell proliferation, and new systems are being exploited to kill microbial organisms. The interest in crown ethers in both biological science and industry is growing.[25] Crown ethers have a firm foundation in biological science and industry that will produce new and innovative applications with future generations of compounds.[26]

Heavy metal cations like Tl^{+}, Cd^{2+}, Hg^{2+}, Pb^{2+} are very toxic and the highly selective complexation by those ligands which may remove only these harmful cations and not affecting the levels of biologically important ones (Na^{+}, K^{+}, Ca^{2+}.. etc.) is both of fundamental interest and of potential practical importance from their therapeutical decorporation point of view and to control the pollution of these metal ions in the environment. Coordination chemistry of macrocyclic ligands with thallium ion has been a fascinating area of current research interest to the modern chemists all over the world. Interest and quest in designing new macrocyclic ligands is due to their potential use in biological systems: as synthetic ionophores, as therapeutic reagents for the treatment of metal intoxication, as cyclic antibiotics, to study the biological guest-host interactions, in solvent extraction and in catalysis.[27-33]

Five types of pathogenic bacteria and one fungi were used in this work which includes four gram positive bacteria, S. aureus, E. faecalis, lactobacillus, B. subtilis; one gram negative bacteria Escherichia coli and one fungi C. albicans. All the used ligands showed very small

activity against the tested bacteria and fungi while all the prepared complexes showed very good results. Table shows the inhibition zones of the ligands and the prepared complexes. All the prepared complexes gave good inhibition zones. These fungi and bacteria are known for its resistance to most of the developed antibiotics and is known to be the major cause of many health issues and infections.[34-36]

MATERIALS AND METHODS

All chemicals used were of S. Aldrich / E. Merck, A.R. grade. The metal contents were estimated by flame photometric method. The melting point of the synthesized compounds, were determined on electrical tempo T-1150 melting point apparatus. Molar conductivities of the compounds were measured using Systronic conductivity meter-306. The conductivities of the compounds were measured at the concentration 10^{-3} M in methanol solvent at $30(\pm0.5)^0$C. IR spectra were recorded by Perkin Elmer RX1 (4000-450 cm^{-1}). UV-visible spectral data were recorded through Systronic double beam spectrophotometer-2203 (600-200 nm). The ^{1}H−NMR spectra of ligand and crown ether complexes were recorded in $CDCl_3$ by Bruker DRX-300.

EXPERIMENTAL

Preparation of thallium salt of nitrophenols; Tl(ONP), Tl(DNP) and Tl(TNP)

About 0.02 mol of appropriate nitrophenol was taken in a conical flask and dissolved in 50 ml of dry ethanol with constant stirring with the help of glass rod. Further 0.02 mol of metal hydroxide was dissolved in ethanol and was slowly added to the alcoholic solution of nitrophenol with constant stirring. The mixture was continuously refluxed on hot plate equipped with magnetic stirrer for 50 minutes and the temperature was maintained at 78^0C. The solution in conical flask was corked and kept standed. On cooling this solution solid crystalline product began to precipitate slowly. Product was filtered, washed with absolute ethanol and dried in an electric oven at 80^0C.

Preparation of 15C5 ether

Preparation of crown ethers which may work as a strong complexing host molecule was one of the important part of this research work. These were prepared by the synthetic methods as reported in literature.[37,38]

Table 1.1: Physical properties of thallium salts.

Compound	Molecular Formula	Colour	Melting point (^{0}C)
Tl.ONP	$C_{16}H_{24}NO_8Tl$	Light yellow	275 d
Tl.DNP	$C_{16}H_{23}N_2O_{10}Tl$	Bright yellow	270 d
Tl.TNP	$C_{16}H_{22}N_3O_{12}Tl$	Light orange	270 e

d – decomposition temp, e – explosion temp

Preparation of adducts of 15-crown-5 ether with thallium salts of 2-nitrophenol, 2,4-dinitrophenol and 2,4,6-trinitrophenol

The dried organic salt (0.002 mol) was suspended in 50 ml dry methanol and heated with constant stirring to get a clear solution. Stoichiometric proportion of 15-crown-5 ether (0.002 mol) was added in this solution. This reaction mixture was refluxed on a hot plate equipped with magnetic stirrer at 50-55^{0}C. A clear solution was formed. It was filtered and concentrated to half of its bulk. On cooling this solution, solid crystalline product began to precipitate. The product was separated and allowed to stand overnight then filtered on a buchner funnel. The compound was washed with a little cold dry methanol and dried over KOH desiccator.

