

**Ministry of Higher Education and Scientific Research
Faculty of Science and Technology
Department of Science of Matter**

**Democratic and People's Republic of Algeria
Abbes Laghrour University of Khenchela**



Thesis

Specialty: Organic Chemistry

Presented to Obtain a Doctoral Degree in Chemistry

By:

Sabeg Yasmina

Entitled:

**Synthesis, Structural Characterization, and Biological
Activity Study of New Cobalt (II) Complexes and
Organometallic Materials**

Dissertation Committee:

Hammadi Fouzai	MCA	Abbes Laghrour Khenchela University	President
Golea Lynda	Professor	Abbes Laghrour Khenchela University	Supervisor
Benali-Cherif Rim	Professor	Abbes Laghrour Khenchela University	Co-supervisor
Sid Assia	Professor	Oum El Bouaghi University	Reviewer
Arrif Souad	MCA	Batna1 University	Reviewer
Boughougal Amina	MCA	Abbes Laghrour Khenchela University	Reviewer

Academic Year: 2025/2026

Dedication

I dedicate this work especially to my dear late father.

To my mother, for her unwavering sacrifices, love, tenderness, support, and prayers,

To my dear brothers and sisters, and all my family.

To my colleagues and friends

Finally, I express my sincere appreciation to all my professors.

To everyone who stood by me during difficult times.

Yasmina

Acknowledgements

First of all, I thank Allah, the Almighty, for granting me the will, health, and patience to finish this work.

I would like to express my deepest and most sincere gratitude to my supervisor, **Professor Golea Lynda**, for her continuous support, constant encouragement, invaluable assistance and confidence she placed in me throughout this academic journey.

I would also like to express my sincere gratitude to my co-supervisor, **Professor Benali Cherif Rim**, for her valuable assistance and support, which played a crucial role in the successful completion of this academic journey.

I am profoundly honored that **Dr. Hammadi Fouzia** of Abbes Laghrour University has kindly agreed to chair the jury of this thesis.

I also sincerely thank **Professor Sid Assia** of Larbi Ben M'hidi University, **Dr. Arrif Souad** of Hadj Lakhdar University and **Dr. Boughougal Amina** of Abbes Laghrour University for accepting to serve as members of the jury and examiners.

I'm very grateful for their careful reading of this work, as well as for their valuable remarks and constructive criticism, which have contributed to improving this dissertation.

I am also grateful to my family, especially my dear mother, who has been my highest support during this period and helped me achieve this academic goal.

I would like to express my sincere gratitude to all the professors, engineers, and my colleagues from the Laboratory of Structures, Properties, and Interatomic Interactions (LASPI2A), Abbes Laghrour-Khenchela University, for their help and for the valuable time they devoted to supporting me.

Sabeg Yasmina

List of Abbreviations

A	A	Acceptor
	AC	Antioxidant capacity
B	B3LYP	Becke 3-Parameter Lee-Yang-Parr
C	CSD	Cambridge Structural Database
	CIF	Crystallographic Information File
D	DNA	Deoxyribonucleic Acid
	D	Donor
	<i>d_{norm}</i>	Normalized Contact Distance
	DFT	Density Functional Theory
	DMSO	Dimethyl Sulfoxide
	DMF	Dimethylformamide
	DHFR	Dihydrofolate reductase
E	EM	Electromagnetic
	E. coli	Escherichia coli
	ELF	Electron Localization Function
	eV	Electro Volt
F	FT-IR	Fourier Transform Infrared
	FIM	Full interaction maps
	FMOs	Frontier Molecular Orbitals
	FPs	Fingerprint Plots
H	HS	Hirshfeld Surface
	HOMO	Highest Occupied Molecular Orbital
	HAT	Hydrogen Atom Transfer
I	IR	Infrared
K	K. pneumoniae	Klebsiella pneumoniae
L	lp	Lone pair
	LOL	Localized Orbital Locator
	LUMO	Lowest Unoccupied Molecular Orbital
	LANL2DZ	Los Alamos National Laboratory 2 Double-Zeta
	LASPI2A	Laboratory of Structures, Properties and Interatomic Interactions
M	MIC	Minimum inhibitory concentration
	MEP	Molecular Electrostatic Potential
	MIR	Mid-infrared
	MD	Molecular docking
	MVD	Molegro Virtual Docker
	M_w	Molecular Weight
	ml	milliliter
N	N-donor	Nitrogen donor
	NCI	Non-Covalent Interaction
	NADPH	Nicotinamide Adenine Dinucleotide Phosphate

	nm	Nanometer
P	Phen	Phenanthroline
	P. aeruginosa	Pseudomonas aeruginosa
	PDB	Protein Data Bank
	PBE0	Perdew-Burke-Ernzerhof hybrid functional
R	RDG	Reduced Density Gradient
	RNA	Ribonucleic Acid
S	Spp	Species (plural)
	Sp	Species
	S. pneumoniae	Streptococcus pneumoniae
	S. aureus	Staphylococcus aureus
	SXRD	Single Crystal X-Ray Diffraction
	SET	Single Electron Transfer
U	UV-Visible	Ultraviolet-Visible
V	VdW	Van der Waals
	VMD	Visual Molecular Dynamics
X	XRD	X-Ray Diffraction

List of Figures

Chapter I: Literature Review

- Figure I.1.** Illustration of hydrogen bond.
- Figure I.2.** Representation of the hydrogen bonds motifs.
- Figure I.3.** Schematic representation of supramolecular arrangement through π - π stacking.
- Figure I.4.** Representation of the models of aromatic ring non-covalent interactions.
- Figure I.5.** Molecular structure of 1,10-phenanthroline.
- Figure I.6.** Molecular structure of benzoic acid.
- Figure I.7.** The general structure of a bacterium.
- Figure I.8.** Different shapes of bacteria.
- Figure I.9.** Structures of the cell wall protecting the plasma membrane in Gram-positive and Gram-negative bacteria.
- Figure I.10.** The bacterium *Escherichia coli*.
- Figure I.11.** The bacterium *Streptococcus pneumoniae*.
- Figure I.12.** The bacterium *Staphylococcus aureus*.
- Figure I.13.** The bacterium *Klebsiella pneumoniae*.
- Figure I.14.** The bacterium *Pseudomonas aeruginosa*.

Chapter II: Materials and Experimental Methods

- Figure II.1.** Molecular vibrational band types.
- Figure II.2.** Working principle of an FT-IR spectrometer.
- Figure II.3.** Diagram representation of absorbed vibration bands in the Mid-Infrared region.
- Figure II.4.** The Perkin-Elmer spectrometer. Abbes Laghrour University, Khenchela.
- Figure II.5.** Illustration of the principle of the UV-Vis spectrophotometer.
- Figure II.6.** Presentation of optical absorption described by the Beer-Lambert law.
- Figure II.7.** The UV-Visible spectrometer at the LASPI2A laboratory, Abbes Laghrour University, Khenchela.
- Figure II.8.** Model of the d_{norm} Hirshfeld surface for benzoic acid.
- Figure II.9.** a) Shape Index mapping on the 3D Hirshfeld surface, b) Curvedness surface map of benzoic acid molecule.
- Figure II.10.** 3D views of fragment patch maps of the benzoic acid molecule as well as (a) enable visualization and (b) disable visualization.
- Figure II.11.** a) 2D fingerprint plotting of the Hirshfeld surface of the complex showing all contacts. a) 2D fingerprint plotting of O-H/H-O contacts with surface visualization of benzoic acid.
- Figure II.12.** Visualization of crystal void along a-axis of packing crystal of benzoic acid.
- Figure II.13.** Schematic representation of Bragg's Law.
- Figure II.14.** Diffractometer Synergy-S at Degli Studi di Milano University, Italy.

- Figure II.15.** Example representation of Electron Localization Function (a) and Localization Orbital Locator (b).
- Figure II.16.** Illustration of the general lock-and-key concept that underlies molecular docking.
- Figure II.17.** Principle of disc method (bacterial activity).
- Figure II.18.** Representation of Mechanism of the DPPH radical scavenging at 517 nm.
- Figure II.19.** Structural representation of the synthesized metal–phenanthroline (C1-C6) complexes.

Chapter III: Results and discussion

- Figure III.1.** Molecular structure of complex (C1) with an octahedral coordination environment.
- Figure III.2.** 3D view of the 1D supramolecular architecture of complex (C1), highlighting the π – π stacking interactions and C—H $\cdots$ O hydrogen bonds that result in the formation of two types of graph-set motifs, $R_2^2(7)$ and $R_2^1(6)$.
- Figure III.3.** Representation of $R_6^4(26)$ supramolecular motifs formed by C22–H22 $\cdots$ O2 and O3–H3A $\cdots$ O4 non covalent interactions.
- Figure III.4.** Packing view showing the chair-like supramolecular pattern within the crystal lattice.
- Figure III.5.** lp– π and π – π stacking interactions highlighted in the supramolecular assemblies of the Co (II) complex (C1), formed between (bzH) molecules and coordinated phenanthroline moieties.
- Figure III.6.** A 3D-colored map of non-covalent interactions surrounding the molecular structure of cobalt complex (C1).
- Figure III.7.** The 3D Hirshfeld surfaces plotted over the dnorm function of [Co (Phen)₂(bz)] · bzH·NO₃ (C1) in the range of -0.15 to 0.6.
- Figure III.8.** The illustration of the two orientations of the dnorm Hirshfeld surface for complex C1 in 0.5 to 1.5 Å surrounded by the strong O–H $\cdots$ O hydrogen bonds and moderate C–H $\cdots$ O hydrogen contacts.
- Figure III.9.** Representation of HSs mapped over via shape index in the range -0.8 at 0.7Å, curvedness surface in -0.4 at 0.2Å and fragment patch in 0 at 29 Å for noval compound (C1).
- Figure III.10.** FT-IR spectrum of title complex (C1).
- Figure III.11.** Ultraviolet–visible (UV–Vis) spectrum of the Co (II) complex (C1).
- Figure III.12.** Optimization molecular structure of Co (II) complex (C1).
- Figure III.13.** Frontier orbitals HOMO-LUMO for complex (C1).
- Figure III.14.** Representation of MEP for complex (C1), (a) 3D map surface. (b) 2D contour plot.
- Figure III.15.** The ELF and LOL maps for compound (C1).
- Figure III.16.** The RDG scatter plots of cobalt (II) complex (C1).
- Figure III.17.** Crystal structure of compound (C2).

- Figure III.18.** The crystal packing with the polyhedral representation clearly exhibits the distorted square-pyramidal geometry.
- Figure III.19.** Illustration of the one-dimensional supramolecular network in compound (C2), showing the C–H···O hydrogen bonds, H···H weak contacts, and π – π stacking interactions.
- Figure III.20.** View of intermolecular $R_2^2(24)$ graph-set motifs created through C19–H19···O4 interactions of (C2).
- Figure III.21.** Visualization of $R_2^2(12)$, $S_1^1(6)$ hydrogen-bonding motifs created through O–H···O strong hydrogen bonds in 2D supramolecular arrangement.
- Figure III.22.** Two-dimensional packing arrangement view of compound (C2).
- Figure III.23.** Full Interaction Map (FIM) illustrating the non-covalent interaction regions around the Cobalt (II) complex (C2).
- Figure III.24.** 3D Hirshfeld surfaces for compound C2 were visualized by mapping d_{norm} (–0.2 to 0.5 Å), shape index (–0.7 to 0.7 Å), curvedness (–0.3 to 0.3 Å), and fragment patch (0 to 19 Å).
- Figure III.25.** Two different orientations of the three-dimensional Hirshfeld surface mapped over d_{norm} for cobalt (II) complex (C2), highlighting the key intermolecular interactions.
- Figure III.26.** Representation of the contacts zones plotted onto surface for (a) H···H, (b) H···C/C···H, and (c) H···O/O···H interactions.
- Figure III.27.** The 2D fingerprint plots for complex (C2) illustrate all intermolecular contacts (a), with their respective percentage contributions displayed separately: (b) H···H (42.1%), (c) H···C/C···H (30.5%), (d) H···O/O···H (17.3%), (e) C···C (6.8%), (f) H···N/N···H (1.9%), and (g) C···N/N···C (1.4%).
- Figure III.28.** Graphical representation of the voids in the crystal packing of compound (C2) : (a) viewed along the c-axis and (b) viewed along the b-axis.
- Figure III.29.** Experimental FT-IR spectrum of compound (C2).
- Figure III.30.** The experimental UV-Vis spectrum of compound (C2).
- Figure III.31.** Theoretical geometry optimization of compound (C2) obtained using DFT calculations.
- Figure III.32.** Frontier molecular orbitals of complex (C2) were calculated at the DFT level using the PBE0 functional with the LANL2DZ basis set.
- Figure III.33.** Molecular electrostatic potential (MEP) maps of cobalt (II) complex (C2) showing (a) surface potential distribution and (b) electrostatic potential contour plot.
- Figure III.34.** ELF (Electron Localization Function) and LOL (Localized Orbital Locator) plots for the Co (II) complex (C2).
- Figure III.35.** The RDG scatter plots of Cobalt (II) complex (C2).
- Figure III.37.** (a) Molecular view and fragment of the optimized structure of complex (C3), (b) emphasizing the geometry around the Ni (II) metal center.
- Figure III.38.** Visualization of π – π stacking interactions in the 1D supramolecular architecture within the complex (C3).

- Figure III.39.** The Full Interaction Map of the Nickel (II) complex (**C3**) visualizes the regions of intermolecular interactions.
- Figure III.40.** Two views of the 3D Hirshfeld surfaces plotted over with d_{norm} , d_i , and d_e for Nickel (II) complex (**C3**).
- Figure III.41.** Two perspectives of the Hirshfeld surfaces mapped over with Shape index, Curvedness, and Fragment patch of complex (**C3**).
- Figure III.42.** 3D Hirshfeld surfaces of all intermolecular interactions for the Nickel (II) complex (**C3**), mapped over d_{norm} in the range of -0.2 to 0.4 a.u.
- Figure III.43.** The 2D fingerprint plots for complex **C3**, presented all interactions (a), which are divided into (b) $\text{H}\cdots\text{H}$ 36.8%, (c) $\text{H}\cdots\text{CL}/\text{CL}\cdots\text{H}$ 28.5%, (d) $\text{H}\cdots\text{O}/\text{O}\cdots\text{H}$ 13.5%, (e) $\text{H}\cdots\text{C}/\text{C}\cdots\text{H}$ 10.8%, (f) $\text{C}\cdots\text{C}$ 8.8 %, (g) $\text{H}\cdots\text{N}/\text{N}\cdots\text{H}$ 0.8%, (h) $\text{C}\cdots\text{N}/\text{N}\cdots\text{C}$ 0.5%, and (i) $\text{C}\cdots\text{CL}/\text{CL}\cdots\text{C}$ 0.2% contacts.
- Figure III.44.** Graphical representation of the voids within the crystal packing of the Nickel (II) complex (**C3**), viewed (a) along the a-axis and (b) along the b-axis.
- Figure III.46.** IR spectrum of Nickel (II) complex (**C3**).
- Figure III.47.** Theoretical geometry optimization of compound (**C3**) obtained using DFT calculations.
- Figure III.48.** Frontier molecular orbitals (HOMO, LUMO, HOMO-1, and LUMO+1) of the nickel complex and their corresponding energy gaps.
- Figure III.49.** Molecular electrostatic potential map (MEP) of complex (**C3**).
- Figure III.50.** ELF (Electron Localization Function) and LOL (Localized Orbital Locator) plots for the Ni(II) complex (**C3**).
- Figure III.51.** The RDG scatter plots of Nickel (II) complex (**C3**).
- Figure III.52.** Disk diffusion assay showing the antibacterial activity of compounds (**C1**), (**C2**), and (**C3**) against *E. coli*, Pseudomonas, and Staphylococcus.
- Figure III.53.** Antioxidant activity of different concentrations of synthesized compounds (**C1-C3**) and ascorbic acid in DPPH scavenging assay.
- Figure III.54.** 2D and 3D plots of the interaction of complexes (**C1-C3**) with the active site of the DNA gyrase/topoisomerase II enzyme (6RD3).

List of Tables

Chapter I: Literature Review

Table I.1. Some simple 1,10-Phenanthroline complexes identified in the literature.

Table I.2. Some mixed-ligand of 1,10-Phenanthroline complexes reported in the literature.

Table I.3. Some simple complexes of benzoic acid reported in the literature.

Table I.4. Selected mixed-ligand of benzoic acid complexes noted in the literature.

Chapter III: Results and discussion

Table III.1. Selected crystallographic data and structure refinement parameters for compound (C1).

Table III.2. Highlights of both bond lengths and bond angle values of complex (C1).

Table III.3. Global reactivity descriptors for title complex (C1).

Table III.5. Representative bond lengths (Å) and bond angles (°) for complex (C2).

Table III.6. Global reactivity descriptors for title complex (C2).

Table III.7. Crystal data and structure refinement parameters for Nickel (II) complex (C3).

Table III.8. Main bond distances and bond angles for the compound (C3).

Table III.9. Summary of Hydrogen bonds present in Nickel (II) complex C3.

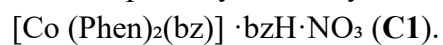
Table III.10. Global reactivity descriptors for title complex (C3).

Table III.11. Antibacterial activity of synthesis complexes (C1-C3) using paper disc-diffusion method and microdilution test.

Table III.12. Interactions and Rerank scores of synthesized complexes (C1-C3) and ciprofloxacin with the 6RD3 enzyme.

List of Schemes

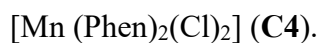
Scheme 1. Reaction pathway for the synthesis of the cobalt (II) complex



Scheme 2. Synthesis of the cobalt (II) complex $[\text{Co}(\text{phen-}\kappa^2\text{N, N}')(\text{bz-}\kappa\text{O})_2\text{H}_2\text{O}]$ (**C2**).

Scheme 3. Detailed reaction showing the synthesis of the nickel (II) complex $[\text{Ni}(\text{phen})(\text{H}_2\text{O})_3\text{Cl}] \cdot \text{H}_2\text{O} \cdot \text{Cl}$ (**C3**).

Scheme 4. Reaction mechanism through Synthesis of manganese (II) complex



Scheme 5. Synthesis of copper (II) complex $[\text{Cu}(\text{Phen})_2(\text{NCS})_2]$ (**C5**).

Scheme 6. Detailed reaction showing the synthesis of $[\text{Ni}(\text{Phen})(\text{bz})(\text{H}_2\text{O})_3] \cdot \text{bzH}$ complex (**C6**).