15C5.Tl(ONP) : $C_{16}H_{24}NO_8Tl$; 1606, 1499, 1331, 1220, 1122, 852, 771, 560, 535

15C5.Tl(DNP) : $C_{16}H_{23}N_2O_{10}Tl$; 1630, 1477, 1348, 1219, 1219, 862, 772, 550, 510

15C5.Tl(TNP) : $C_{16}H_{22}N_3O_{12}Tl$; 1623, 1436, 1327, 1219, 1086, 870, 772, 545, 482

Mechanism of Complexation

Metal cation-crown ether complexation processes can be explained by the multistep Eigen-Winkler mechanism:

$Tl(Pic) + L \rightarrow [Tl^+.L](Pic^-)$

Where, Tl^+ = solvated metal ion, L = free macrocyclic ligand, $Tl^+.L$= solvent-separated metal-macrocyclic ligand pair, $(Tl.L)^+$ = complex with metal cation embedded in the macrocyclic cavity.

Antifungal and Antibacterial Assay

Five bacterial isolates i.e. Escherichia coli, Staphylococcus aureus, E. faecalis, B. subtilis, Lactobacillus and one fungal isolate of C. albicans were used in this work. The isolates were planted on the surface of an agar on petriplates incubated at 37°C for 24 hrs and stored at 4°C for the later use.

Preparation of Bacterial Suspensions

The bacterial suspensions were prepared by transferring a colony from each bacterial isolate using a metal loop into test tubes containing liquid nutrient broth and were incubated at 37°C for 18 hrs.

The Antibacterial Test of the Prepared Complexes

An amount of 18-20 ml of freshly prepared solid nutrient agar was transferred to sterilized glass petridishes in sterilized environment (inside the biological safety cabinets; Laminar air flow) and left to cool and solidify. 0.1 ml from each bacterial suspension was transferred to the dishes containing the solidified nutrient agar and was uniformly inoculated using a spreader. The streaking was done in at least three directions over the surface of the agar to obtain uniform growth, and final sweep was made around the rim of the agar. The plates were allowed to stand for 5 minutes to dry, after that four to five wells with a diameter of 0.6 mm were made in each dish using a sterile borer.

RESULT AND DISCUSSION

UV-Visible study

Ultraviolet-visible spectra of synthesized compounds provide small evidence of bonding in complexes. Saturated crown ethers do not show any absorption above 220 nm. The electronic spectral studies of synthesized complexes shows only some deviation of π - π*, n - π*, σ - π* and σ - σ* transitions due to shifting of electron density from donor hetero atoms to cationic species. The slight change in spectral band position is usually taken as either solvent effect or interaction of electron cloud of donor atom of ligand with thallium ion. The bond energy in organic compound possess energy equivalent to absorption energy of ultraviolet or visible radiation as they form bonds by ion-dipole interactions and/or involvement of non-bonding electrons with central metal ions.[39-42] The n - σ* transition of phenolic (C–O) group is observed at high energy and phenyl ring π - π*, σ - σ* transitions between 180–255 nm region. The antibonding orbitals σ* and π* are quantized energy level of higher energies. Besides bonding electronic transitions, intermolecular transition known as charge transfers (C–T) transitions of high intensity are also observed in synthesized complexes.[43,44]

FTIR study

The 15C5 crown ethers in uncoordinated state display ν(C–O–C) stretching vibration band near 1100±22 cm^{-1}. The FTIR spectra of aromatic as well as aliphatic crown ether shows the presence of ether linkages by a strong broad band around 1230 cm^{-1} for aromatic-O-aliphatic and a band at 1100 cm^{-1} for aliphatic-O-aliphatic group. The free nitro groups of nitrophenols display $–NO_2$, ν_{as} and ν_s stretching around 1620±15 cm^{-1}, 1260±30 cm^{-1}. The $\nu(-NO_2)$ bending band is found at 840±20 cm^{-1}, shifted to lower frequency by 10-15 cm^{-1} upon complexation.[45] The FTIR band observed near 740-780 cm^{-1} is attributed to phenyl ring (C−H) out of plane bending band. The absorption at about 1110 cm^{-1} is attributed to phenolic (C–O) stretching band. In present study all nitrophenols display ν(O−H) frequency as broad band in the region 3140-3320 cm^{-1} and ν(C–O) near 1120±10 cm^{-1}.[46,47] The ν(O–H) disappears in thallium salts and ν(C–O) band shifted to higher frequency due to acquiring higher (C–O) bond order on deprotonation in thallium salts. This increase is attributed to bonding of phenolic oxygens (C–O) in all complexes.

At around 1605 cm^{-1}, 1620±2 cm^{-1} and 1640-1645 cm^{-1} are stretching bands of $–NO_2$ in Tl(ONP), Tl(DNP) and Tl(TNP). These vibrations shifted to lower frequency in complexes. The $\nu(NO_2)$ located near 840±15 cm^{-1} also shifted to lower vibrational frequency in complexes. The crown ethers display $\nu(CH_2)$ stretching vibrations at 2925±10 cm^{-1} and these are little affected or unaffected on bonding with metal ions in complexes. The crown ethers in uncoordinated state display ν(C-O-C) stretching vibration band near 1115±10 cm^{-1}, which is shifted to lower frequency by 10-60 cm^{-1} in almost all complexes. These bands shifting suggest involvement of crown ether's skeletal oxygens in bond formation with thallium ion. Some complexes shows a broad band at around 3350-3420 cm^{-1}, with maxima at 3405±10 cm^{-1}. In the far-infrared region new bands are found in the 425-590 cm^{-1} region, which may be assigned to the $\nu(M–O_{crown})$ stretching frequency.[48-50] Thus infrared spectrum studies of complexes suggest complexation of thallium salts of nitrophenols with 15C5 ether.

Table 1.2: Prominent IR bands of thallium complexes (in cm^{-1})

Compound	ν_{as} (C–O–C)	ν_1 (–NO_2), ν_3 (–NO_2)	ν (C–H) Phenolic out of Plane	ν_s(C–H)$_{bending}$, ν_{as}(–CH_2–)$_{bending}$	ν(N=O)$_{str}$ in C–NO_2	ν(M–O) / ν(M–O_{crown})
15C5.Tl(ONP)	1122	1606, 852	771	1499, 1331	1220	535, 560
15C5.Tl(DNP)	1219	1630, 862	772	1477, 1348	1219	510, 550
15C5.Tl(TNP)	1086	1623, 870	772	1436, 1327	1219	482, 545

^{1}H-NMR Study

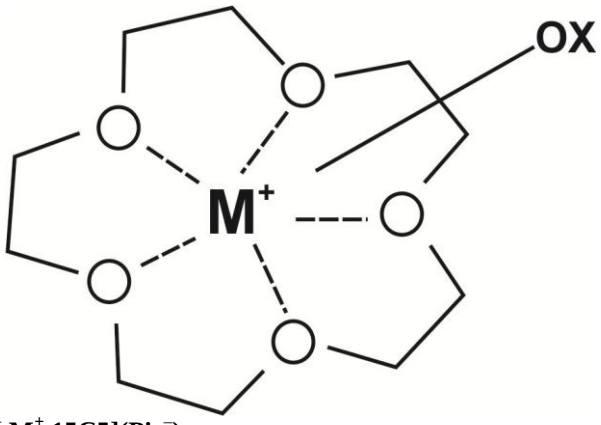
Information on some crown ether interactions leading to supramolecule formation is available from measurements of the chemical shift (δ) variations.[51,52] The ^{1}H-NMR study of synthesized crown ether complexes provides important information regarding structure of complexes.[53]

^{1}H-NMR Chemical shift (δ) for free crown ethers and synthesized complexes

Compound	δ(1H)
15C5	3.621
Tl^+-15C5	3.627

The chemical shift of ^{1}H in 15C5 moved downfield upon complexation. The chemical shift variation indicates a possible change in the structure and/or electronic environment of ^{1}H in these systems on complexation. This is due to possible conformational change in the macrocyclic skeleton during complexation which could affect the electron density on proton through the Fermi contact term.[54] After formation of the [Tl^+-L](Pic^-) complex, the proton chemical shift of δ(–CH_2–O–) shows significant downfield shifts [Δδ(–CH_2–O–)=0.08-0.25 ppm], indicating metal-ligand bond formation.[55-57] The relative change in the downfield shift shows the relative strength of the synthesized complexes.[58,59] Thus coordination of ligand molecule with metal ion provides much information regarding bonding. The proton NMR spectrum of 15C5 polyether shows ^{1}H-NMR peaks δ (1H) = 3.920–3.926 (20H, 5 –CH_2CH_2O–) in $CDCl_3$.[60,61] The shift of –CH_2– signals in complexes

from free crown ether suggests the coordination of crown ether oxygen of 15C5 with thallium salts. Figure-1 shows the proposed structures of complexes $[Tl^{+}.L](Pic^{-})$, where M = Tl^{+}, L = 15C5 and OX = ONP^{-}/ DNP^{-}/TNP^{-} based on all reported evidences.



[M^{+}.15C5](Pic^{-})
[M is $Tl^{(I)}$ and, Pic^{-} = OX = ONP^{-}/DNP^{-}/TNP^{-}]
Proposed structure of $Tl^{(I)}$-15C5 complexes
Figure 1

Antimicrobial evaluation of the prepared complexes

Antimicrobial test was performed using Kirby Bauer disc diffusion method.[62,63] Five bacterial isolates, Escherichia coli, Staphylococcus aureus, E. faecalis, B-Subtilis, Lactobacillus and one fungal isolate of C. albicans were used in this work. The isolates were planted on the surface of an agar on petriplates incubated at 37°C for 24 hrs and stored at 4°C for the later use. Stericle filter paper dishes are placed in 4-5 places on the petriplates. The test compound was then added at the centre of each paper. The plates were inverted and then incubated for 16 hrs. After incubation depending on the strain and chemical complex inhibition zones were developed around each test sample. The diameter of the zone of inhibition around each disc was measured to the nearest millimeter.[64,65] Controlled experiments were performed and only equivalent volume of solvents were added and applied on the paper discs. The antimicrobial activities were expressed as minimum inhibitory concentration (MICS) values[66,67] corresponding to the lowest concentration of the compound that produces a measureable zone of inhibition. All the used ligands showed very less activity against the tested bacteria and fungi while all the prepared complexes showed very good results. Table shows the inhibition zones of the prepared complexes. All the prepared complexes gave good inhibition zones. Results of antimicrobial tests of synthesized complexes are listed in table-2.