Table of Contents

General introduction	1
References	3

Chapter I: Literature Review

I.1. Introduction.....	4
I.2. Metal-organic Chemistry	4
I.3. Supramolecular Chemistry	5
I.4. Non-covalent interactions.....	5
I.4.1. Hydrogen bond interaction	6
I.4.2. π - π stacking interactions	7
I.4.3. Van der Waals forces.....	8
I.5. Ligands	9
I.5.1. 1,10-Phenanthroline.....	9
I.5.1.1. Definition.....	9
I.5.1.2. Coordination behavior of the 1,10-phenanthroline as ligand	10
I.5.1.2.1. Simple complexes of 1,10 phenanthroline as an organic ligand	10
I.5.1.2.2. Mixed-ligand complexes of 1,10-phenanthroline as an organic ligand.....	12
I.5.1.3. Application of complexes based on 1,10-phenanthroline as a ligand.....	14
I.5.2. Benzoic acid	15
I.5.2.1. Definition.....	15
I.5.2.2. Coordination behavior of the benzoic acid as ligand	16
I.5.2.2. Simple complex of benzoic acid.....	16
I.5.2.2.2. Mixed-ligand complexes of benzoic acid	18
I.5.2.3. Application of complexes based on benzoic acid as an organic ligand.....	20
I.6. Biological activities	21
I.6.1. Antibacterial activity.....	21
I.6.2. Definition of bacteria.....	21
I.6.3. Bacterial classifications	22
I.6.4. Bacterial species	23
I.6.4.1. Escherichia coli.....	23
I.6.4.2. Streptococcus pneumoniae	24
I.6.4.3. Staphylococcus aureus.....	24
I.6.4.4. Klebsiella pneumoniae	25
I.6.4.5. Pseudomonas aeruginosa	25
I.6.5. Antioxidant activity	26
I.6.5.1. Definition.....	26
I.6.5.2. Free radicals.....	26
I.7. Conclusion	27
References	28

Chapter II: Materials and Experimental Methods

II.1. Introduction	36
Part 1: Materials and Equipment	36
II.2. Chemical characterization techniques	36
II.2.1. FT-IR Spectroscopy	36
II.2.2. Ultraviolet-Visible Absorption Spectroscopy	40
II.2.3. Hirshfeld surface analysis	43
II.2.3.1. Hirshfeld Surface Properties	43
II.2.3.1.1. The normalized contact distance (d _{norm})	43
II.2.3.1.2. Shape index and Curvedness surfaces	44
II.2.3.1.3. Fragment patch	45
II.2.3.2. The 2D-fingerprint of the Hirshfeld surface	45
II.2.3.3. Void surface	46
II.2.4. Single-Crystal X-Ray Diffraction (SXRD)	47
II.2.5. Density Functional Theory (DFT) Calculations	49
II.2.6. Molecular Electrostatic Potential (MEP)	50
II.2.7. Computational ELF and LOL Study	51
II.2.8. Reduced Density Gradient (NCI-RDG)	52
II.2.9. Molecular docking	52
II.2.9.1. Principle of Molecular Docking	53
II.2.9.2. Types of Molecular Docking techniques	53
II.2.10. In vitro activity	54
II.2.10.1. Antibacterial activity	55
II.2.10.2. Antioxidant activity	56
Part 2: Experimental Methods	57
II.3. Experimental Method for the Synthesis of Complexes	59
II.3.1. The synthesis of [Co (Phen) ₂ (bz)·bzH·NO ₃] complex (C1)	59
II.3.2. The synthesis of [Co (Phen)(bz) ₂ H ₂ O] complex (C2)	59
II.3.3. The synthesis of [Ni (Phen) (H ₂ O) ₃ Cl] ·H ₂ O·Cl complex (C3)	60
II.3.4. The synthesis of [Mn (Phen) ₂ (Cl) ₂] complex (C4)	61
II.3.5. The synthesis of [Cu (Phen) ₂ (NCS) ₂] complex (C5)	62
II.3.6. The synthesis of [Ni (Phen) (bz) (H ₂ O) ₃]·bzH complex (C6)	62
II.4. Conclusion	63
References	64

Chapter III: Results and discussion

III.1. Introduction	69
Part 1: Structural characterization of synthesized compounds	70
III.2. Study of novel (benzoato)-bis(1,10-phenanthroline)-cobalt (II) nitrate benzoic acid complex (C1)	70
III.2.1. Crystallographic study of new complex (C1)	70
III.2.2. Full interaction maps of Co (II) complex (C1)	74

III.2.3. Hirshfeld surface analysis of cobalt (II) complex (C1)	75
III.2.4. Infrared spectroscopy analysis of complex (C1)	78
III.2.5. Ultraviolet-visible (UV-Vis) spectroscopy of complex (C1).....	79
III.2.6. Theoretical investigations.....	79
III.2.6.1. Geometric optimization of complex (C1).....	79
III.2.6.2. Frontier Molecular orbital analysis of complex (C1)	80
III.2.6.3. Molecular Electrostatic Potential analysis of complex (C1)	82
III.2.6.4. ELF and LOL analyses for Cobalt complex (C1).....	83
III.2.6.5. Reduced density gradient (RDG) analysis of complex (C1)	84
III.3. Study of complex Aqua-bis(benzoato- κ O) (1,10-phenanthroline- κ^2 N, N') cobalt (II) (C2)	85
III.3.1. Crystal structure analysis of complex (C2)	85
III.3.2. Full interaction maps of complex (C2).....	90
III.3.3. Hirshfeld surface analysis of Complex (C2)	91
III.3.4. The two-dimensional fingerprint plots	92
III.3.5. Crystal Void Analysis of Complex (C2)	94
III.3.6. Infrared spectroscopy of complex (C2).....	95
III.3.7. Ultraviolet-Visible spectroscopy analysis of complex (C2).....	96
III.3.8. Theoretical investigations.....	97
III.3.8.1. Geometric optimization of complex (C2).....	97
III.3.8.2. Frontier Molecular orbitals analysis of compound (C2)	98
III.3.8.3. Molecular Electrostatic Potential analysis of compound (C2)	99
III.3.8.4. ELF and LOL analyses for Cobalt complex (C2).....	100
III.3.8.5. Topological analysis using RDG (Reduced Density Gradient)	101
III.4. Study of new complex Aqua-chloro (1,10-phenanthroline- κ^2 N, N') nickel (II) chloride monohydrate (C3)	102
III.4.1. Crystal structure analysis of complex (C3)	102
III.4.2. Full interaction map for the Nickel (II) complex (C3)	105
III.4.3. Hirshfeld surface analysis of Nickel (II) complex (C3)	106
III.4.4. 2D Fingerprint plots of complex (C3)	109
III.4.5. Crystal Void Analysis of Complex (C3)	110
III.4.6. Infrared spectroscopy of complex (C3).....	110
III.4.7. Theoretical Investigations.....	111
III.4.7.1. Geometrical optimization of complex (C3).....	111
III.4.7.2. Molecular Electrostatic Potential analysis of compound (C3)	113
III.4.7.3. ELF and LOL analyses for Cobalt complex (C3).....	114
III.4.7.4. Topological analysis using RDG of complex (C3).....	115
Part 2: Biological Activities	115
III.5. Antibacterial activity	115
III.6. Antioxidant activity	117
III.7. Molecular Docking	118
III.8. Conclusion.....	121
References	122
General Conclusion.....	128

Appendix
Abstract

General Introduction

General Introduction

Metal-organic chemistry, or coordination chemistry, is a scientific field of modern chemical research, providing several applications across many domains during the last few years [1]. It focuses on the synthesis of new metal complexes and understanding how the central metals coordinate with organic ligands that exhibit novel and valuable properties. In particular, the transition metal complexes have been widely investigated since they have become a crucial bridge between chemistry and other sciences [2-4]. Through the non-covalent interactions, including hydrogen bonds, π - π stacking interactions, van der Waals forces, hydrophobic interactions, and lone pair- π interactions, these structural molecules are stabilized in the crystal lattice and reinforce the formation of supramolecular systems for compounds that undergo self-assembly processes [5-6].

Choosing suitable ligands in coordination chemistry is fundamental for predicting metal-ligand interactions and understanding the stability, reactivity, and geometry of novel compounds, which are characterized by well-defined geometries, strong electron-donating abilities and efficient chelating properties. Furthermore, the behavior of complexes depends on the nature of the metals and their oxidation state and electronic configurations. In this case, N-heterocyclic molecules and aromatic carboxylic acids serve as effective N-donor and O-donor compounds, respectively [7]. Their aromatic rings reinforce the stability of complexes and are distinguished by the capability of forming supramolecular designs, making these coordination ligands widely used by scientists in metal-organic chemistry.

In this work, the present work focuses on the synthesis of new compounds based on 1, 10-phenanthroline and benzoic acid as organic ligands with transition metals and the study of their physico-chemical and biological properties. On the other hand, the molecular structures of these complex-type crystalline materials were determined using structural and computational characterization methods. The work is organized into three chapters:

Chapter one of this dissertation describes the concept of metal-organic chemistry of transition metal complexes, and the modern view of coordination chemistry focuses on supramolecular architectures built by the presence of the aromatic systems of ligands and non-covalent interactions, including H-bond interactions, π - π stacking contacts, van der Waals forces, lone pair- π interactions, and C-H $\cdots\pi$ contacts, which play a vital role in the stability of metal-ligand compounds. In this chapter, we report a bibliographic study of previous work done

on the simple and mixed-ligand complexes of 1,10-phenanthroline and benzoic acid and their applications in various fields. Finally, this chapter highlights the concept of antibacterial and antioxidant activities.

Chapter two is divided into two main parts; the first part is dedicated to various experimental and computational methods and equipment used to characterize the prepared metal-organic complexes. The most method used to determine the structure of crystals is single-crystal X-ray diffraction. Complementary, spectroscopic methods, including FT-IR and UV-Vis, confirmed the presence of functional groups. Additionally, the Hirshfeld surface analysis approach is used to visualize the types of interactions present within molecular structures. The theoretical techniques, which include density functional theory (DFT) calculations, together with ELF, LOL, MEP, and RDG approaches, are used for molecular modeling. In addition, molecular docking is used to evaluate the interactions between compounds and target proteins. In the second part, the experimental protocols used for the synthesis of laboratory complexes are described.

Chapter three of this thesis presents and discusses the obtained results, organized into two main parts; the first part focuses on the crystallographic, spectral, and theoretical studies of three novel laboratory complexes. In the second part, *in vitro* and *in silico* biological activities of these laboratory complexes have been evaluated and described. The dissertation ends with a general conclusion that summarizes the main results obtained in this study.

Collectively, this thesis gives a comprehensive foundation for understanding the coordination chemistry of functionalized 1,10-phenanthroline ligands bearing electronegative substituents with different metals, opening avenues for their tailored use in fields ranging from catalysis to medicinal and biological chemistry.

References

- [1] He, C., Liu, D., Lin, W. (2015). Nanomedicine applications of hybrid nanomaterials built from metal–ligand coordination bonds: nanoscale metal–organic frameworks and nanoscale coordination polymers. *Chemical reviews*, 115(19), 11079-11108.
- [2] Kazemi, M., Javahershenas, R., Klika, K. D. (2025). Recent advances in the application of transition metal catalysts to the synthesis of imidazolines. *Mini-Reviews in Organic Chemistry*, 22(6), 653-670.
- [3] Zhu, J. H., Gu, M., Chen, Y., Li, M., Chen, X., Yoon, J., Peng, X. (2025). Chemiluminescent transition metal complexes: Mechanisms and applications. *Coordination Chemistry Reviews*, 530, 216495.
- [4] Abbass, L. M., Yousif, N. M., Sadeek, S. A., Zordok, W. A., El-Attar, M. S., El-Faragy, A. F., & Mouneir, S. M. (2025). Structural characterization, XRD, DFT calculations, docking, antimicrobial, anticancer applications, and electrochemical performance studies of some new schiff base transition metal complexes. *Applied Organometallic Chemistry*, 39(4), e70099.
- [5] Talreja, S., Tiwari, S. (2023). Supramolecular chemistry: unveiling the fascinating world of non-covalent interactions and complex assemblies. *J. Pharm. Pharmacol. Res*, 7, 133-139.
- [6] Liu, C. Z., Hou, S. S., Zhang, C., Wang, T., Zhai, B. (2025). Non-Covalent Interactions Directed Supramolecular Helices from H-bonded Building Blocks. *European Journal of Inorganic Chemistry*, 28(3), e202400652.
- [7] Zhao, X. L., Sun, W. Y. (2014). The organic ligands with mixed N-/O-donors used in construction of functional metal–organic frameworks. *CrystEngComm*, 16(16), 3247-3258.

Chapter I
Literature Review

I.1. Introduction

The metal-organic chemistry of transition metal complexes has been extensively studied over the last few years [1], as they represent a significant bridge between chemistry and materials science and are capable of contributing to highly applied research. Metal-organic complexes containing heterocyclics and carboxylic acids are extremely useful compounds; they have seen significant development due to their many applications in biology [2], medicine [3], pharmaceuticals [4], and catalysis [5]. Remarkably, mixed-ligand complex types have attracted great interest in metal-organic chemistry due to their stability and higher reactivity. The diversity of ligands in the same compound is able to incorporate multiple functional groups, leading to the emergence of novel compounds that provide new molecular geometries with higher physico-chemical properties.

This chapter covers a wide range of studies, including supramolecular chemistry, non-covalent interactions, coordination complexes based on 1,10-phenanthroline and benzoic acid as organic ligands, and their applications in biology and other fields.

I.2. Metal-organic Chemistry

Metal-organic chemistry is a branch of organic and inorganic chemistry that explains how metals coordinate with organic molecules to form new compounds [6]. In a broad sense, metal-organic chemistry includes the organometallic and coordination compounds. In this case, transition metal complexes demonstrate considerable advantages in the various applications and have become one of the most rapidly expanding research areas in chemistry [7-9]. The techniques used to synthesize a specific molecular architecture depend on both the metal ion and its affinity for particular coordination compounds, as well as the nature of the ligand utilized as a chelating agent [10]. Transition metals are chemical elements, typically those whose atoms possess a partially filled d subshell, facilitating the production of cations. For example, it was reported that cobalt is one of the transition metals with the symbol (Co) from the d-block. Its ordinary state is solid, and it has a hexagonal crystalline structure. Its most well-known oxidation states are +2 and +3; its Co^{2+} ion is characterized by its hardness as an acceptor ion. This atom is found in hundreds of enzymes that participate in the exchange of oxygen and carbon dioxide in red blood cells, so it is an essential trace element for humans.

I.3. Supramolecular Chemistry

Supramolecular chemistry is a different view of the traditional study of the coordination method of compounds and works to investigate how host-guest molecules build this super design due to the presence of non-covalent interactions, including reversible acceptor-donor binding, π - π aromatic interactions, lp- π interactions, van der Waals forces, C-H $\cdots\pi$ contacts, etc., which principally play a pivotal role in forming complex architectural assemblies within molecular structures [11,12]. In 1979, another description of supramolecular chemistry, namely “chemistry beyond the molecule,” was proposed by the chemist Jean-Marie Lehn, while other concepts under other terms, like “the chemistry of non-covalent bonds,” have existed. A Supramolecular system is characterized by spontaneously forming highly similar, repetitive, and selectively organized structures within a single molecular system that is inspired by the arrangement of DNA or RNA bases in biological science [13,14]. On the other hand, the classical host-guest system strategy, which is limited to lock-and-key interactions, was developed; it became based on the selectivity of molecular recognition and self-assembly in the formation of supramolecular arrangements [15]. Furthermore, the importance of supramolecular systems is highlighted in many applications, including molecular sensors, catalysis, and physical and polymer chemistry, especially in biological science, which is capable of delivering the medicinal agents based on the variation of temperature and PH in metabolism [16].

I.4. Non-covalent interactions

In chemistry, the non-covalent intramolecular and intermolecular interactions of all types are most essential to reinforce stability and understand the chemical and mechanical properties of molecular structures. In 1873, Johannes Diderik van der Waals, was the first scientist, introduced the presence of intermolecular forces [17]. In addition, in 1920 Latimer, Rodebush, and Linus Pauling processed and understood the non-covalent interactions [18]. Overall, the significant NCIs typically include hydrogen bonding, H-binding, hydrophobic effects, aromatic contacts, and electrostatic forces [19, 20]. These weak and reversible interactions enable the self-assembly of supramolecular architectures and crystal packing, contrary to the strong covalent bonds. Additionally, these cooperative interactions are considered a challenge in biological research, which is largely used to construct and develop the drug design and medicinal active agents [21]. They also have an efficient effect on the physical properties of materials, including color and luminescence [22]. Notably, both experimental and theoretical

studies are capable of identifying and describing the non-covalent interactions in crystal engineering as well as in different dimensional supramolecular organizations.

I.4.1. Hydrogen bond interaction

In 1939, Linus Pauling introduced the concept of hydrogen bonding in his book "Nature of the Chemical Bond". Hydrogen binding (see Figure I.1), defined by weak reversible interactions between coordinate hydrogen atoms, emanates from a molecule or a molecular fragment described as $D-H\cdots A$, where H is less electronegative than D (the donor atom) and A (the acceptor), with A denoting the oxygen, nitrogen, or sulfur chemical elements, according to IUPAC recommendation 2011 [23].

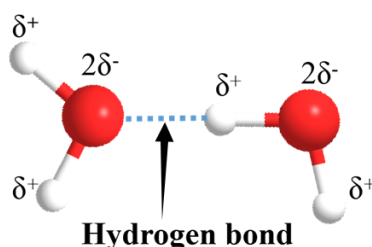


Figure I.1. Illustration of hydrogen bond.

The determination of hydrogen bond interactions is based on the $H\cdots A$ distance being shorter than the sum of van der Waals forces. Furthermore, the concept of this non-covalent binding allowed the classification of $C-H\cdots\pi$, $C-H\cdots O$, and $C-H\cdots N$ as directional H-bond contacts, with various studies in the literature proving its influence in the stability and self-assembly of supramolecular arrangements within molecular structures [24-27]. Furthermore, the categories of the attractive donor-acceptor interactions were explained by their strength, which has been estimated by many studies to be in the range from 0.1 and 60 kcal mol⁻¹. Additionally, the $D-H\cdots A$ angle value evaluated must be larger than 110°, as defined by IUPAC, with the highest electronegativity of D and A. In this sense, there are three types: strong H-bond interactions with distances in the range of (2.2-2.5) Å, such as $O-H\cdots O$, $O-H\cdots N$, $N-H\cdots N$, and $N-H\cdots O$, are the most important non-covalent donor-acceptor directional contacts. In particular, moderate and weak hydrogen bonds are characterized by the ranges of 2.5-3.2 Å and 3.2-4.0 Å lengths, respectively, including mostly the $C-H\cdots O$, $C-H\cdots N$, and $C-H\cdots Cl$ interactions. In addition, the $O-H\cdots\pi$, $N-H\cdots\pi$, and $C-H\cdots\pi$ contacts are considered weaker forces than their predecessors, but they are not less significant than them, as they play a pivotal

role in crystal packing and protein-small molecule interactions [28]. In crystal engineering, the importance of hydrogen bond interactions also lies in their role as a determinant of trendy hydrogen binding motifs (see Figure I.2) in the supramolecular arrangement [29].

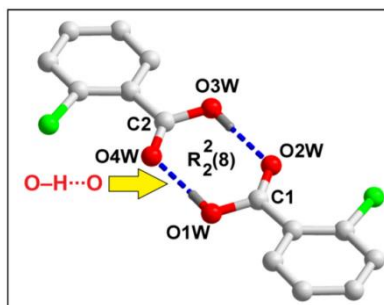


Figure I.2. Representation of the hydrogen bonds motifs [30].

I.4.2. π - π stacking interactions

The study of crystal engineering and supramolecular systems (see Figure I.3) of molecules qualified for the self-assembly phenomenon in both solid and solution states is based on understanding their properties and the nature of non-covalent interactions, specifically π - π interactions [31]. The concept of π - π stacking attractive interactions is employed to identify and describe the interactions between two or more aromatic rings or between the delocalized π -system (which is electron-rich) with a cation or an anion from other units [32]. In 1990, Hunter and Sanders explained that aromatic-aromatic (π - π) interactions are electrostatic interactions. Additionally, the intermolecular aromatic ring non-covalent interactions highlighted into three models (Figure I.4): face-to-face (sandwich) stacking interactions, offset, and edge-to-face (T-shaped) interactions [33].

The efficient role of π -stacking interactions is not limited to chemistry but extends to many other fields, such as biomedical, biological, and biotechnological. The π - π interactions have been used in many applications; they were mainly relied upon for drug delivery for cancer [34, 35].