Table 2: Antimicrobial activity of synthesized complexes.

Compound	Antibacterial activity										Antifungal activity	
	Gram Positive								Gram Negative			
	S.aureus		E.faecalis		B.substillis		Lactobacillus		E.coli		C.albicans	
	1 mg	2mg	1 mg	2mg	1 mg	2 mg	1 mg	2 mg	1 mg	2 mg	1 mg	2mg
[Tl^{+}.15C5].(ONP^{-})	--	--	--	--	-	-	-	--	-	-	-	-
[Tl^{+}.15C5].(DNP^{-})	-	--	--	--	-	-	-	--	-	-	-	--
[Tl^{+}.15C5].(TNP^{-})	+	+	-	-	+	-	+	+	-	-	+	+

-Very active – Moderately active + Not active

Phenolic compounds can act as permeabilizers and thus destabilizes the outer membrane of gram negative bacteria, gram positive bacteria and fungi making it more easy for the complexes to pass through the bacterial membrane.[68,70] From data of table 2 it can be seen that the [Tl^{+}.15C5].(ONP^{-}) and [Tl^{+}.15C5]. (DNP^{-}) possesses modest but net antibacterial activity against the two bacteria species, S. aureus and E. faecalis used in our experiments, whereas the metal complexe [Tl^{+}.15C5].(TNP^{-}) acts much more effectively against E. faecalis and E. coli than the parent ligand, but much less efficient against C. albicans, Lactobacillus and S. aureus as compared to [Tl^{+}.15C5].(DNP^{-}). Activity of $Tl^{(I)}$-15C5 complexes against Lactobacillus and activity of $Tl^{(I)}$-15C5 Complexes against E. coli has been shown in percentage inhibition vs. average activity with time graph shown in figure. 2 and figure 3.

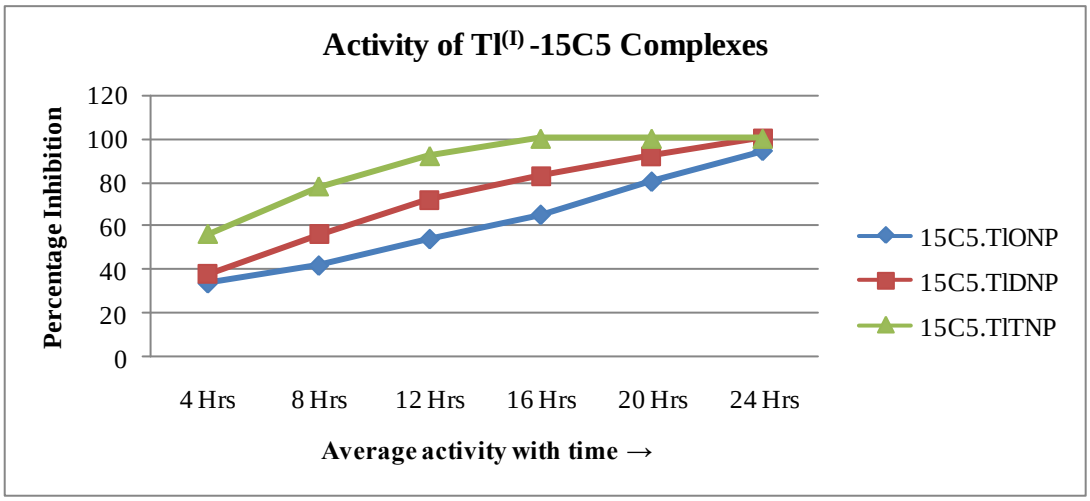


Figure 2: Activity of $Tl^{(I)}$-15C5 Complexes against Lactobacillus.