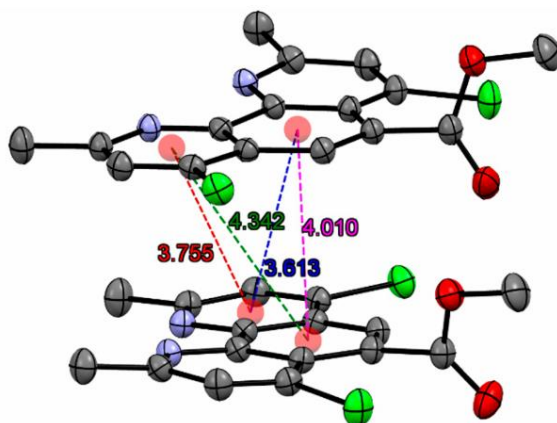


Figure I.3. Schematic representation of supramolecular arrangement through π - π stacking.

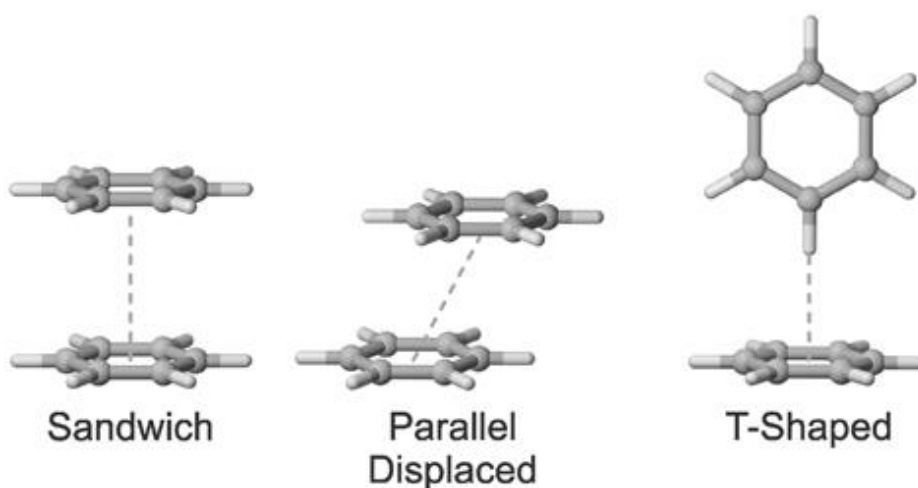


Figure I.4. Representation of the models of aromatic ring non-covalent interactions.

I.4.3. Van der Waals forces

Van der Waals forces are non-covalent interactions that result from electrostatic forces between polarizable neutral atoms or molecules. These quantum mechanical interactions result from short-lived variations in electronic charge density. Additionally, London dispersion interactions, the main van der Waals (*vdW*) forces, reinforce stability and influence the molecular dynamics of materials in various domains, including chemistry, physics, biology, and materials science [36]. Moreover, their significance is also highlighted in the spectroscopic [37], mechanical [38], and kinetic [39] properties of condensed matter.

I.5. Ligands

I.5.1. 1,10-Phenanthroline

Heterocyclic compounds are cyclic carbon chains that have one or more heteroatoms, such as nitrogen, oxygen, sulfur, and phosphorus. The most common heterocyclic compounds contain nitrogen or oxygen atoms and an aromatic system, which are capable of their reinforced stability, substitution reactions with preserved aromaticity, and exhibiting special spectroscopic characteristics. The heteroatoms present in this class of molecules result in variety in their biological and physical properties, which led to a profound study of heterocyclic compounds.

I.5.1.1. Definition

1,10-phenanthroline (Phen) is a rigid heterocyclic bidentate organic ligand (see [Figure I.5](#)), and it has a chelating ability with transition metals, enabling the formation of a wide range of stable coordination complexes [\[40\]](#). Furthermore, phenanthroline exhibits a high affinity for forming and stabilizing the supramolecular arrangement in molecular structures through the π - π noncovalent interactions, thereby playing a significant role in organometallic and inorganic chemistry and the development of coordination chemistry. Additionally, the phenanthroline molecule with its transition metal complexes display characteristic biological and antibacterial activity [\[41\]](#), antifungal activities [\[42\]](#), and photophysical properties [\[43\]](#). In biological research, the N-donor ligand and its metal complexes exhibit interactions with DNA, collecting significant attention due to their potential applicability as novel medicinal agents, as DNA serves as an essential molecular target in the development of anticancer substances [\[44, 45\]](#).

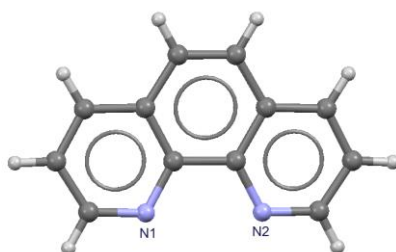


Figure I.5. Molecular structure of 1,10-phenanthroline.

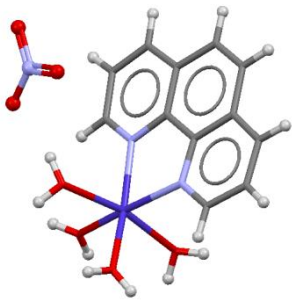
I.5.1.2. Coordination behavior of the 1,10-phenanthroline as ligand

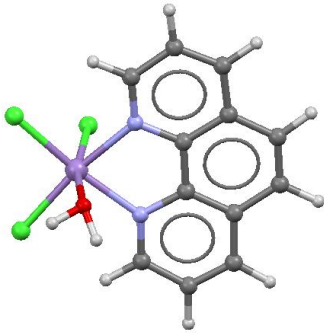
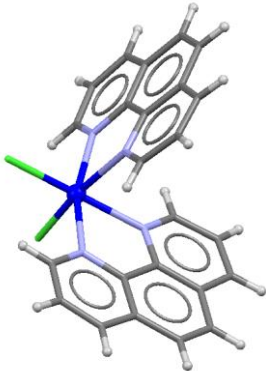
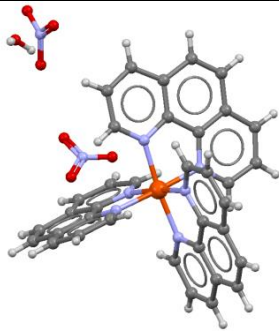
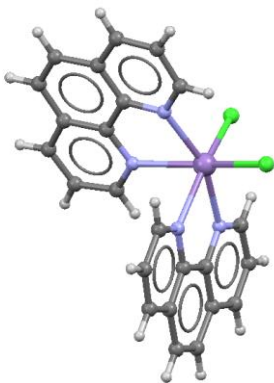
1,10-phenanthroline, an N-donor heterocyclic compound, and its derivatives are generally used as ligands in the formation of stable coordination complexes with various geometric structures. This behavior is due to their two nitrogen atoms and their applications in analytical chemistry, catalysis, and biochemistry [46]. Over the past few years, because of their properties, 1,10-phenanthroline bidentate complexes have obtained significant interest in the field of coordination chemistry [47]. In this case, hydrogen-bonding interactions, including O–H···O, C–H···O, and N–H···O as well as π - π stacking and C–H··· π contacts, play vital roles in stabilizing these compounds and reinforce the supramolecular arrangement of molecular structures. Furthermore, coordination complexes based on phenanthroline as an organic ligand are not limited to simple complexes. They also lead to the synthesis of other modern types known as mixed-ligand complexes, which occur when other ligands that coordinate with the same metal ion are present.

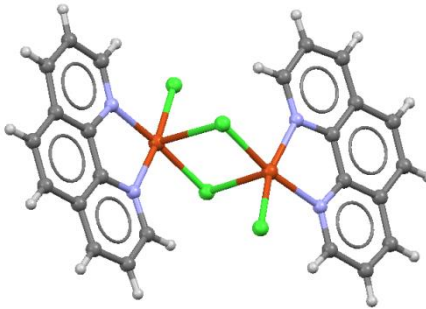
I.5.1.2.1. Simple complexes of 1.10 phenanthroline as an organic ligand

The 1,10 phenanthroline can coordinate with transition metals and build various geometries (e.g., octahedral, square planar, and square pyramidal). Table I.1 reports some synthesis of phenanthroline (Phen) complexes.

Table I.1. Some simple 1,10-Phenanthroline complexes identified in the literature.

Chemical Formula	Crystal system	Representation	Ref
$\text{C}_{12}\text{H}_{16}\text{CoN}_2\text{O}_4^{2+} \cdot 2(\text{NO}_3^-)$	Monoclinic C2/c		[48]

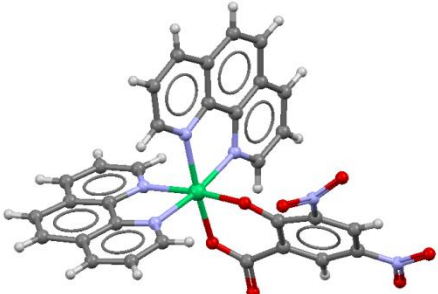
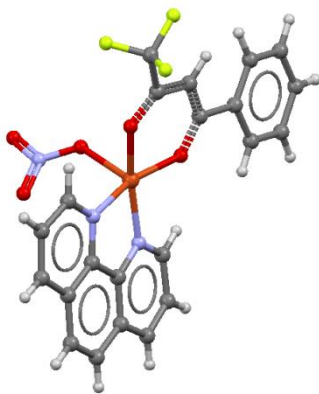
$\text{MnC}_{12}\text{H}_{10}\text{N}_2\text{OCl}_3$	Triclinic P-1		[49]
$\text{C}_{24}\text{H}_{16}\text{Cl}_2\text{CoN}_4$	Monoclinic P2 ₁ /c		[50]
$[\text{FeC}_{12}\text{H}_8\text{N}_2]_3(\text{NO}_3)_3 \cdot \text{H}_2\text{O}$	Monoclinic, C2/c		[51]
$\text{C}_{24}\text{H}_{16}\text{Cl}_2\text{MnN}_4$	Monoclinic P2 ₁ /c		[52]

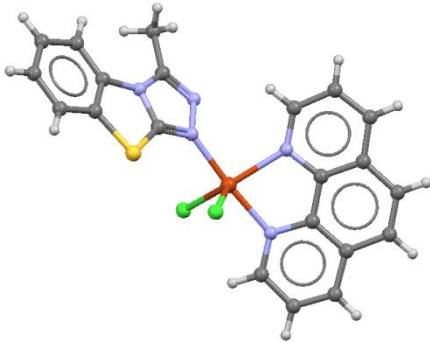
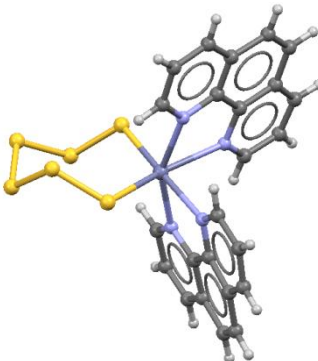
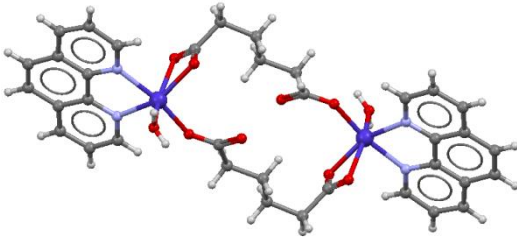
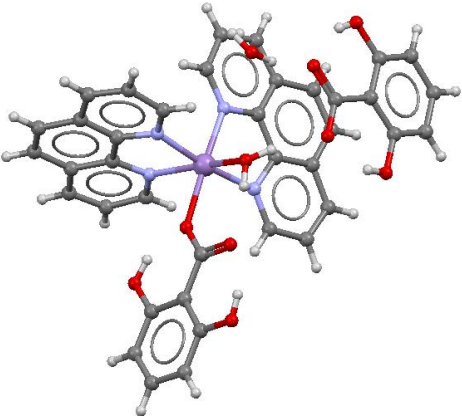
$C_{24}H_{16}Cl_4Cu_2N_4$	Monoclinic Cc		[53]
---------------------------	------------------	--	------

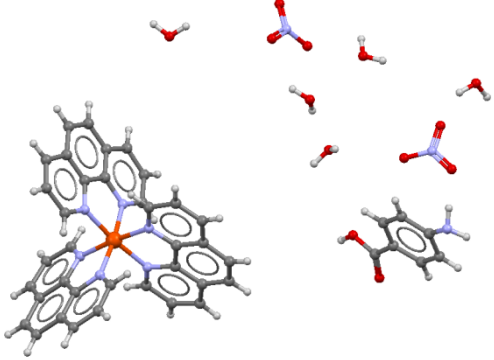
I.5.1.2.2. Mixed-ligand complexes of 1,10-phenanthroline as an organic ligand

The mixed ligand coordinate compounds are defined by two or more types of molecules binding with the center metal. Many mixed ligand complexes involving 1,10-phenanthroline (Phen) were mentioned in the literature. Furthermore, this particular class of metal complexes increases structural diversity and improves functional properties of materials. Table I.2 showcases some mixed ligand complexes based on phenanthroline.

Table I.2. Some Mixed-ligand of 1,10-Phenanthroline complexes reported in the literature.

Formula chemical	Crystal system	Representation	Ref
$C_{31}H_{18}N_6NiO_7$	Monoclinic $P2_1/c$		[54]
$C_{22}H_{14}CuF_3 N_3 O_5$	Monoclinic $P2_1/n$		[55]

CuCl₂(TZL)(PHEN)	Monoclinic C2/c		[56]
C₂₄H₁₆N₄S₆Zn	Monoclinic P-1		[57]
C₃₆H₃₆C₀₂N₄O₁₀	Triclinic P-1		[58]
C₃₁H₂₃MnN₄O₅⁺C₇H₅ O₄·0.5(H₂O)	Orthorhombic Pbcn		[59]

$C_{43}H_{35}FeN_9O_{10}$	Triclinic <i>P</i> 1		[60]
---------------------------	-------------------------	--	------

I.5.1.3. Application of complexes based on 1,10-phenanthroline as a ligand

Most of the complexes based on 1,10-phenanthroline and its derivatives proved their effectiveness across various fields. *M. Aljahdali and Ahmed A. EL-Sherif* (2013) reported three mixed ligand complexes of cobalt (II), nickel (II), and copper (II) as transition metals containing 1,10-phenanthroline (Phen) and 2-(1-(2-phenyl-hydrazono)-propan-2-ylidene) hydrazine-carbothioamide. They revealed the biological activities of these compounds, which include the antifungal properties against *Aspergillus flavus*, *Candida albicans*, and *Penicillium italicum*, and antibacterial potential against *Escherichia coli*, *Staphylococcus aureus*, *Bacillus subtilis*, and *Pseudomonas aeruginosa* [61]. Furthermore, in 2017, *L. Viganor et al.* reported that the complexes including the phenanthroline heterocyclic ligand are an alternative to traditional antibiotics [62].

M. Masmoudi et al. (2025) found that the complexes of copper (II), cobalt (II), and iron (II) with adenine and phenanthroline revealed cytotoxic activity, which means they have anticancer properties. These compounds demonstrate light cytotoxic effects against the human pancreatic (AsPC-1) and colon adenocarcinoma (Caco-2) cancer cells [63].

N. Rentschler et al. (2020) reported that the homoleptic copper(I) and ruthenium (II) complexes with bidentate phenanthroline as photosensitizers enhance the capability for solar energy conversion and luminescent applications [64]. Additionally, the work carried out by *E. Benazzi et al.* (2018) reported that the Cu-phenanthroline complexes have the electrochemical properties that are used, like redox mediation agents in dye-sensitized solar cells [65].

I.5.2. Benzoic acid

Carboxylic acids are organic molecules that are characterized by the presence of one or more carboxyl functional groups (-COOH) and are weak acids. This class of compounds is polar, capable of forming strong hydrogen bond interactions. They are established abundantly in nature, in the form of fatty acids, and they are highly significant in coordination chemistry. Overall, these compounds with important pharmacological and biological properties. The carboxylic acids can be classified into two types, according to the nature of the carbon chain bound with the COOH functional group, which involves both aliphatic and aromatic carboxylic acid compounds.

I.5.2.1. Definition

The benzoic acid (*bnH*) is an aromatic carboxylic compound with the molecular formula $C_7H_6O_2$ that is a white solid organic molecule featuring the COOH function group (see [Figure I.6](#)). In 1955, *G. A. Sim et al.* reported the crystal structure of benzoic acid with space group P21/c and C-C aromatic ring distances at $0.05\text{\AA}$ [66]. Benzoic acid has both antibacterial and antifungal effects. Benzoic acid is a fairly efficient preservative at 0.1% concentration, on condition that the pH does not exceed the value of 5. Additionally, the benzoic acid proved the antifungal effects against some infections [67]. Furthermore, this organic molecule has several uses, including corrosion inhibition in paints and emulsions, antifreeze formulations, clogging agents, and oil well modifiers. However, the concentration of benzoic acid and its derivatives in water must be determined with extreme accuracy to avoid the risks of poisoning humans and the environment [68].

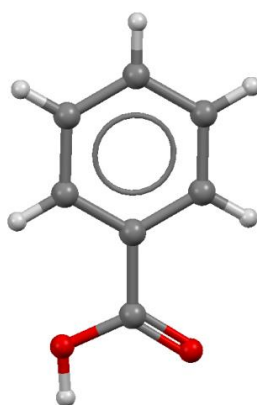


Figure I.6. Molecular structure of benzoic acid.

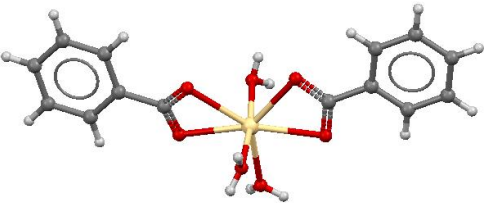
I.5.2.2. Coordination behavior of the benzoic acid as ligand

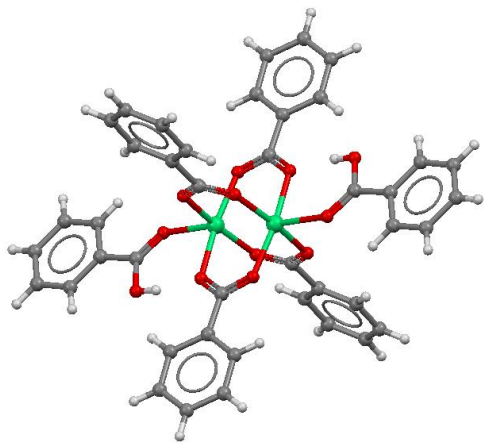
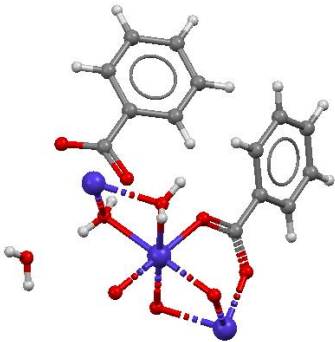
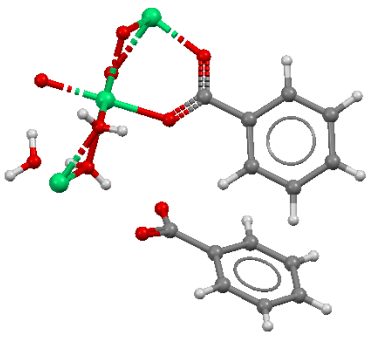
Benzoic acid and its derivatives are widely used as organic ligands in the synthesis of stable metal complexes with different molecular geometries due to their carboxylate functional groups. In coordination chemistry the benzoic acid and its derivatives revealed their ability to bind with metal centers through monodentate or bidentate modes. In such compounds, the donor properties of this organic ligand play a crucial role in forming strong hydrogen bonds, and the aromatic ring of benzoic acid in the complexes allows the formation of π - π stacking interactions, thus reinforcing the supramolecular architectures and enhancing the stability and rigidity of compounds. Furthermore, the benzoate ligand has the most interest due to its solubility in water, which is the greenest solvent. Through X-ray diffraction analysis, many structural compounds based on the benzoate ligand have been isolated, notably simple complexes and, significantly, mixed ligand complexes.

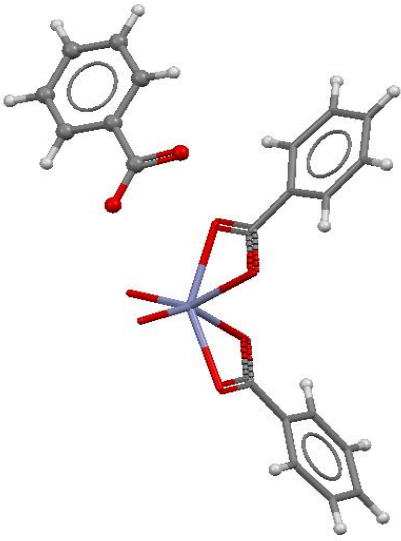
I.5.2.2. Simple complex of benzoic acid

In coordination chemistry, there is the most interest in the use of carboxylate ligands, especially benzoic acid. These ligands have been broadly proven to lead to thermodynamic stability, high kinetics, and their capability of chelating with transition metals [69]. Furthermore, these metal-organic complexes have proven the physico-chemical and biological properties. Table I.3 summarizes several complexes of benzoic acid that have been reported in literature.

Table I.3. Some simple complexes of benzoic acid reported in literature.

Chemical Formula	Crystal system	Representation	Ref
$C_{14}H_{16}CdO_7$	Orthorhombic Pbca		[70]

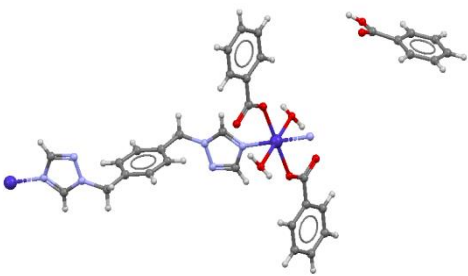
$C_{42}H_{32}Ni_2O_{12}$	Monoclinic $P2_1/n$		[71]
$CoC_{14}H_{16}O_7$	Monoclinic $I2/a$		[72]
$C_{14}H_{16}NiO_7$	Monoclinic $I2/a$		[73]

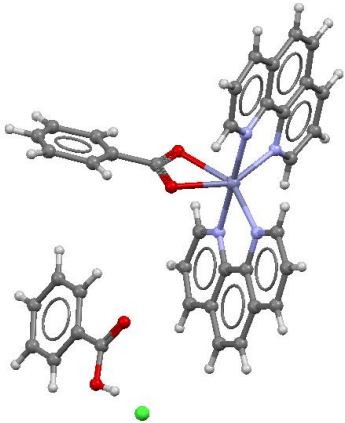
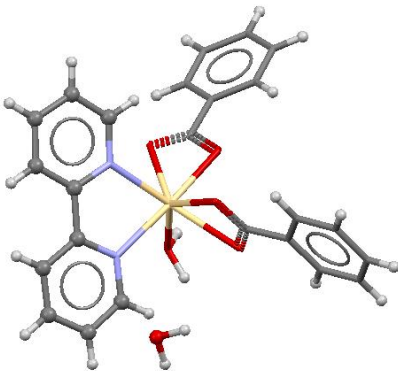
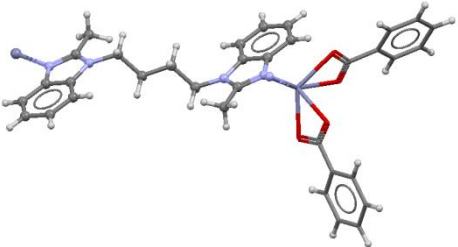
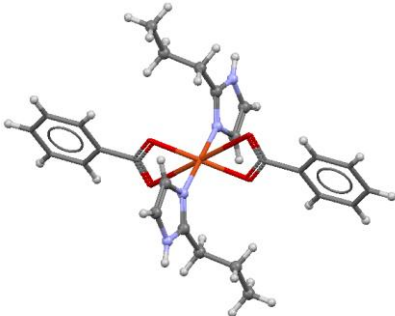
$\text{C}_{14}\text{H}_{14}\text{O}_6\text{Zn} \cdot (\text{C}_7\text{H}_6\text{O}_2)$	Monoclinic Fdd2		
--	--------------------	--	--

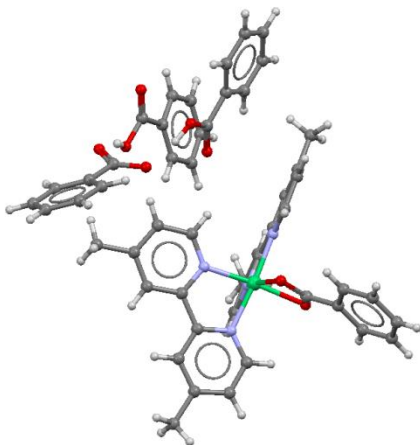
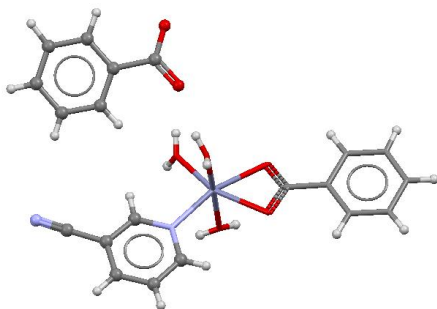
I.5.2.2.2. Mixed-ligand complexes of benzoic acid

Mixed-ligand complexes of benzoic acid have played a significant role in the growth of coordination chemistry and have been widely studied due to their molecular structural variety, as well as their various applications in many fields [69]. Furthermore, these transition metal coordinate compounds can present a challenge in molecular biology, supramolecular chemistry, and crystal engineering [74]. Table I.4 presents selected mixed-ligand complexes of benzoic acid.

Table I.4. Selected mixed-ligand of benzoic acid complexes noted in literature.

Chemical Formula	Crystal system	Representation	Ref
$\text{C}_{40}\text{H}_{38}\text{CoN}_6\text{O}_1$	Monoclinic P21/c		[75]

$\text{C}_{31}\text{H}_{21}\text{N}_4\text{O}_2\text{Zn}^+$ $2(\text{C}_7\text{H}_6\text{O}_2) \text{Cl}^-$	Monoclinic $\text{C}2/\text{c}$		[74]
$\text{C}_{24}\text{H}_{20}\text{CdN}_2\text{O}_5 \cdot \text{H}_2\text{O}$	Monoclinic $\text{P}-1$		[76]
$\text{C}_{34}\text{H}_{32}\text{ZnN}_4\text{O}_4$	Monoclinic $\text{C}2/\text{c}$		[77]
$\text{C}_{26}\text{H}_{30}\text{N}_4\text{O}_4\text{Cu}$	Triclinic $\text{P}-1$		[78]

$\text{C}_{31}\text{H}_{29}\text{N}_4\text{NiO}_2^+$ $2(\text{C}_7\text{H}_6\text{O}_2) \text{C}_7\text{H}_5\text{O}_2^-$	Monoclinic $\text{P2}_1/\text{n}$		[79]
$\text{C}_{13}\text{H}_{15}\text{N}_2\text{O}_5\text{Zn}^+ \cdot \text{C}_7\text{H}_5\text{O}_2^-$	Monoclinic $\text{P}-1$		[80]

I.5.2.3. Application of complexes based on benzoic acid as an organic ligand

In coordination chemistry, metal-organic compounds containing benzoic acid exhibit significant applications in different fields due to their physico-chemical properties. Therefore, many research papers reported the role of these metal complexes in different sciences.

In 2024, *Orson L. Sydora* published an article under the title "Transition metal benzoate complexes", revealing the crucial role of these coordinate compounds in organometallic chemistry and their new views of carboxylic acid as ligands [81].

A.A.Osowole et al. (2015) reported that the mixed complexes of manganese (II), nickel (II), copper (II), zinc (II), and iron(II) containing the benzoic acid and drug paracetamol indicated the potential antioxidant and biological effects, such as antimicrobial activities against *Pseudomonas spp.*, *Bacillus spp.*, *Streptococcus spp.*, *Salmonella sp.*, *Staphylococcus sp.*, *Proteus*, *Candida albicans*, and *Escherichai Coli* [82]. As well as in 2016, *I. Kani et al.* isolated the mononuclear manganese (II) complex based on benzoic acid and demonstrated catalase-like activity and antifungal and antimicrobial properties [83].

S. Mohd et al. also reported the biological potential of the coordination zinc complex involving both 3-cyanopyridine and benzoate as organic ligands. They demonstrated the toxicokinetic and pharmacokinetic properties [80].

I.6. Biological activities

I.6.1. Antibacterial activity

Antibacterial activity is described as the capacity of compounds to suppress the development of pathogenic bacteria by creating inhibitory chemicals such as organic acids, hydrogen peroxide, and bacteriocins, which have antagonistic effects on pathogens. The disc diffusion technique is a quick and simple approach to evaluate the antimicrobial activity of different substances. In this case, many bacterial suspensions were generated using the direct colony approach. Additionally, A lowest inhibitory concentration (MIC) of the tested antimicrobial agent that suppresses observable bacteria growth under precise test conditions is used. Researchers depend on measuring the diameter (in millimeter) of the zone of full inhibition to estimate antibacterial activity. Notably, the cytotoxicity studies are evaluated by giving IC₅₀ values (the concentration that kills or inhibits cell viability by 50%).

I.6.2. Definition of bacteria

Bacteria are microscopic prokaryotic cells, and their DNA is free in the cytoplasm, not located in the nucleus. Furthermore, Bacterial cells might be advantageous or pathogenic to humans, plants or animals. The vast majority of bacteria contain circular molecules of extra-chromosomal DNA called plasmids. Aside from the ribosome, there are no other organelles in the cytoplasm. Notably, bacterial ribosome is smaller than that of eukaryotic cells [84]. The bacterial structure is showcased in Figure I.7.

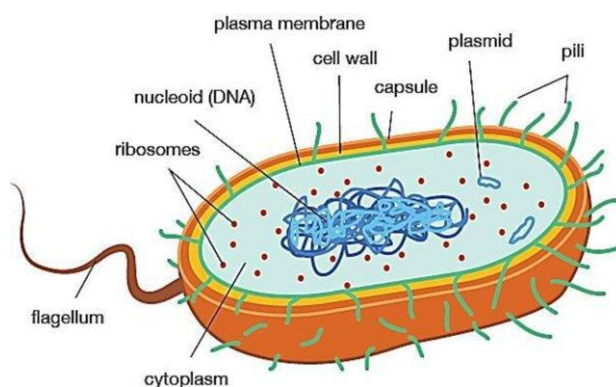


Figure I.7. The general structure of a bacterium.

I.6.3. Bacterial classifications

The most common classification of bacterial cells is based on their shape (morphological) characteristics. The main types of bacteria are:

- Elongated bacterial forms, "rods or bacilli", separated into clusters or chains, with variable diameters and lengths, such as *Escherichia coli*, *Salmonella*, *Bacillus*, etc... *Bacilli* vary in shape; some are fusiform or curve into "vibrios" and "spirals", like *Treponema* (Figure I.8).
- Bacteria forms referred to as shells or cocci, chained, isolated or grouped, including *Streptococcus*, *Staphylococcus*, and others.
- A specific category of filamentous bacteria, similar to moulds: actinomycetes.

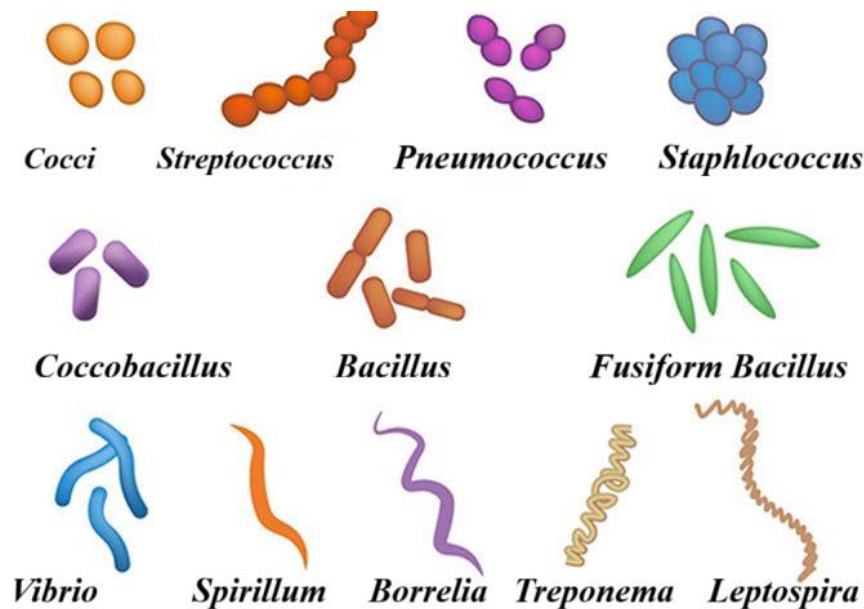


Figure I.8. Different shapes of bacteria.

Most scientists use Gram staining, which enables them to distinguish between two classes of bacteria (see Figure I.9): Gram-positive bacteria possess a robust and continuous cell wall (20-80 nm), mostly constituted of peptidoglycan covalently bonded to various cell wall polymers that exhibit a blue-violet color, including teichoic acid, polysaccharides and phospholipids. Gram-negative bacteria possess a thin peptidoglycan layer (5-10 nm) and an external membrane structure that displays a pink color [85].

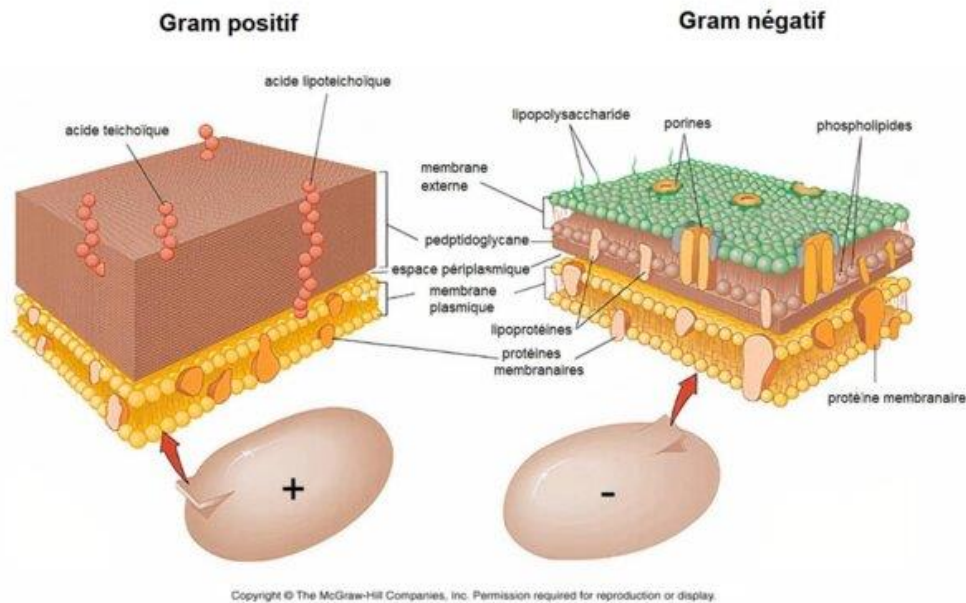


Figure I.9. Structures of the cell wall protecting the plasma membrane in Gram-positive and Gram-negative bacteria [85].

I.6.4. Bacterial species

I.6.4.1. *Escherichia coli*

Escherichia coli (*E. coli*) is a Gram-negative bacterium belonging to the family Enterobacteriaceae that proliferates within 24 hours on agar medium at 37°C, producing round, smooth colonies with defined borders, illustrated in Figure I.10. It has virulence and induces intestinal infections (diarrhea) as well as extra-intestinal infections (urinary tract infections, meningitis) [86].



Figure I.10. The bacterium *Escherichia coli*.

I.6.4.2. *Streptococcus pneumoniae*

Streptococcus pneumoniae (*S. pneumoniae*) is a Gram-positive bacterium arranged in chains (Figure I.11); it has an anaerobic metabolism but might be cultivated in the presence of oxygen (O₂). Furthermore, cocci bacteria can be distinguished from *staphylococci* by the presence of catalase [87].



Figure I.11. The bacterium *Streptococcus pneumoniae*.

I.6.4.3. *Staphylococcus aureus*

Staphylococcus aureus is a Gram-positive bacterium from the family *Micrococcaceae*, as showcased in Figure I.12 [88]. Additionally, the strain grows extensively on agar medium. The culture is generated in 18-24 hours at 37°C. In contrast, *S. aureus* is more harmful to humans and presents as superficial or deep abscesses.

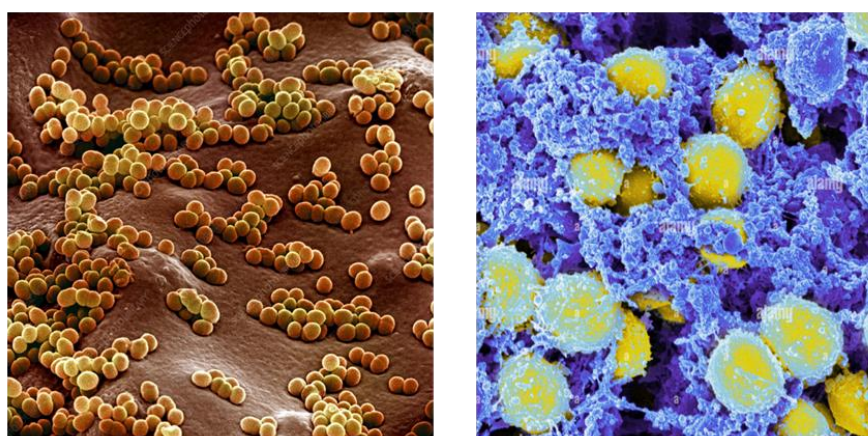


Figure I.12. The bacterium *Staphylococcus aureus*.

I.6.4.4. *Klebsiella pneumoniae*

Klebsiella pneumoniae may be found in surface water, soil, and wood. Due to this bacterium, foods and plants can cause pulmonary abscesses, urinary tract infections and chronic bronchitis co-infections. *Klebsiella pneumoniae* is a Gram-negative bacillus that belongs to the *Enterobacteriaceae* family (see [Figure I.13](#)) [89]. *K. pneumoniae* is facultatively anaerobic, non-motile, and non-sporulating. Additionally, growth is achieved on non-selective and lactose-selective medium after 24 hours of incubation at 37°C.