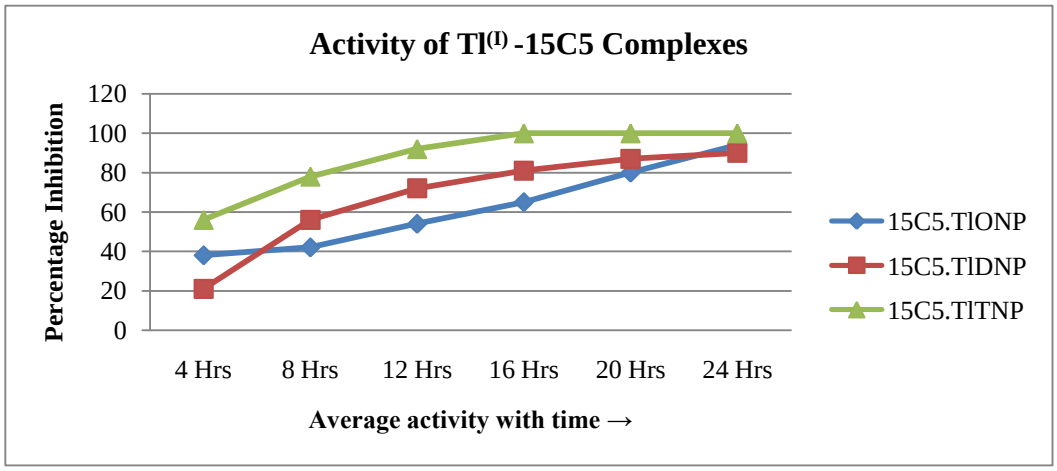


Figure 3: Activity of $Tl^{(I)}$-15C5 Complexes against E. Coli.

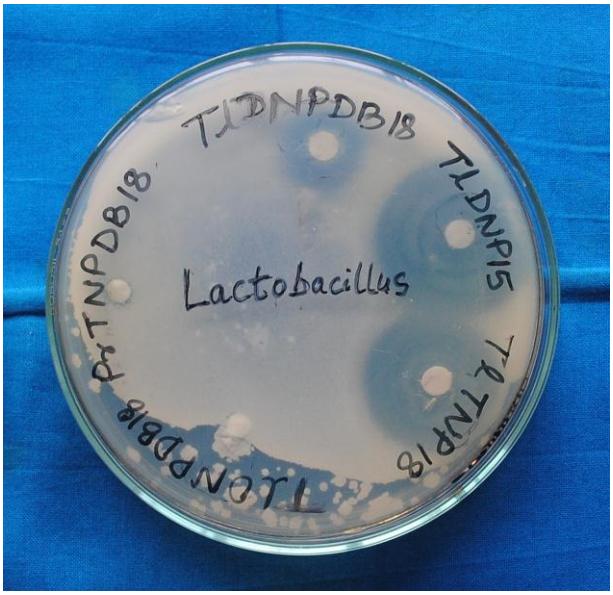


Figure 4: Microbial study against Lactobacillus.

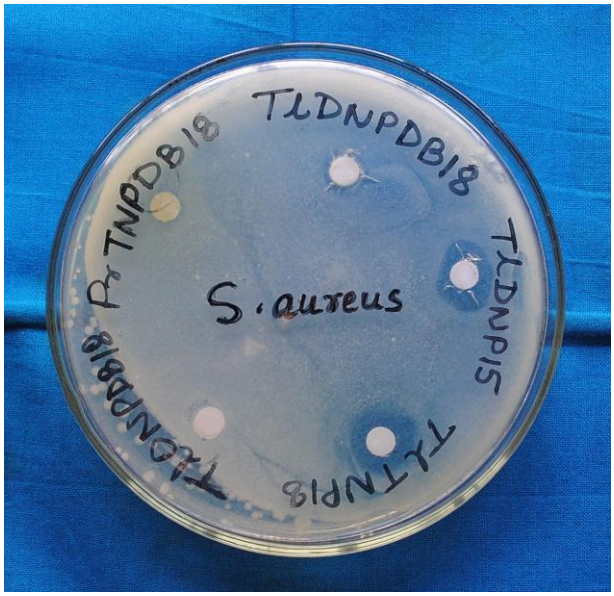


Figure 5: Microbial study against S. aureus.

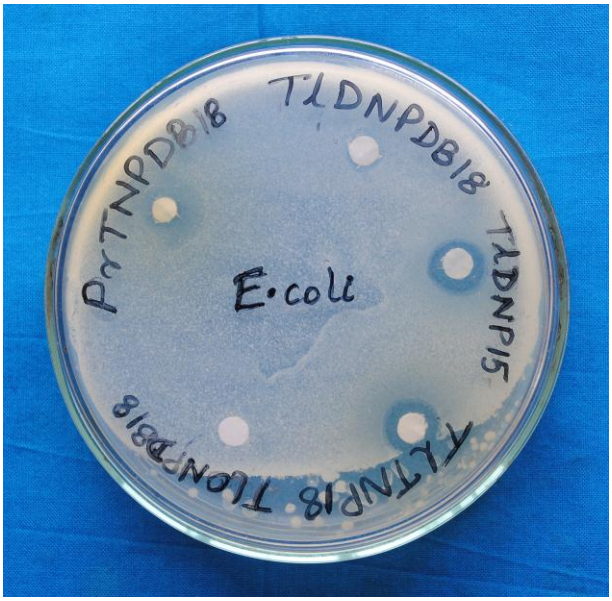


Figure 6: Microbial study against E. coli.