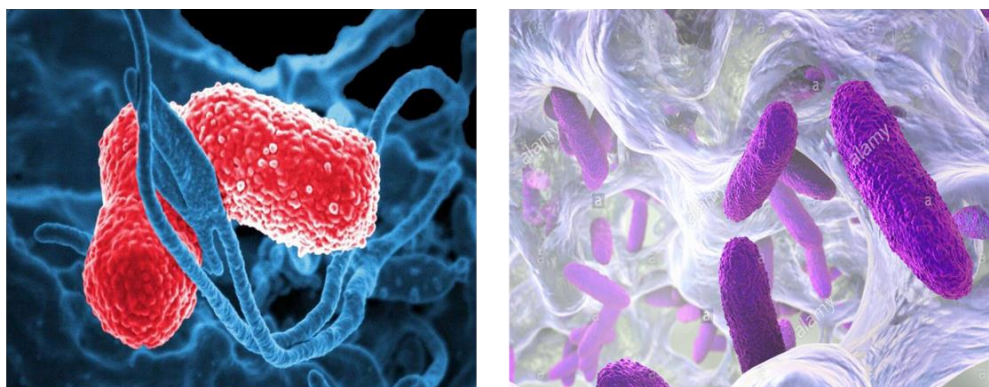


Figure I.13. The bacterium *Klebsiella pneumoniae*.

I.6.4.5. *Pseudomonas aeruginosa*

Pseudomonas aeruginosa bacteria lead to urinary tract infections and branch infections [90]. Additionally, they can cause skin infections in burn victims and thrive in the lungs of people with cystic fibrosis. *Pseudomonas aeruginosa* is a Gram-negative bacillus bacterium belonging to the *Pseudomonas* family, as illustrated in [Figure I.14](#). *P. aeruginosa* grows in large colonies in ordinary medium at 30°C.



Figure I.14. The bacterium *Pseudomonas aeruginosa*.

I.6.5. Antioxidant activity

Due to their medicinal and pharmacological qualities, natural antioxidants have become much more significant in recent years. Furthermore, studies in a variety of scientific domains have shown that coordination compounds made from organic ligands and transition metals can have comparable characteristics and could be used as substitutes for naturally occurring antioxidants.

I.6.5.1. Definition

The antioxidant activity of a substance refers to its ability to resist oxidation. An antioxidant is defined as any compound that appreciably inhibits the oxidation of a substrate found at low concentrations compared to those of an oxidizable [91]. Well-known antioxidants are ascorbic acid (vitamin C), β -carotene (provitamin A), pycnogenol, rutin, quercetin, and tocopherol. Naturally occurring antioxidants possess hydroxy phenolic groups in their molecular structures, and their antioxidant properties are partly due to the ability of these natural compounds to trap free radicals.

I.6.5.2. Free radicals

Free radicals are produced in the human body due to several external triggers: ultraviolet (UV) radiation, ionizing radiation, asbestos, combustion fumes, medications, preservatives, solvents, pesticides. Additionally, free radicals are derived by biological phenomena, including cellular respiration. For instance, there are reactive oxygen species, such as superoxide ($\text{O}_2^{\bullet-}$) and hydroxyl ($\text{OH}^{\bullet}$) radicals and peroxides ($\text{ROO}^{\bullet}$), as well as molecules like singlet oxygen ($^1\text{O}_2$) and hydrogen peroxide (H_2O_2). The invariable production of the free radicals in the human body can be dangerous due to their active derivatives, which are physiologically inescapable. When this equilibrium is disrupted by these reactive molecules, "oxidative stress" ensues. On the other hand, this toxicity is regulated by an effective defense system that mitigates the concentration of free radicals. These defense systems can be presented as follows:

- Specific enzymatic systems.
- Antioxidants of dietary or synthetic origin.

I.7. Conclusion

In conclusion, this chapter presented an overview of the concept of metal-organic compounds and important notions related to coordination chemistry and supramolecular chemistry. Additionally, this chapter highlighted the vital roles and significant influences of non-covalent interactions (hydrogen bonds, Van der Waals forces, and π - π stacking interactions) in the reinforcement of the stability and rigidity of complexes metals. Furthermore, we discussed the different complexes based on 1,10 phenanthroline and benzoic acid as organic ligands and their applications. Besides that, a number of studies have been reviewed from the literature. These show the many different structures or properties for this type of coordination compound. Hence the biggest mystery in organic as well as inorganic chemistry today is N-heterocyclic and carboxylic acid compounds together. In the end a full account of their antibacterial and antioxidant activities was given.

References

- [1] Prajapati, M., Singh, V., Jacob, M. V., Kant, C. R. (2023). Recent advancement in metal-organic frameworks and composites for high-performance supercapatteries. *Renewable and Sustainable Energy Reviews*, 183, 113509.
- [2] Laishram, R., Singh, A. R., Devi, S. S., Thomson, N., Chanu, W. P., Sieroń, L., & Lonibala, R. (2025). Co-crystals of manganese (II) 1, 10-phenanthroline-based complexes with 4-hydroxybenzoic acid and hippuric acid: synthesis, crystal structure and antibacterial activity. *Polyhedron*, 117682.
- [3] Dabrowiak, J. C. (2017). *Metals in medicine*. John Wiley Sons.
- [4] Jurca, T., Marian, E., Vicaș, L. G., Mureșan, M. E., Fritea, L. (2017). Metal complexes of pharmaceutical substances. *Spectrosc. Anal. Dev. Appl*, 123.
- [5] Drake, T., Ji, P., Lin, W. (2018). Site isolation in metal–organic frameworks enables novel transition metal catalysis. *Accounts of chemical research*, 51(9), 2129-2138.
- [6] Kitagawa, S. (2014). Metal–organic frameworks (MOFs). *Chemical Society Reviews*, 43(16), 5415-5418.
- [7] Avşar, C., Findik, B. T., Dede, B., Erdem-Tuncmen, M., Karipcin, F. (2025). Transition metal complexes of N-furfuryl-N'-benzoylthiourea: A study of synthesis, antibacterial activities, quantum chemical calculations and molecular modeling simulations. *Polyhedron*, 267, 117357.
- [8] Singh, N., Khan, N. A., Taha, A., Joshi, M. C., Kumar, P., Vedeshwar, A. G., Hashmi, A. A. (2025). Synthesis, spectroscopic characterization, DFT calculations, and antimicrobial studies of novel transition metal complexes of tridentate Schiff base ligand derived from o-vanillin. *Journal of Molecular Structure*, 1332, 141722.
- [9] Das, B. (2025). Transition Metal Complex-Loaded Nanosystems: Advances in Stimuli-Responsive Cancer Therapies. *Small*, 21(7), 2410338.
- [10] Tanase, T. (2024). Introduction: What Is a Metal Complex?
- [11] Duncan, A. J. E. (2017). *Explorations in crystal engineering: supramolecular templates, helical assemblies, pharmaceutical reactivity, and applications to radio-imaging* (Doctoral dissertation, University of Iowa).
- [12] Khlobystov, A. N., Blake, A. J., Champness, N. R., Lemenovskii, D. A., Majouga, A. G., Zyk, N. V., Schröder, M. (2001). Supramolecular design of one-dimensional coordination polymers based on silver (I) complexes of aromatic nitrogen-donor ligands. *Coordination Chemistry Reviews*, 222(1), 155-192.
- [13] Steed, J. W., Atwood, J. L. (2022). *Supramolecular chemistry*. John Wiley Sons.

- [14] Schneider, H. J. (2009). Binding mechanisms in supramolecular complexes. *Angewandte Chemie International Edition*, 48(22), 3924-3977.
- [15] Schneider, H. J. (2009). Binding mechanisms in supramolecular complexes. *Angewandte Chemie International Edition*, 48(22), 3924-3977.
- [16] Wang, A., Shi, W., Huang, J., Yan, Y. (2016). Adaptive soft molecular self-assemblies. *Soft Matter*, 12(2), 337-357.
- [17] Tang, K. T., Toennies, J. P. (2010). Johannes Diderik van der Waals: a pioneer in the molecular sciences and Nobel prize winner in 1910. *Angewandte Chemie International Edition*, 49(50), 9574-9579.
- [18] Latimer, W. M., Rodebush, W. H. (1920). Polarity and ionization from the standpoint of the Lewis theory of valence. *Journal of the American Chemical Society*, 42(7), 1419-1433.
- [19] Lehn, J. M. (1995). *Supramolecular chemistry: concepts and perspectives*. John Wiley & Sons.
- [20] Steed, J. W., Atwood, J. L. (2022). *Supramolecular chemistry*. John Wiley & Sons.
- [21] Kumar, P., Banerjee, S., Radha, A., Firdoos, T., Sahoo, S. C., Pandey, S. K. (2021). Role of non-covalent interactions in the supramolecular architectures of mercury (II) diphenyl dithiophosphates: An experimental and theoretical investigation. *New Journal of Chemistry*, 45(4), 2249-2263.
- [22] Laishram, R., Singh, A. R., Devi, S. S., Thomson, N., Chanu, W. P., Sieroń, L., Lonibala, R. (2025). Co-crystals of manganese (II) 1, 10-phenanthroline-based complexes with 4-hydroxybenzoic acid and hippuric acid: synthesis, crystal structure and antibacterial activity. *Polyhedron*, 117682.
- [23] Arunan, E., Desiraju, G. R., Klein, R. A., Sadlej, J., Scheiner, S., Alkorta, I., Nesbitt, D. J. (2011). Definition of the hydrogen bond (IUPAC Recommendations 2011). *Pure and applied chemistry*, 83(8), 1637-1641.
- [24] Grabowski, S. J. (2020). *Understanding hydrogen bonds: theoretical and experimental views* (Vol. 19). Royal Society of Chemistry.
- [25] Grabowski, S. J. (2024). Hydrogen bond types which do not fit accepted definitions. *Chemical Communications*, 60(49), 6239-6255.
- [26] Nishio, M., Hirota, M., Umezawa, Y. (1998). *The CH/π interaction: evidence, nature, and consequences*. John Wiley & Sons.
- [27] Doreswamy, S., Santhosh, C., Lohith, T. N., Neetha, S., Sharath, K., Sridhar, M. A., Sadashiva, M. P. (2025). The study of the role of non-covalent interactions (CH...N, CH...π, CO...CO, and π...π) towards crystal packing of benzyl 4-(4-fluorophenyl) thiazole-2-

carboxylate: A combined experimental and computational approach. *Journal of Molecular Structure*, 1329, 141323.

[28] Tsuzuki, S., Honda, K., Uchimaru, T., Mikami, M., Tanabe, K. (2000). Origin of the Attraction and Directionality of the NH/ π Interaction: Comparison with OH/ π and CH/ π Interactions. *Journal of the American Chemical Society*, 122(46), 11450-11458.

[29] Bernstein, J., Davis, R. E., Shimon, L., Chang, N. L. (1995). Patterns in hydrogen bonding: functionality and graph set analysis in crystals. *Angewandte Chemie International Edition in English*, 34(15), 1555-1573.

[30] Boro, M., Banik, S., Gomila, R. M., Frontera, A., Barcelo-Oliver, M., Bhattacharyya, M. K. (2024). Supramolecular Assemblies in Mn (II) and Zn (II) Metal–Organic Compounds Involving Phenanthroline and Benzoate: Experimental and Theoretical Studies. *Inorganics*, 12(5), 139.

[31] Claessens, C. G., Stoddart, J. F. (1997). π – π Interactions in self-assembly. *Journal of physical organic chemistry*, 10(5), 254-272.

[32] Martinez, C. R., Iverson, B. L. (2012). Rethinking the term “pi-stacking”. *Chemical Science*, 3(7), 2191-2201.

[33] Zhuang, W. R., Wang, Y., Cui, P. F., Xing, L., Lee, J., Kim, D., Oh, Y. K. (2019). Applications of π – π stacking interactions in the design of drug-delivery systems. *Journal of controlled release*, 294, 311-326.

[34] Liu, Y., Wu, Y., Luo, Z., Li, M. (2023). Designing supramolecular self-assembly nanomaterials as stimuli-responsive drug delivery platforms for cancer therapy. *Iscience*, 26(3).

[35] Nycz, J. E., Martinsinovich, N., Wantulok, J., Chen, T., Książek, M., Kusz, J. (2024). Synthesis and spectroscopic characterization of selected water-soluble ligands based on 1, 10-phenanthroline core. *Molecules*, 29(6), 1341.

[36] Hermann, J., DiStasio Jr, R. A., Tkatchenko, A. (2017). First-principles models for van der Waals interactions in molecules and materials: Concepts, theory, and applications. *Chemical Reviews*, 117(6), 4714-4758.

[37] Reilly, A. M., Tkatchenko, A. (2014). Role of dispersion interactions in the polymorphism and entropic stabilization of the aspirin crystal. *Physical review letters*, 113(5), 055701.

[38] Shtogun, Y. V., Woods, L. M. (2010). Many-body van der Waals interactions between graphitic nanostructures. *The Journal of Physical Chemistry Letters*, 1(9), 1356-1362.

[39] Gao, W., Tkatchenko, A. (2013). Electronic structure and van der Waals interactions in the stability and mobility of point defects in semiconductors. *Physical review letters*, 111(4).

- [40] Koning, B., de Boer, J. W., Meetsma, A., Kellogg, R. M. (2004). Synthesis and complexation characteristics of phenanthroline and bipyridine diols. *Arkivoc*, 2004(2), 189-205.
- [41] Adelaide, O. M., Abidemi, O. O., Olubunmi, A. D. (2013). Synthesis, characterization and antibacterial studies of some copper (II) complexes of 2, 2'-bipyridine and 1,10-phenanthroline. *J. Chem. Pharm. Res*, 5, 69-73.
- [42] Ndosiri, N. B., Agwara, M. O., Paboudam, A. G., Ndifon, P. T., Yufanyi, D. M., Amah, C. (2013). Synthesis, characterization and antifungal activities of Mn (II), Co (II), Cu (II), and Zn (II) mixed-ligand complexes containing 1, 10-phenanthroline and 2, 2'-Bipyridine.
- [43] Chandraleka, S., Ramya, K., Chandramohan, G., Dhanasekaran, D., Priyadharshini, A., Panneerselvam, A. (2014). Antimicrobial mechanism of copper (II) 1, 10-phenanthroline and 2, 2'-bipyridyl complex on bacterial and fungal pathogens. *Journal of Saudi Chemical Society*, 18(6), 953-962.
- [44] Khan, I. M., Ahmad, A., Aatif, M. (2011). Synthesis, single-crystal characterization, antimicrobial activity and remarkable in vitro DNA interaction of hydrogen-bonded proton-transfer complex of 1, 10-phenanthroline with 2, 4, 6-trinitrophenol. *Journal of Photochemistry and Photobiology B: Biology*, 105(1), 6-13.
- [45] Khan, I. M., Ahmad, A., Aatif, M. (2011). Synthesis, single-crystal characterization, antimicrobial activity and remarkable in vitro DNA interaction of hydrogen-bonded proton-transfer complex of 1, 10-phenanthroline with 2, 4, 6-trinitrophenol. *Journal of Photochemistry and Photobiology B: Biology*, 105(1), 6-13.
- [46] Dey, D., Roy, A. B., Ranjani, A., Gayathri, L., Chandraleka, S., Dhanasekaran, D., Biswas, B. (2015). Synthesis and bio-catalytic activity of isostructural cobalt (III)-phenanthroline complexes. *Journal of Chemical Sciences*, 127(4), 649-661.
- [47] Zavarize, D. G., Oliveira Neto, J. G. D., Abreu, K. R., Ayala, A. P., Sousa, F. F. D., Santos, A. O. D. (2025). A Novel Fe (III)-Complex with 1, 10-Phenanthroline and Succinate Ligands: Structure, Intermolecular Interactions, and Spectroscopic and Thermal Properties for Engineering Applications. *Processes*, 13(5), 1267.
- [48] Li, Z. G., Wang, G. H., Niu, J. J., Xu, J. W., Hu, N. H. (2007). Tetraaqua (1, 10-phenanthroline-κ²N, N') cobalt (II) dinitrate: a hydrogen-bonded supramolecular network. *Crystal Structure Communications*, 63(3), m94-m96.
- [49] Swarnabala, G., Reddy, K. R., Tirunagar, J., Rajasekharan, M. V. (1994). Mononuclear manganese (III) aquo complexes. Crystal and molecular structures of [Mn (phen)(OH₂) Cl₃] and [Mn (acac) 2-(OH₂)₂] ClO₄ · 2H₂O (acacH= acetylacetone, phen= 1, 10-

phenanthroline). *Transition Metal Chemistry*, 19(5), 506-508.

[50] Chen, X., Han, S., Wang, R., Li, Y. (2016). Four supramolecular isomers of dichloridobis (1,10-phenanthroline) cobalt (II): synthesis, structure characterization and isomerization. *Crystal Structure Communications*, 72(1), 6-13.

[51] Odoko, M., Okabe, N. (2004). Tris (1, 10-phenanthroline- κ 2N, N') iron (III) trinitrate monohydrate. *Structure Reports*, 60(12), m1822-m1824.

[52] Cechova, D., Martiskova, A., Moncol, J. (2014). Structure of cis-dichlorobis (1, 10-phenanthroline) manganese (II) and cis-dichlorobis (2, 2'-bipyridine) manganese (II). *Acta Chimica Slovaca*, 7(1), 15.

[53] Dey, P., Hossain, A., Seth, S. K. (2024). On the importance of unconventional Cu $\cdots$ π interaction in tetrachloro-bis (1, 10-phenanthroline)-dicopper (II) complex: insights from experiment and theory. *Journal of Molecular Structure*, 1295, 136642.

[54] Tang, Z., Wu, D., Wen, D. (2022). Crystal structure of (bis (1, 10-phenanthroline- κ 2 N, N'))-(3,5-dinitrosalicylato- κ 2O,O') nickel (II), C₃₁H₁₈N₆NiO₇. *Zeitschrift für Kristallographie-New Crystal Structures*, 237(6), 981-983.

[55] Omoregie, H. O., Eseola, A. O., Akong, R. A. (2022). Mixed ligand complexes of copper (II) with benzoyltrifluoroacetone, 1, 10-phenanthroline and 2, 2'-bipyridine: structure, spectroscopic and antimicrobial properties. *Journal of Molecular Structure*, 1250, 131826.

[56] Kamat, V., Revankar, V. (2018). 1,10-Phenanthroline-copper mediated ligand transformations: Synthesis and characterization of unusual mixed ligand complexes of copper (II). *Inorganica Chimica Acta*, 476, 77-82.

[57] Lin, X., Zhou, P., Gao, Y., Li, T., Chen, X., Li, H., Zheng, H. (2023). Implementation of Thermal-Trigged Binary–Ternary Switchable Memory Performance in Zn/polysulfide/organic Complex-Based Memorizers by Finely Modulating the S62–Relaxation. *Inorganic Chemistry*, 63(1), 775-783.

[58] Zheng, Y. Q., Kong, Z. P., Lin, J. L. (2002). Supramolecular assemblies via hydrogen bonding and π - π stacking interactions: crystal structures of [Co (phen)(H₂O) ₄] L · 0.5 H₂O and [CO₂ (phen) ₂ (H₂O) 2L₂] with H₂L= adipic acid. *Journal of Coordination Chemistry*, 55(11), 1249-1257.

[59] Li, Q., He, L., Jin, H. (2012). Aqua (2, 6-dihydroxybenzoato- κ O1) bis (1, 10-phenanthroline- κ 2N, N') manganese (II) 2, 6-dihydroxybenzoate hemihydrate. *Structure Reports*, 68(6), m798-m798.

[60] Huang, M. L. (2012). Crystal structure of tris (1, 10-phenanthroline- κ 2 N, N')-iron (II) dinitrate-4-aminobenzoic acid-water(1:1:2), [Fe(C₁₂H₈N₂)₃][NO₃]₂ · C₇H₇NO₂ · 2H₂O. *Zeitschrift*

für Kristallographie-New Crystal Structures, 227(2), 110-112.

- [61] Aljahdali, M., El-Sherif, A. A. (2013). Synthesis, characterization, molecular modeling and biological activity of mixed ligand complexes of Cu (II), Ni (II) and Co (II) based on 1, 10-phenanthroline and novel thiosemicarbazone. *Inorganica Chimica Acta*, 407, 58-68.
- [62] Viganor, L., Howe, O., McCarron, P., McCann, M., Devereux, M. (2017). The antibacterial activity of metal complexes containing 1,10-phenanthroline: potential as alternative therapeutics in the era of antibiotic resistance. *Current topics in medicinal chemistry*, 17(11), 1280-1302.
- [63] Masmoudi, M., Silva, C., Andrade, N., Martel, F., Brandão, P. (2025). Coordination Complexes of Co, Cu, and Fe with Adenine and Phenanthroline: Synthesis, Characterization, and Cytotoxic Studies. *Journal of Molecular Structure*, 143128.
- [64] Rentschler, M., Schmid, M. A., Frey, W., Tschierlei, S., Karnahl, M. (2020). Multidentate phenanthroline ligands containing additional donor moieties and their resulting Cu (I) and Ru (II) photosensitizers: A comparative study. *Inorganic Chemistry*, 59(20), 14762-14771.
- [65] Benazzi, E., Magni, M., Colombo, A., Dragonetti, C., Caramori, S., Bignozzi, C. A., Roberto, D. (2018). Bis (1, 10-phenanthroline) copper complexes with tailored molecular architecture: From electrochemical features to application as redox mediators in dye-sensitized solar cells. *Electrochimica Acta*, 271, 180-189.
- [66] Sim, G. A., Robertson, J. M., Goodwin, T. H. (1955). The crystal and molecular structure of benzoic acid. *Acta Crystallographica*, 8(3), 157-164.
- [67] Singh, S., Jedrzejewski, M. J., Air, G. M., Luo, M., Laver, W. G., Brouillette, W. J. (1995). Structure-based inhibitors of influenza virus sialidase. A benzoic acid lead with novel interaction. *Journal of medicinal chemistry*, 38(17), 3217-3225.
- [68] Zholdakova, Z. I., Sinitsyna, O. O., Kharchevnikova, N. V., Pechnikova, I. A., Mamonov, R. A., Belyaeva, N. I. (2021). Scientific substantiation of Maximum Permissible Concentrations (MPCs) for benzoic acid and sodium benzoate in water based on modern data (literature review). *Hygiene and Sanitation*, 100(10), 1064-1069.
- [69] Krešáková, L., Miño, A., Holub, M., Kuchar, J., Werner, A., Tomás, M., Černák, J. (2021). Heteroleptic complexes of Ni (II) with 2, 2'-bipyridine and benzoate ligands. Magnetic properties of [Ni (bpy)(Bz) 2]. *Inorganica Chimica Acta*, 527, 120588.
- [70] Moreno-Gomez, L., Sanchez-Ferez, F., Calvet, T., Font-Bardia, M., Pons, J. (2020). Zn (II) and Cd (II) monomer, dimer and polymer compounds coordinated by benzoic acid and 4-acetylpyridine: Synthesis and crystal structures. *Inorganica Chimica Acta*, 506, 119561.

- [71] Deng, J. H., Yi, Y. P., Xiong, Z. X., Yuan, L., Mei, G. Q. (2009). Tetra- μ -benzoato- κ 8O: O'-bis [(benzoic acid- κ O) nickel (II)]. *Structure Reports*, 65(11), m1484-m1484.
- [72] Vráblová, A., Černák, J., Rajnák, C., Dlháň, L., Tomás, M., Falvello, L. R., Boča, R. (2018). Exceptionally slow magnetic relaxation in cobalt (II) benzoate trihydrate. *Dalton Transactions*, 47(43), 15523-15529.
- [73] Vráblová, A., Falvello, L. R., Campo, J., Miklovič, J., Boča, R., Černák, J., Tomás, M. (2016). Preparation, First Structure Analysis, and Magnetism of the Long-Known Nickel Benzoate Trihydrate—A Linear Ni $\cdots$ Ni $\cdots$ Ni Polymer and Its Parallels with the Active Site of Urease. *European Journal of Inorganic Chemistry*, 2016(6), 928-934.
- [74] Dutta, D., Sharma, P., Gomila, R. M., Frontera, A., Barcelo-Oliver, M., Verma, A. K., Bhattacharyya, M. K. (2022). Solvent-driven structural topologies in phenanthroline-based co-crystals of Zn (ii) involving fascinating infinite chair-like {[bzH)₄ Cl₂] 2-} n assemblies and unconventional layered infinite {bz-H 2 O-Cl} n anion-water clusters: antiproliferative evaluation and theoretical studies. *New Journal of Chemistry*, 46(12), 5638-5652.
- [75] Zhang, S. Y., Zhang, Z. J., Shi, W., Zhao, B., Cheng, P., Liao, D. Z., Yan, S. P. (2011). Structural evolution and magnetic properties of Co II coordination polymers varied from 1D to 3D constructed by 1, 4-bis (1, 2, 4-triazol-1-ylmethyl) benzene. *Dalton Transactions*, 40(31), 7993-8002.
- [76] Zhu, L. G., Hu, M. L. (2006). Aquadibenzoato (2, 2'-bipyridine) cadmium (II) monohydrate. *Structure Reports*, 62(3), m653-m655.
- [77] Liu, Y. Y., Jiang, Y. Y., Yang, J., Liu, Y. Y., Ma, J. F. (2011). Syntheses, structures and photoluminescence of zinc (II) and silver (I) coordination polymers based on 1,1'-(1,4-butanediyl)-bis-(2-methylbenzimidazole) and different carboxylate ligands. *CrystEngComm*, 13(20), 6118-6129.
- [78] Peng, X., Cui, G. H., Li, D. J., Liu, T. F. (2010). Synthesis, characterization, and theoretical calculations of mononuclear copper (II) benzoate complex with 2-propylimidazole, [Cu (PIM)₂ (PhCOO)₂]. *Journal of Molecular Structure*, 967(1-3), 54-60.
- [79] Krešáková, L., Holub, M., Tomás, M., Falvello, L. R., Rohlíček, J., Konieczny, P., Černák, J. (2024). Heteroleptic Ni (II) complexes containing chelating benzoato ligand with sharp bite angle: syntheses, crystal structures, and magnetism. *Inorganica Chimica Acta*, 571, 122178.
- [80] Nashre-ul-Islam, S. M., Borah, K. K., Öztürkkan, F. E., Raza, M. A., Frontera, A., Gil, D. M. (2022). Antiparallel $\pi\cdots\pi$ and C-H $\cdots$ H-C contacts in a novel Zn (II) coordination solid involving π -hole tetrel bonding interactions: A combined experimental and theoretical study, Hirshfeld surface analysis, molecular docking and potential drug property. *Journal of*

Molecular Structure, 1268, 133686.

- [81] Sydora, O. L. (2024). Transition metal benzoate complexes. *Polyhedron*, 252, 116854.
- [82] OSOWOLE, A. A., Agbaje, O. B., WAKIL, S. S. (2015). Synthesis, characterization and biological activity of some mixed metal (II) complexes of paracetamol and benzoic acid. *Int. J. Appl. Med. Sci.*, 1(2), 77-87.
- [83] Kani, I., Atlier, Ö., Güven, K. (2016). Mn (II) complexes with bipyridine, phenanthroline and benzoic acid: Biological and catalase-like activity. *Journal of Chemical Sciences*, 128(4), 523-536.
- [84] Sowmya, V., Behera, L., Mounika, A., Thera, U. K. (2020). Chapter-1 Phytochemical Activities of Botanical Pesticides in Plant Pest Management. *Recent Trends in*, 1, 1.
- [85] El Kihel, A. (2022). *Nouveaux biomatériaux photosensibles pour des applications antimicrobiennes* (Doctoral dissertation, Université de Limoges).
- [86] Allocati, N., Masulli, M., Alexeyev, M. F., Di Ilio, C. (2013). Escherichia coli in Europe: an overview. *International journal of environmental research and public health*, 10(12), 6235-6254.
- [87] Janoff, E. N., Musher, D. M., Redel, H., Blaser, M. (2019). Streptococcus pneumoniae. In *Mandell, Douglas, and Bennett's Principles and Practice of Infectious Diseases, 9th Edition: Volume 1-2* (pp. 2473-2491). Elsevier.
- [88] Ondusko, D. S., Nolt, D. (2018). Staphylococcus aureus. *Pediatrics in review*, 39(6), 287-298.
- [89] Russo, T. A., Marr, C. M. (2019). Hypervirulent klebsiella pneumoniae. *Clinical microbiology reviews*, 32(3), 10-1128.
- [90] Xue, L., Liao, F., Tang, F., Chen, S., Hu, M., Qiao, L., Li, D. (2024). The formation of bixbyite-type Mn₂O₃ via pyocyanin-dependent Mn (II) oxidation of soil-derived Pseudomonas aeruginosa. *Geomicrobiology Journal*, 41(6), 660-671.
- [91] Jimsheena, V. K., Gowda, L. R. (2009). Colorimetric, high-throughput assay for screening angiotensin I-converting enzyme inhibitors. *Analytical chemistry*, 81(22), 9388-9394

Chapter II
Materials and Experimental
Methods

II.1. Introduction

Characterization techniques in metal-organic chemistry employ various experimental and computational methods that are necessary for characterizing novel synthesized materials, specifically focusing on their interactions with transition metals within molecular structures. This chapter is dedicated to the presentation of these different techniques. The single crystal X-ray diffraction analysis is the primary efficient tool to determine the crystalline structure. Complementary FTIR and UV-visible spectroscopy explain the functional groups highlighted in complexes. Additionally, the Hirshfeld surface analysis is used to visualize and investigate the types of interactions present in molecules using the *CrystalExplorer* software.

This present study involves a comparative evaluation of experimental and computational methods. Additionally, we reported results on frontier molecular orbitals, electron localization function (ELF), localized orbital locator (LOL), molecular electrostatic potential (MEP), and reduced density gradient (RDG). On the other hand, the molecular docking was used to describe how our transition metal complex selectively interacts with natural macromolecule target sites and demonstrates the flexibility and efficiency of chemical compounds in biological research. We also demonstrated experimental techniques for studying biological activity (antimicrobial and antioxidant activity).

Part 1: Materials and Equipment

II.2. Chemical characterization techniques

II.2.1. FT-IR Spectroscopy

Infrared spectroscopy is a technique for qualitative analysis to detect the presence or absence of functional groups in organic and inorganic molecules, and it was discovered in 1800 by Frederick William Herschel [1]. The normal region of the infrared spectrum is from about 4000 to 400 cm^{-1} (about 2.5 μm to 25 μm), and this region is what chemists (or organic chemists) use most often for functional analyses of molecules. This technique allows one to study the vibrations of molecules upon exposure to an electromagnetic wave with a frequency (or wavelength) in the infrared region, which is roughly between about 0.8 and 1000 μm [2].

An examination of vibrational modes of chemical bonds in molecules is the foundation of Fourier Transform Infrared (FT-IR) spectroscopy. The specific rotations and vibrations of a system depicted as two atoms connected by a bond in a given substance is associated with absorption of different wavelengths of infrared radiation. When the energy frequency of

incident radiation matches the vibrational frequencies of functional groups of the molecule, IR-active vibrations of a functional group appear in the IR spectrum [3]. This action is dependent on the changes in dipole moment of polar bonds within the molecular framework. On the other hand, non-polar bonds do not show up in the spectrum since they are inactive in infrared spectroscopy. Overall, the spectroscopic action manifests when infrared electromagnetic radiation selectively excites the bonds in the molecule before the molecule returns to its original state and dissipates the absorbed energy as heat (Figure II.1) [4].

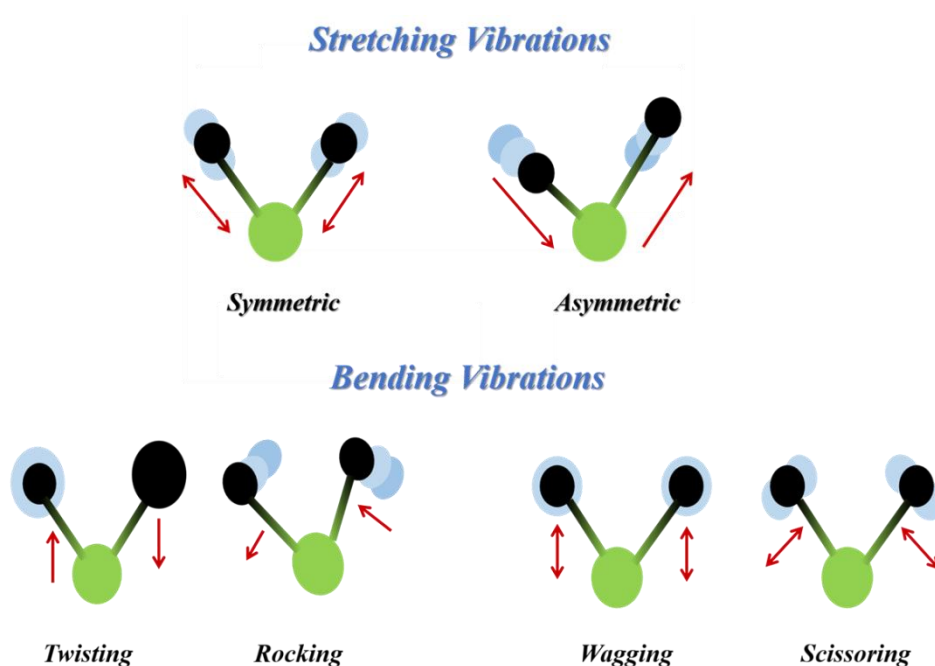


Figure II.1. Molecular vibrational band types.

Infrared spectroscopy is the measurement of electromagnetic radiation absorbance in three regions: Far-infrared at $10\text{--}400\text{ cm}^{-1}$, Mid-infrared at $400\text{--}4000\text{ cm}^{-1}$, and Near-infrared at $4000\text{--}14000\text{ cm}^{-1}$. The mid-infrared region is most essential for determining organic and inorganic materials and is also the region where we determine if a molecule has certain functional groups. In this range, two main types of molecular vibrations are measured; these are stretching molecular vibrations (ν) referring to bond length changes in double and/or triple bonds, and bending molecular vibrations, which refers to bond angles of single bonding compounds in the molecular structure (Figure II.2) [5].

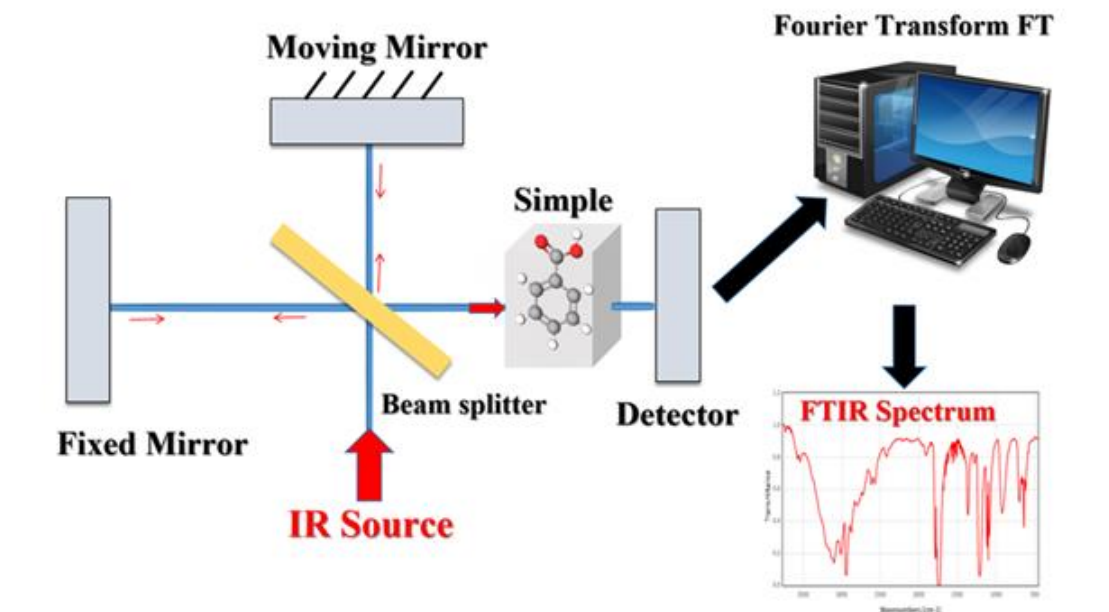


Figure II.2. Working principle of an FT-IR spectrometer.

Organic compound qualitative analysis is the predominant application of IR spectroscopy. Spectra of compounds have distinct traits that are specific to their molecular characteristics. The functional group frequency region ($3600\text{--}1200\text{ cm}^{-1}$) and fingerprint region ($1200\text{--}600\text{ cm}^{-1}$) are frequently the areas examined in interpreting IR spectra. In many situations, corroborating evidence of a compound identification is achieved by interpreting functional group region and then comparing the fingerprint region with spectral libraries. The functional group region emphasizes functional groups of a molecule by the frequency of absorption. There are both tables in standard spectrum manuals and references that provide ranges of absorbance for functional groups. Common functional groups with distinct absorbances are aldehydes, ketones, esters, alkenes, alkynes, alcohols, amines, amides, carboxylic acids, nitro groups, and nitriles (Figure II.3). Although most functional groups are located in the $3600\text{--}1200\text{ cm}^{-1}$ range, some can also be found in the fingerprint region. For example, C–O bonds can be detected around 1000 cm^{-1} , and C–Cl absorbances are typically in the $600\text{--}800\text{ cm}^{-1}$ range.

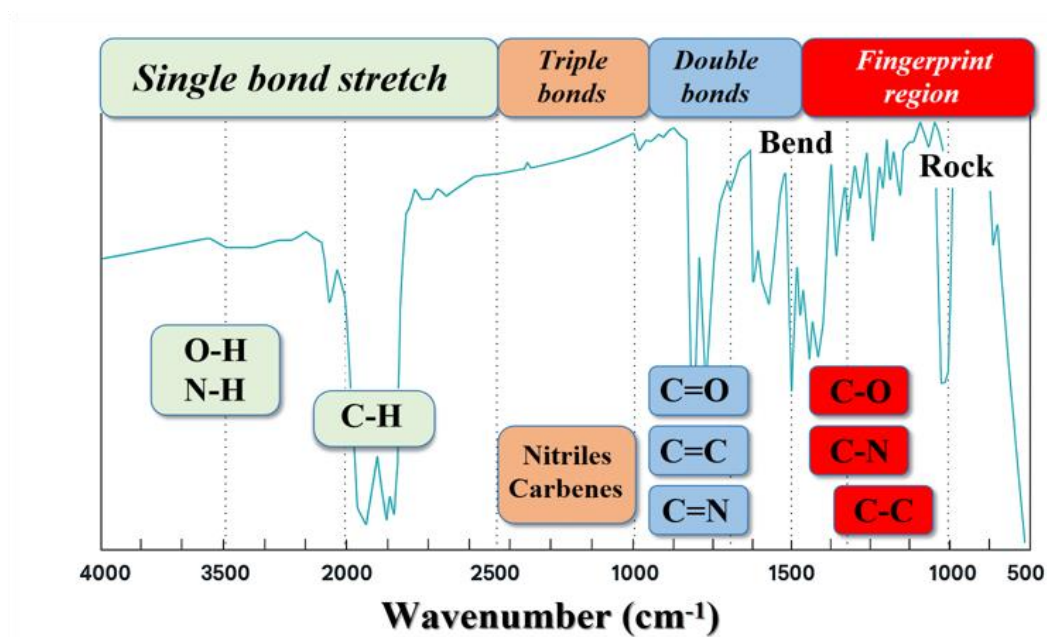


Figure II.3. Diagram representation of absorbed vibration bands in the Mid-Infrared region.