ACKNOWLEDGEMENT

I am thankful to the UGC-ERO, Kolkata for providing partial financial assistance to this research under UGC-Minor Research Programme. I am also thankful to the Head, SAIF, CDRI, Lukhnow, for providing FTIR-spectra, ^{1}H-NMR spectra and necessary facilities.

REFERENCES

1. G. W. Gokel, W. M. Leevy and M. E. Weber, *Chem. Rev*, 2004; 104: 2723- 2750. DOI:10.1021/cr020080k
2. M. E. Sanchez and M. S. Vazquez, *Computational and Theoretical Chemistry*, 2011; 966: 127-132.
3. E. E. Kasapbasi and M. Yurtsever, *Turk. J. Chem*, 2012; 36: 147-158.
4. C. J. Samuel, A. Fernandez, M. L. Torres, D. V. Garcia, A. J. Suarez, J. M. Vila and J. J. Fernandez, *Organometallics*, 2009; 28(23): 6657-6665.
5. J. M. C. Costa and P. M. S. Rodrigues, *Portugaliae Electrochimica Acta*, 2002; 20(3): 167-178.
6. C. M. Choi, J. Heo and N. J. Kim, *Chemistry Central Journal*, 2012; 6(1): 1-8. DOI: 10.1186/1752-153X-6-84
7. V. W. Yam, Y. L. Pui and K. K. Cheung, *Inorganica Chimica Acta*, 2002; 335: 77-84. DOI: 10.1016/S0020-1693(02)00809-5
8. K. N. Alasundkar, M. B. Deshmukh, D. K. Salunkhe and S. A. Sankpal, *Der Chemica Sinica*, 2011; 2(2): 118-124.
9. A. Spath and B. Konig, *Beilstein J. Org. Chem*, 2010; 6(32): 1-111. DOI: 10.3762/bjoc.6.32.
10. A. A. Sinelshchikov, Yu G. Gorbunova, L. A. Lapkina, N. Y. Konstantinov and A. Y. Tsivadze, *Russian Journal of Inorganic Chemistry*, 2011; 56(9): 1370-1379. DOI: 10.1134/S0036023611090270.
11. V. S. Ijeri and A. K. Srivastava, *J. Chem. Eng. Data*, 2002; 47: 346-350. DOI: 10.1021/je010278m.
12. J. Zolgharnein, F. Riahii and S. Amani, *Journal of Inclusion Phenomena and Macrocyclic Chemistry*, 2003; 45(1): 13-17. DOI: 10.1023/A:1023001331866.
13. K. P. Birin, Yu G. Gorbunova and A. Yu Tsivadze, *Russian Journal of Inorganic Chemistry*, 2007; 52(2): 191-196. DOI: 10.1134/S003602360702009X.
14. V. Shivaiah and S. K. Das, *Inorg. Chem*, 2005; 44(21): 7313-7315. DOI: 10.1021/ic0511761.
16. R. R. Julian and J. L. Beauchamp, *J. Am. Soc. Mass Spectrom*, 2002; 13(5): 493-498. DOI: 10.1016/S1044-0305(02)00368-9.
17. C. J. Pedersen. *Journal of the American Chemical Society*, 1967; 89(26): 7017-7036. DOI:10.1021/ja01002a035.
18. C. J. Pedersen. *Journal of the American Chemical Society*, 1971; 36(2): 254-257. DOI:10.1021/jo00801a003.
19. A. Manjula, M. Nagarajan, *Arkivoc*, 2001; 8: 165-183.
20. D. J. V. Unen, J. F. J. Engbersen, D. N. Reinhoudt, *Biotechnology and Bioengineering*, 2002; 77(3): 248-255. DOI:10.1002/bit.10032.
21. S. Zaitsev, D. Solovyeva, I. Zaitsev, M. Tsarkova, *Nanoscience and Nanotechnology Research*, 2013; 1(1): 9-12. DOI:10.12691/nnr-1-1-3.
22. D. N. Reinhoudt, M. Crego-Calama, *Science*, 2002; 295(5564): 2403-2407. DOI:10.1126/science.1069197.
23. T. Itoh, Y. Takagi, T. Murakami, Y. Hiyama, H. Tsukube, *The Journal of Organic Chemistry*, 1996; 61(6): 2158-2163. DOI:10.1021/jo951598.
24. A. M. Santos, M. Vidal, Y. Pacheco, J. Frontera, C. Baez, O. Ornellas, G. Barletta, K. Griebenow, *Biotechnology and Bioengineering*, 2001; 74(4): 295-308. DOI:10.1002/bit.1120.
25. S. Vogel, K. Rohr, O. Dahl, J. Wengel, *Chemical Communications*, 2003; 1: 1006-1007. DOI:10.1039/B301100C
25. P. A. Guy, E. Gremaud, J. Richoz and R. J. Turesky, *J. Chromatogr. A*, 2000; 883(1-2): 89-102. DOI: 10.1016/S0021-9673(00)00361-7
26. S. R. Luna, F. Medrano, M. I. Bernal and C. G. Alcantar, *J. Mex. Chem. Soc*, 2009; 53(4): 209-219.
27. M. Lee, D.V. Schoonover, A. P. Gies, D. M. Hercules, H. W. Gibson. *Macromolecules*, 2009; 42 (17): 6483-6494. DOI:10.1021/ma901248m.
28. N. F. Carvalho, J. R. Pliego Jr.. *The Journal of Organic Chemistry*, 2016; 81(18): 8455-8463. DOI:10.1021/acs.joc.6b01624.
29. Y. Liu, J. Shen, C. Sun, C. Ren, H. Zeng, *Journal of the American Chemical Society*, 2015; 137(37): 12055-12063. DOI:1021/jacs.5b07123.
30. Y. Yoshida, M. Maesato, Y. Nakamura, M. Ishikawa, H. Yamochi, G. Saito, H. Kishida, H. Kitagawa. *Inorganic Chemistry*, 2019; 58(24): 16703-16711. DOI:10.1021/acs.inorgchem.9b02814.