In this study, the Fourier-transform infrared (FT-IR) spectra of the synthesized complexes were collected in the mid-infrared (4000–400 cm^{-1}) range. A little amount of each compound was finely ground and mixed with potassium bromide (KBr) to prepare transparent pellets to ensure the highest signal and spectral results. The FT-IR measurements were carried out by a Perkin-Elmer spectrometer at the LASPI2A laboratory, under the supervision of Prof. Abdecharif Boumaza at Abbes Laghrour University, Khenchela, Algeria ([Figure II.4](#)).



Figure II.4. The Perkin-Elmer spectrometer. Abbes Laghrour University, Khenchela.

II.2.2. Ultraviolet-Visible Absorption Spectroscopy

UV-Vis spectrophotometry is a spectroscopic technique used for both qualitative and quantitative analysis, which allows the calculation of the absorbance (optical density) of a chemical molecule of interest. Qualitative analysis of pharmaceuticals is an integral part of both drug discovery and quality assurance. UV-visible spectroscopy offers a relatively simple method for the qualitative analysis of drugs by determining their absorbance at specific wavelengths. In a practical setting, we can make a determination of presence and/or purity of drugs based on the characteristics of their UV absorption spectrum. During early drug discovery, all potential candidate drugs would be subjected to UV-visible spectrophotometry to compare absorption spectra, thus allowing for a preliminary determination of whether the chemical structure of drugs would have therapeutic effects or to detect protein structure, for example, from the UV absorbance spectra. Lastly, UV-visible spectrophotometry allows us to analyze bioactive compounds in extracts and can be used to measure the biological activity of these extracts [6,7].

Typically, the method pertains to the UV spectrum from $\{\lambda = 10 \text{ nm to } \lambda = 400 \text{ nm}\}$, and the visible range $\{\lambda = 400 \text{ nm to } \lambda = 800 \text{ nm}\}$. To obtain the UV-visible spectrum of a particular substance, a diluted solution of a specific concentration should be prepared and placed in a glass vial; the solvent should be transit in the chosen wavelength range. Be careful to choose an appropriate solvent because the properties of the solvent will influence the properties of the spectrum. Inside the UV-Vis spectrophotometer a beam of intensity I_0 passes through a material of thickness l . If the material in question is absorbent, some of the incident light I_0 will be absorbed. The intensity I of the beam is a function of the concentration of the molecules of the dissolved substance, and expressed by Beer-Lambert's law [8- 11] (Figure II.5).

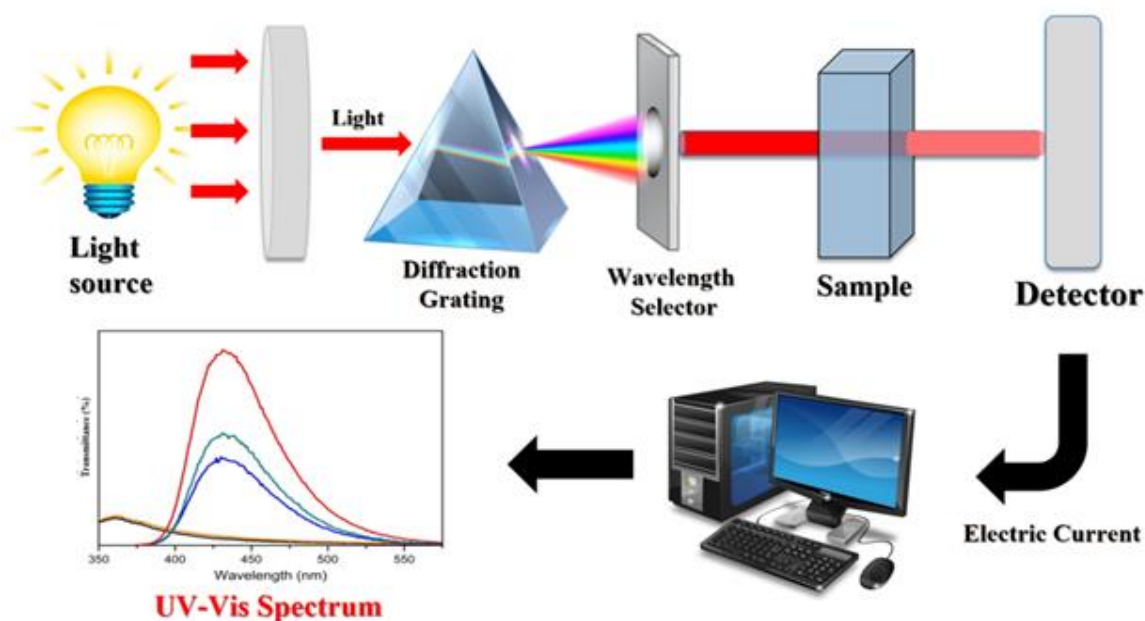


Figure II.5. Illustration of the principle of the UV–Vis spectrophotometer.

The Beer-Lambert Law is widely useful in the UV-Vis spectroscopy method. Specifically, the absorbance is proportionally related to the concentration of the sample solution that absorbs the monochromatic light scattering (Figure II.6) [12,13].

The Beer-Lambert Law equation is expressed as

$$A = \log I / I_0 = \epsilon lc$$

Where:

A: Absorbance (optical density).

I₀: Initial intensity of the incident ultraviolet or visible light beam.

I: Intensity of the emitted (transmitted) ultraviolet or visible light beam.

ε: Extinction coefficient (l.mol⁻¹.cm⁻¹).

C: The molar concentration of an absorbing substance in mol/l.

l: Thickness of the quartz cell (1cm).

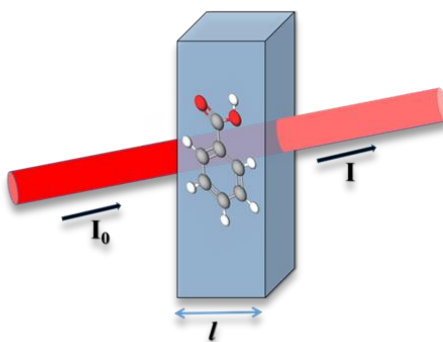


Figure II.6. Presentation of optical absorption described by the Beer-Lambert law.

This study recorded the ultraviolet–visible (UV–Vis) spectra of the synthesized metal-organic complexes in the range of 200 to 800 nm. The spectra were taken by solubilizing the crystalline compounds at low concentration in DMSO and DMF as solvents using quartz cuvettes, to obtain suitable absorbance. All measurements were performed at room temperature. Distilled water was used as a reference to provide a stable baseline. The UV-Vis data were collected by using a Spectro Scan 80D spectrophotometer at the LASPI2A laboratory in the presence of Prof. Abdelkader Djelloul at Abbas Laghrour University, Khenchela, Algeria (Figure II.7).

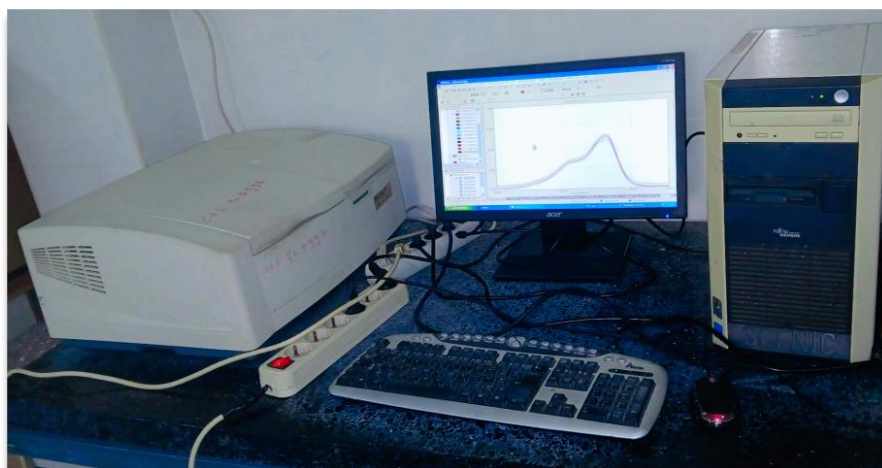


Figure II.7. The UV-Visible spectrophotometer at the LASPI2A laboratory, Abbas Laghrour University, Khenchela.

II.2.3. Hirshfeld surface analysis

CrystalExplorer is a popular tool for visualizing the Hirshfeld surfaces (*HSs*) of solid-state chemical compounds in the Crystallographic Information File (CIF). The idea of the Hirshfeld surface was only introduced by Spackman and Byrom in 1997 [14]. *HS* examination has evolved to be a strong and widely used method for distinguishing the crystal space into separate areas depending on the local electronic density of the molecule, with the promolecule being the chosen reference [15]. Structurally, the Hirshfeld surface envelops the entire molecule with a specific mapping in the crystalline system, defined by a weight function under the condition $\omega(r) > 0.5$, as follows:

$$\omega(r) = \frac{\rho_{\text{promolécule}}(r)}{\rho_{\text{procrystal}}(r)} = \frac{\sum \rho_A(r)[A \in \text{molécule}]}{\sum \rho_A(r)[A \in \text{cristal}]}$$

This 3D surface tool is used to explore and visualize the intermolecular contact regions within the crystal lattice. Furthermore, the Hirshfeld surfaces were mapped over through iso-surfaces of promolecules into various models, including d_{norm} , shape index, curvedness, and fragment patch surfaces.

II.2.3.1. Hirshfeld Surface Properties

II.2.3.1.1. The normalized contact distance (d_{norm})

The normalized contact distance (d_{norm}) Hirshfeld surface is defined using atomic properties, including van der Waals (*vdW*) radii, and the (d_e , d_i) pairs of distances between the *HS* surface and the external and internal atoms, respectively. As shown by the ensuing equation:

$$d_{\text{norm}} = \frac{d_i - r_i^{\text{vdw}}}{r_i^{\text{vdw}}} + \frac{d_e - r_i^{\text{vdw}}}{r_i^{\text{vdw}}}$$

The d_{norm} surface makes use of color coding to assess the patterns exhibited on the *HS* surface: red areas mark contacts shorter than the sum of van der Waals radii, suggesting strong donor–acceptor interactions between the molecules; blue areas mark weaker interactions longer than the van der Waals limit; and white areas signify contacts equal to this sum of the *Vdw* (Figure II.8).

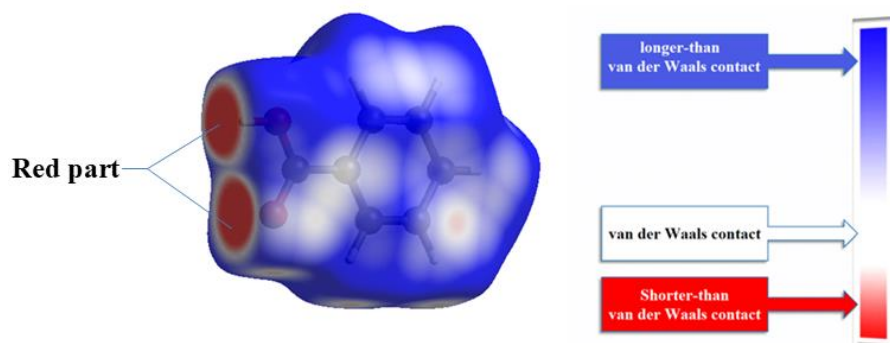


Figure II.8. Model of the d_{norm} Hirshfeld surface for benzoic acid.

II.2.3.1.2. Shape index and Curvedness surfaces

The curvedness and shape index surfaces proposed by Koenderink can be used for curvature measurement of Hirshfeld surfaces [16]. The shape index (S) map is a practical crystallographic tool to understand weak contacts between atoms in molecules. The three-dimensional surface is particularly useful since it delineates π - π interactions through adjacent red and blue triangle regions. Additionally, the presence of red points in blue areas indicates flat inter-ring contacts, which are also suggested by the flat areas displayed in the curvedness (C) function map (Figure II.9).

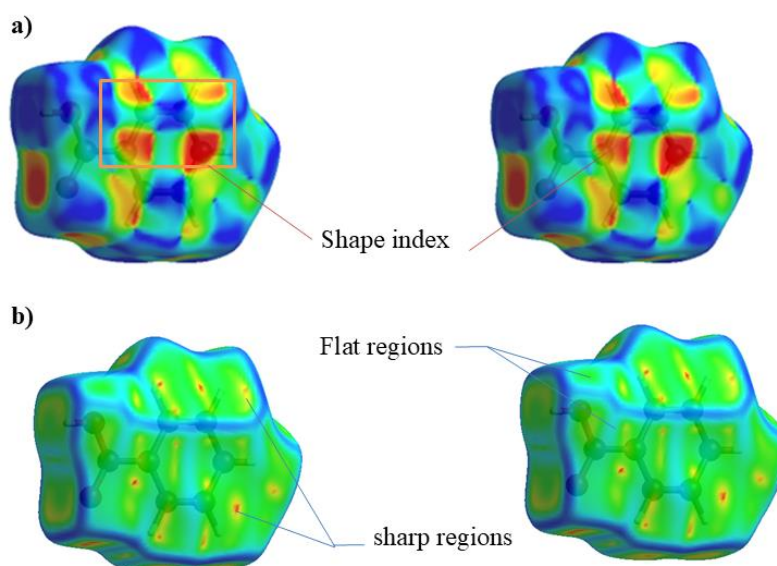


Figure II.9. a) Shape Index mapping on the 3D Hirshfeld surface, b) Curvedness surface map of benzoic acid molecule.

II.2.3.1.3. Fragment patch

Hirshfeld surface patch analysis, which is routinely used only by us, reverse maps how each neighboring molecule contacts a reference molecule. It creates distinct surface patches of interaction type and strength: large patches on benzoic acid for the strong O–H $\cdots$ O hydrogen bonds that stabilize the dimers, and smaller patches on the C–H $\cdots$ π and π – π stacking that are also present. The procedure is done using a triangulated Hirshfeld surface; the fraction of the surface points is plotted against the nearest distances to all nuclei inside and outside the surface, d_i and d_e . Therefore, all possible interaction types are distinguished by this method, including hydrogen bonds, close and distant van der Waals contacts, C–H $\cdots$ π , and π – π stacking interactions. This way, the method quantitatively and visually classifies distinctly molecular crystals by interaction character, enabling easy distinction of similarities and differences that crystal-packing diagrams can obscure (Figure II.10).

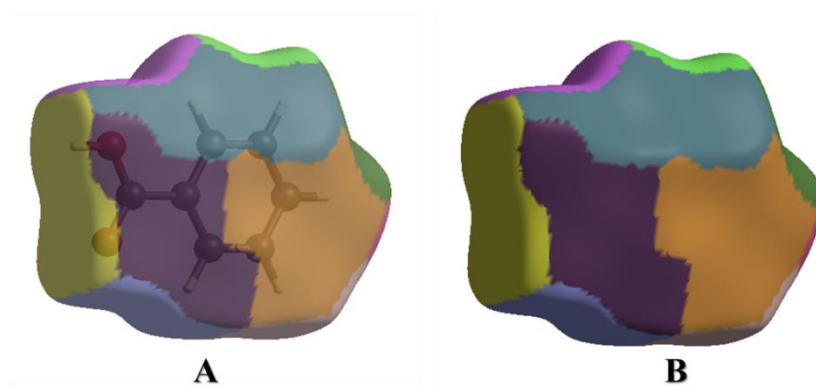


Figure II.10. 3D views of fragment patch maps of the benzoic acid molecule as well as (a) enable visualization and (b) disable visualization.

II.2.3.2. The 2D-fingerprint of the Hirshfeld surface

Two-dimensional fingerprint plots are used to describe and summarize the contributions of both weak and strong close contacts. These include van der Waals forces, C $\cdots$ C interactions, hydrogen bonding, and halogen bonding, which are identified in the molecular structure based on the internal (d_i) and external (d_e) distances from the same point on the Hirshfeld surface to neighboring atoms of the molecule (Figure II.11) [17].

We used CrystalExplorer, version 17.1, to map and visualize the Hirshfeld surfaces of all synthesized complexes. Several models of the Hirshfeld surface were obtained from the isosurfaces of promolecule electron density in the forms of d_{norm} , shape index, curvedness, and fragment patch surfaces. Moreover, 2D fingerprint plots were used as summary plots to collect

information about the character and types of close intermolecular contacts in the crystal structures, based on the pairs of d_e and d_i distance parameters. The details concerning intermolecular interactions with the nearest ghost atomic fragments in the crystal lattice are included in the relevant Crystallographic Information File (CIF) data.

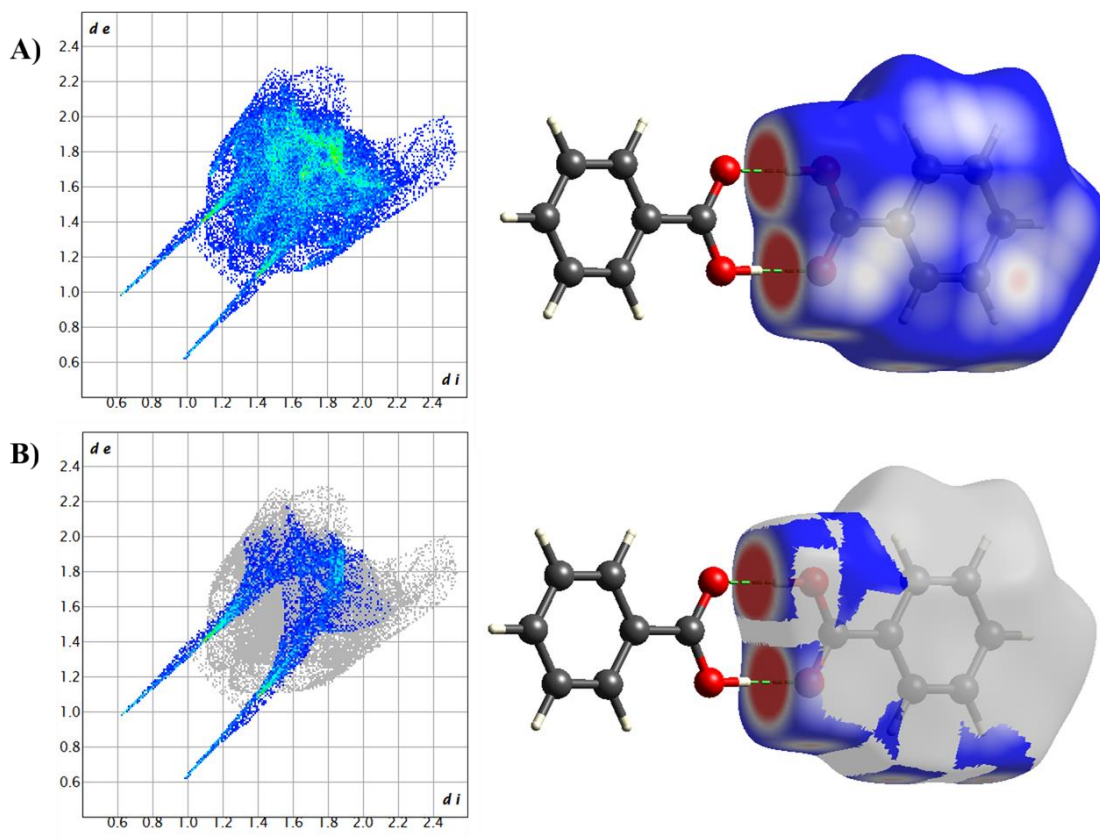


Figure II.11. a) 2D fingerprint plotting of the Hirshfeld surface of the complex showing all contacts. b) 2D fingerprint plotting of O-H/H-O contacts with surface visualization of benzoic acid.