31. Y. Sun, C. Chen, P. J. Stang. *Accounts of Chemical Research*, 2019; *52*(3): 802-817. DOI:10.1021/acs.accounts.8b00663
32. A. Goswami, S. Saha, P. K. Biswas, M. Schmittel. *Chemical Reviews*, 2020; 120(1): 125-199. DOI:10.1021/acs.chemrev.9b00159
33. P. D. Sala, R. D. Regno, C. Talotta, A. Capobianco, N. Hickey, S. Geremia, M. D. Rosa, A. Spinella, A. Soriente, P. Neri, C. Gaeta. *Journal of the American Chemical Society*, 2020; 142(4): 1752-1756. DOI:10.1021/jacs.9b12216
34. E. Banin, K. M. Brady, E. P. Greenberg, *Applied and Environmental Microbiology*, 2006; 72: 2064-2069. DOI:10.1128/AEM.72.3.2064-2069.2006.
35. R. B. Mutalik, V. G. Gaikar, *Process Biochemistry*, 2006; 42(1): 133-141. DOI:10.1016/j.procbio.2005.06.019
36. M. P. Bos, J. Tommassen, *Infection and Immunity*, 2005; 73(9): 6194-6197. DOI:10.1128/IAI.73.9.6194-6197.2005.
37. C. J. Pedersen, *Journal of the American Chemical Society*, 1970; 92: 386.
38. R. Ranjan, P. Bhardwaj, S. Chitlangia, J. K. Nayak, *Asian Journal of Research in Chemistry*, 2016; 9(5): 212-216.
39. R. Ranjan and R. Sinha., *Asian J. Research Chem*, 2012; 5(11): 1335-1337.
40. R. Ranjan, *Asian J. Research Chem*, 2012; 5(12): 1480-1482.
41. Y. Inokuchi, M. Nakatsuma, M. Kida, T. Ebata. *The Journal of Physical Chemistry A*. 2016, 120 (32), 6394-6401. DOI:10.1021/acs.jpca.6b06626.
42. Y. Inokuchi, O. V. Boyarkin, R. Kusaka, T. Haino, T. Ebata, T. R. Rizzo, *The Journal of Physical Chemistry A*, 2012, *116* (16), 4057-4068. DOI:10.1021/jp3011519.
43. Y. Inokuchi, T. Ebata, T. R. Rizzo, *The Journal of Physical Chemistry A*, 2018; 122(15): 3754-3763. DOI:10.1021/acs.jpca.7b12385
44. Y. Inokuchi, T. Ebata, T. R. Rizzo. *The Journal of Physical Chemistry A*, 2019; 123(31): 6781-6786. DOI:10.1021/acs.jpca.9b05706.
45. R. A. Condrate, K. Nakamoto, *The Journal of Chemical Physics*, 1965, 42(7), 2590-2598. DOI:10.1063/1.1696337
46. J. D. Rodriguez, T. D. Vaden, J. M. Lisy, *Journal of the American Chemical Society*, 2009; 131(47): 17277-17285. DOI:10.1021/ja906185t.
47. C. Perez, J. C. Lopez, S. Blanco, M. Schnell, *The Journal of Physical Chemistry Letters*, 2016; 7(20): 4053-4058. DOI:10.1021/acs.jpclett.6b01939.
48. D.Li, X. Gan, M. Tan, X. Wang. *Polyhedron*, 1997; 16(23): 3991-3995. DOI:10.1016/S0277-5387(97)00181-2.
49. K. Nakamoto. Infrared and Raman Spectra of Inorganic and Coordination Compounds. 3rd Ed, John Wiley, New York, 1978.
50. D. J. Olszanski, G. A. Melson. *Inorganica Chimica Acta*, 1978; 26: 263-269. DOI:10.1016/S10020-1693(00)87225-4
51. P. K. Harris, B. E. Mann, NMR and the Periodic Table, Academic Press, London, 1978.
52. S. Stoss, W. Schroth, E. Kleinpeter, *Magnetic Resonance in Chemistry*, 1992; 30(5): 425-433. DOI:10.1002/mrc.1260300514.
53. I. Starke, A. Koch, E. Uhlemann, E. Kleinpeter. *Journal of Molecular Structure*, 1995; 351: 165-179. DOI:10.1016/0022-2860(94)08492-Z.
54. F R. Fulmer, A. J. M. Miller, N. H. Sherden, H. E. Gottlieb, A. Nudelman, B. M. Stoltz, J. E. Bercaw, K. I. Goldberg, *Organometallics*, 2010; 29(9): 2176-2179. DOI:10.1021/om100106e.
55. M. S. Islam, R. A. Pethrick, M. J. Wilson. *Journal of the Chemical Society, Faraday Transactions*, 1997, 93(3), 387-392. DOI:10.1039/A604125F.
56. H. Haddadi, N. Alizadeh, M. Shamsipur, Z. Asfari, V. Lippolis, C. Bazzicalupi, *Inorganic Chemistry*, 2010; 49(15): 6874-6882.
57. M. J. Wilson, R. A. Pethrick, D. Pugh, M. S. Islam. *Journal of the Chemical Society, Faraday Transactions*, 1997; 93(11): 2097-2104. DOI:10.1039/A607934B.
58. M. Shamsipur, M. Irandoust, *Journal of Solution Chemistry*, 2008; 37(5): 657-664. DOI:10.1007/s10953-008-9261-7.
59. B. P. Czech, D. H. Desai, J. Koszuk, A. Czech, D. A. Babb, T. W. Robison, R. A. Bartsch, *Journal of Heterocyclic Chemistry*, 1992, 29(4), 867-875. DOI:10.1002/jhet.5570290433.
60. A. Higelin, C. Haber, S. Meier, I. Krossing, *Dalton Transactions*, 2012; 41(39): 12011-12015. DOI:10.1039/C2DT30379E.
61. H. Hamaed, K. E. Johnston, B. F. T. Cooper, V. V. Terskikh, E. Ye, C. L. B. Macdonald, D. C. Arnold, R. W. Schurko. *Chemical Science*, 2014; 5: 982-995. DOI:10.1039/C3SC52809J.
62. J. J. Biemer, *Annals of Clinical & Laboratory Science*, 1973; 3(2): 135-140.
63. V. J. Boyle, M. E. Fancher, R. W. Ross Jr., *American Society for Microbiology, Antimicrobial Agents and Chemotherapy*, 1973; 3(3): 418-424. DOI:10.1128/AAC.3.3.418.
64. P. Sanpui, A. Murugadoss, P. V. D. Prasad, S. S. Ghosh, A. Chattopadhyay, *International Journal of Food Microbiology*, 2008; 124(2): 142-146. DOI:10.1016/J.ijfoodmicro.2008.03.004.
65. M. Yildiz, A. Kiraj, B. Dulger. *Journal of the Serbian Chemical Society*, 2007; 72(3): 215-224. DOI:10.2298/JSC0703215Y.
66. J. P. Costa, M. J. F. Pinheiro, S. A. Sousa, A. M. B. do Rego, F. Marques, M. C. Oliveira, J. H. Leitao, N. P. Mira, M. F. N. N. Carvalho. *Antibiotics*, 2019; 8(3): 144, 1-13. DOI:10.3390/antibiotics8030144.
67. X. Yang, D. Wang, Q. Zhou, F. Nie, H. Du, X. Pang, Y. Fan, T. Bai, Y. Xu. *BMC Microbiology*, 2019; 19: 240, 1-7. DOI:10.1186/s12866-019-1613-5.
68. L. J. Nohynek, H. L. Alakomi, M. P. Kahkonen, M. Heinonen, I. M. Helander, K. O. Caldentey, and R.

H. Puupponen. *Nutrition and Cancer*, 2006; 54(1): 18-32. DOI:10.1207/15327914nc5401_4.

69. A. Kellelt, O. Howe, M. O'Connor, M. McCann, B. S. Creaven, S. McClean, A. F. Foltyn-Arfa Kia, D. O'Shea and M. Devereux. *Journal of Medicinal Chemistry*, 2012; 55(5): 1957-1968. DOI:10.1021/jm201041d.
70. E. Bazrafshan, F. K. Mostafapour and H. J. Mansourian, *Health Scope*, 2013; 2(2): 60-65. DOI:10.17795/jhealthscope-12993.