II.2.3.3. Void surface

The void area approach (Figure II.12) has garnered much attention from crystallographers for its potential to observe and evaluate voids that exist within the packing of crystals. Three-dimensional void mapping based on pro-crystal iso-surfaces can predict the mechanical attributes of the crystal packing [18]. Intermolecular voids are the result of regions of low electron density within the molecule [19]. CrystalExplorer software was used to determine the void volume, except the percent of void volume was calculated by the equation below:

$$\text{Void\%} = \frac{\text{Void volume}}{\text{Total volume}} \times 100$$

46

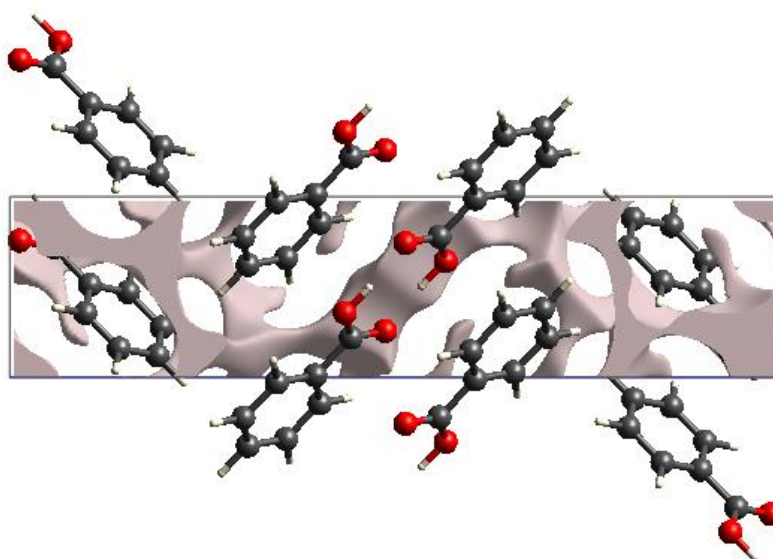


Figure II.12. Visualization of crystal void along a-axis of packing crystal of benzoic acid.

II.2.4. Single-Crystal X-Ray Diffraction (SXRD)

X-ray diffraction is an experimental technique used to investigate a crystalline sample. The experiment's principle involves directing a beam of X-rays (usually monochromatic) at a crystal and measuring the intensity of the X-rays that are diffracted by it. The wavelength of X-rays is comparable to the distances between atoms, which allows for the possibility of obtaining structural information on the studied compounds. When an X-ray beam impinges on the crystal, electrons in the crystal begin to oscillate and are subsequently accelerated. Each electron emits electromagnetic waves of the same energy as a result of being accelerated. The electromagnetic (EM) waves then interfere with one another constructively or destructively. As a repeating unit the atoms in the crystal are arranged and the transmitted rays emerge from the crystal in a particular direction and with an increased intensity. Using Bragg's law (Figure II.13), one can describe when rays will be diffracted at a set angle off the incident ray [20-22]. As followed by the equation below:

$$n\lambda = 2d \sin (\theta)$$

Where:

n: The order of diffraction (an integer, 1, 2, 3...).

λ : Wavelength of the incident X-ray.

d : The distance between adjacent lattice planes.

θ : Bragg angle (angle between incident beam and crystal plane).

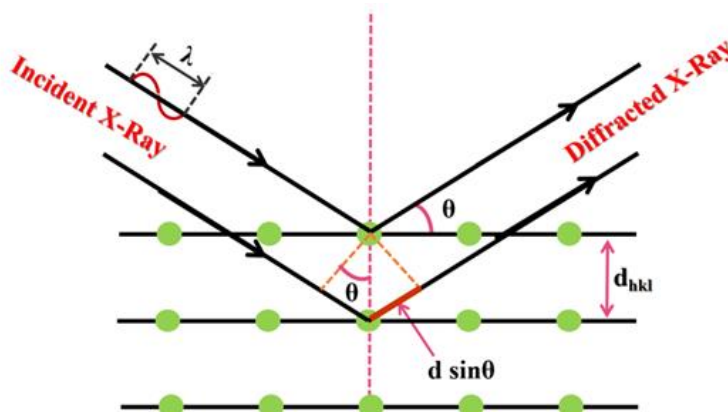


Figure II.13. Schematic representation of Bragg's Law.

In our efforts to reduce impurities, high-purity single crystals of the synthesized compounds were cautiously chosen. Data was acquired on two unique diffractometers: a 4-circle XCalibur diffractometer with an Eos detector and monochromatic graphite $\text{MoK}\alpha$ radiation ($\lambda=0.71073$ Å) in 35160 Buca, İzmir, Turkey, at Dokuz Eylul University. Lastly, we used a RIGAKU XtaLAB Synergy-S diffractometer with a HyPix-6000HE detector and a $\text{CuK}\alpha$ radiation source ($\lambda=1.54184$ Å) in Italy. The crystal structures of the metal-organic complexes were solved using SHELXT and SHELXL software (2018 version) using Charge Flipping, respectively. All non-hydrogen atoms were refined anisotropically, and hydrogen atoms were located and refined with isotropic displacement parameters, deduced from electron density difference maps. Structural parameters, the data collection parameters, and the crystallographic information files (CIFs) were processed in Olex2 (versions 1.5 and 1.3) and the multi-scan absorption corrections were applied. Molecular graphics and structure visualization were performed in Mercury software.



Figure II.14. Difractometer Synergy-S at Degli Studi di Milano University, Italy.

II.2.5. Density Functional Theory (DFT) Calculations

Hohenberg, Kohn, and Sham initiated the use of quantum mechanical calculations with the introduction of density functional theory (DFT) calculations in 1964 and 1965 [23, 24]. The DFT approach is used to study the electronic structure and properties of atoms, molecules, and crystalline systems by calculating the electronic structures based on electron density versus a wave function. DFT methods are based on two theorems: the Hohenberg-Kohn theorem states the wave function of a system is uniquely defined by ground-state electron density, and the Kohn-Sham theorem dedicates total energy to be a functional of electron density or that total energy can be decomposed into contributions of kinetic, electrostatic, and exchange-correlation. On the other hand, changes to the electron density cause changes to the energy of the electronic system. The ground-state electron density is obtained by lowering the total energy. From the quantum chemical perspective, DFT provides a computationally feasible method to circumvent the complexity of the Schrödinger equation since it obtains the energy of multi-electron systems in terms of electron density in which electron-electron interactions are incorporated. The Schrödinger equation can be written as follows [25]:

$$\mathbf{H} \Psi = \mathbf{E} \Psi$$

Where:

H: The Hamiltonian operator.

Ψ: The wave function.

E: Represent the energy of the system.

With this Density Functional Theory (DFT) tool, you can tweak the geometry of your molecules and check out the HOMO-LUMO energy calculated using Gaussian software [26]. Really, it just shows you the energy difference between those two orbitals in three dimensions. HOMO is the highest one that's filled, while LUMO is the lowest that's empty. When that gap ($\Delta E = E_{\text{LUMO}} - E_{\text{HOMO}}$) shrinks, the molecule gets more reactive and less stable, especially if it's pretty polar. The electrophilicity index (ω) signifies the electrophilic reactivity, electronegativity (χ), chemical potential (μ), and chemical hardness or electronic stability of molecular structures and can be calculated from the energies of orbitals [27, 28].

II.2.6. Molecular Electrostatic Potential (MEP)

The Molecular Electrostatic Potential (MEP) surface analysis is a computational approach that enables estimating the reactivity and selectivity of molecule receptors to electrophilic and nucleophilic attacks through predicting the active sites in molecular structures using several programs, the most commonly used being the MolView software [29]. Furthermore, the MEP tool can visualize accurately the charge of anions, specifically in metal-organic complexes, and illustrate the distribution of electron density within three-dimensional molecules.

This tool highlights the regions that enable the determination of the electrophilic and nucleophilic attack sites using the color coding appearing in the MEP maps. Respectively, the electrophilic attack sites showcased by negative zones with red and yellow colors and the nucleophilic attack represented by cyan and blue colors are positive zones. Lastly, the green area illustrates the zero potential in molecular structures [30]. According to the following equation, the MEP value is calculated:

$$V(\vec{r}) = - \int \frac{\rho(\vec{r})}{|\vec{r} - \vec{r}'|} d\vec{r}' + \sum_{\alpha=1}^N \frac{Z_{\alpha}}{|\vec{R}_{\alpha} - \vec{r}|}$$

Where:

$V(\vec{r})$: The molecule electrostatic potential.

Z_α : The nuclear charge of nucleus α attributed to $\vec{R}_\alpha$, $\vec{R}_\alpha$ denote the position of nucleus.

$\rho(\vec{r})$: The electronic density function of the molecule at point $\vec{r}$.

II.2.7. Computational ELF and LOL Study

Electron Localization Function (ELF) provides a quantum chemical means of evaluating and then visualizing localization of electrons and its distribution throughout solids and molecules with specific emphasis on which pairs of electrons are localized in bonds that contribute to the local chemical bonding. ELF diagnostics were introduced in 1990 by Becke and Edgecombe [31] and represent a comparative measure of the kinetic energy density of localized pairs of electrons in a system to the density of a reference homogeneous electron gas. On the other hand, the LOL approach is similar to ELF but more interested in visualizing the localization of orbitals that are maximized during overlap in molecular space. The ELF and LOL range from 0 to 1, where values near to one for the Electron Localization Function correspond to stronger localization and values closer to 0 correspond to delocalized or free electrons, whether in metallic bonds or in non-bonding electrons. Especially, the strong orbital localization is reflected by a value close to 1 for the Localized Orbital Locator.

We calculate ELF and ELF (see Figure II.15) by using electron density functions and related kinetic energy densities. The ELF approach lets us map out exactly where electrons gather in a molecule.

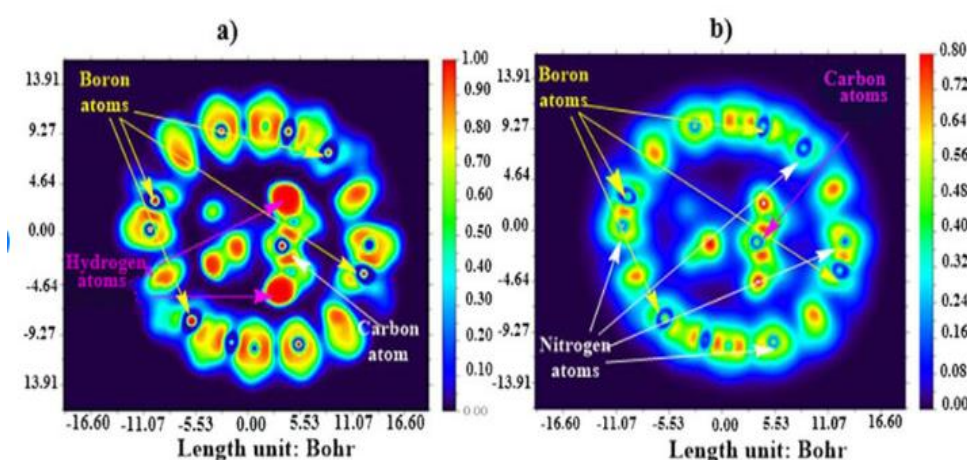


Figure II.15. Example representation of Electron Localisation Function (a) and Localisation Orbital Locator (b).

II.2.8. Reduced Density Gradient (NCI-RDG)

The reduced density gradient is an analytical approach used to distinguish and visualize non-covalent interactions (NCIs), such as van der Waals forces, steric repulsion, H-bonds, and π - π interactions across molecular structures. This theoretical technique, RDG, is based on the electron density and the associated gradient that is plotted using the Multiwfn or VMD software [32, 33]. Additionally, the RDG method enables the understanding of repulsive and attractive interactions within chemical systems. In this context, this RDG plot plays a crucial role in explaining the reactivity by highlighting the weak force contacts and determining the stability in metal-organic complexes. The interpretation of the reduced density gradient, achieved by color coding of isosurfaces resulting from the sign (λ_2) second eigenvalue function, is that the blue areas with negative λ_2 value indicate bonding interactions, and also the red positive λ_2 value zones reveal non-bonding contacts present in molecular systems.

II.2.9. Molecular docking

Molecular modeling is an essential approach in computational chemistry that involves visualizing and understanding the three-dimensional structure of molecules, creating models, and estimating chemical phenomena by comprehending the parameters of compounds. Additionally, it facilitates the studying and explication of the experimental procedures in chemistry. Molecular modeling is like a bridge between theoretical and experimental scientific research in various domains of biological and pharmaceutical sciences and medicinal chemistry [34]. On the other hand, this computational tool is used to efficiently prepare 3D models of proteins and ligands for molecular docking by calculation, minimize energy, remove a water molecule, and add hydrogen atoms using AutoDock tools and Open Babel software approaches [35].

Molecular docking is a modeling method widely utilized to predict the binding sites of the stable ligand-macromolecule complexes. While molecular docking explains how tiny molecules (ligands) fit a given target receptor, such as proteins, this informatic approach is used to resolve chemical problems by means of the lock-and-key mode concept. The objective of Molecular docking is to describe the selectivity of molecular interactions at natural protein target sites with an organic, metal-organic, or inorganic small molecule in a cell [36]. In drug discovery, this modeling tool has led to access to modern strategies that have increased the production of effective biologically active drugs, including antibiotics, antifungals [37],

analgesics, anticancer drugs, antimalarials, and antispasmodics [38]. The Protein Data Bank (PDB) serves as a global library for protein and nucleic acid structures, while chemical databases like the Cambridge Structural Database (CSD) or PepChem let scientists grab or build 3D models of ligands, sometimes with the help of software like Arguslab or ChemDraw.

II.2.9.1. Principle of Molecular Docking

Molecular docking employs a search algorithm to identify the best structural complementarity between a receptor and its ligand. Essentially, it examines the shape of the molecule and then adjusts the shapes within the binding pocket to find a position of lowest energy. Subsequently, to identify the position of lowest energy, various scoring functions, such as force field-based, empirical, knowledge-based, or consensus scoring, are run. Each scoring function aims to inform the researcher about the best binding position.

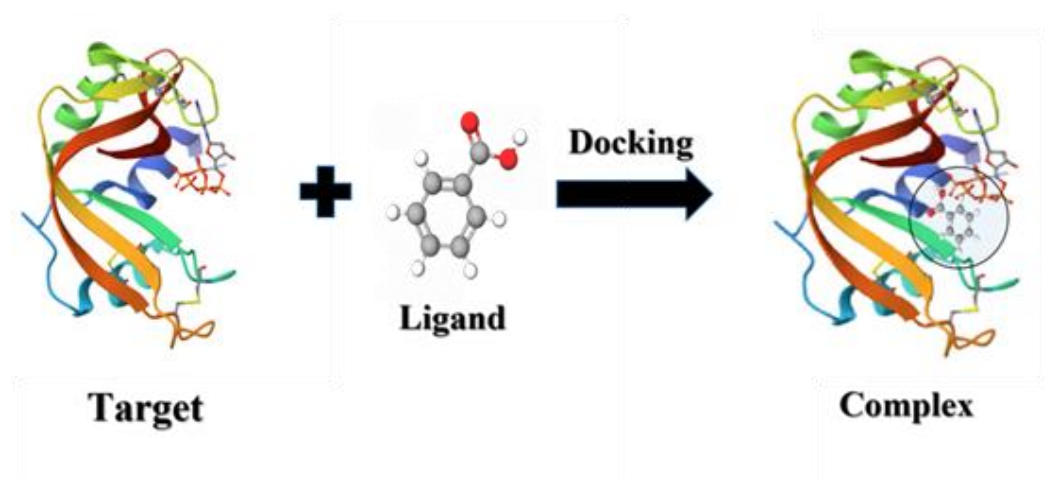


Figure II.16. Illustration of the general lock-and-key concept that underlies molecular docking.

II.2.9.2. Types of Molecular Docking techniques

Molecular docking techniques are primarily classified based on their molecular flexibility and types of receptors and small molecular types used. Two general approaches are typically referred to in the literature [39]; the first classification is based on the nature of the interacting molecules that is, the type of interaction between these receptors and ligands, which is subsequently classified into protein-ligand docking and protein-protein docking types. The second classification levels totally focus on the flexibility of the molecules which, can be divided into three main categories as follows:

- **Rigid Docking:** In rigid docking, both the ligand and the receptor are viewed as completely rigid. The ligand can be optimally located in the receptor's binding cavity for fast calculations and easy assessment of binding interactions.
- **Semi-Flexible Docking:** In semi-flexible docking, the ligand can change its conformation to generate a suitable complex in the active site of the receptor while obtaining minimal energy. The receptor, on the other hand, remains rigid. Semi-flexible docking has garnered popularity with most docking programs (e.g., GOLD) due to a clear trade-off between computational time and accuracy.
- **Fully-Flexible Docking:** In fully-flexible docking, the ligand and some of the amino acid side chains from the active site of the receptor are allowed to move and change their conformation. Fully-flexible docking allows the system to reach more accurate and stable low-energy structures that are more comparable to biological conditions.

In this work, molecular docking studies were performed for all synthesized coordination complexes, by which their complexation with selected protein targets could be elucidated, using Molegro Virtual Docker (MVD) 2019.7.0 software. Protein-ligand (protein-tin complex) interactions were visualized with PyMOL 1.9.0.0 and Discovery Studio Visualizer 2024 software. The three-dimensional (3D) structure of the target macromolecule (protein) was obtained from the website <http://www.rcsb.org/pdb>, where the structure is in .pdb format in the Protein Data Bank (PDB). The 3D structure of the ligands was built with ChemDraw 3D software and was energy minimized prior to docking. Docking results were also validated and evaluated with the MolDock Scoring Function used in the MVD software.

II.2.10. In vitro activity

In vitro tests happen in the lab, not in a living body, like in Petri dishes, test tubes, and that sort of thing. Scientists use these setups to work with cells, tissues, or even tiny organisms they've taken from animals or people. But here's the catch: just because something works in a dish doesn't mean it'll work in a real, living body. So, scientists always need to follow up with in vivo studies to see if those early results actually hold up. Lately, researchers have turned to *in vitro* studies to examine microorganisms. However, these setups miss out on the real back-and-forth and competition between microbes that actually occurs inside the human body. As a result, people have overlooked the connection between microbes and chronic diseases. Additionally, most of what we know about how pathogens trigger disease comes from experiments with microbes that are already well-known and easy to grow, excluding many other

microorganisms from the scope of research.

II.2.10.1. Antibacterial activity

The emergence and spread of infectious diseases remain a serious threat to public health, and microorganisms are the principal drivers of such health problems in humans and animals. Infectious agents can be categorized as fungi, bacteria, viruses, and parasites. Antibacterial activity refers to the ability of a compound to kill or inhibit the growth of bacteria. Such active agents must be reasonably non-toxic to adjacent healthy cells and tissues [40].

Recent advances have introduced new techniques for evaluating antimicrobial activity; however, classical methods techniques remain widely used for testing bacteria and fungi. The antimicrobial assessment methods developed in the 1960's provided researchers with rapid, simple approaches for evaluating plant extracts and pure compounds [41]. These methods are based on the diffusion of antimicrobial compound through solid or semi-solid culture media, following by the observation of microbial growth inhibition (Figure II.17). The disk diffusion and dilution assays are the most techniques used in many studies. Although these methods were developed to overcome limitations such as slow response, low sensitivity, or variability. The disk diffusion method sticks around for its simplicity, reliability and accessibility in most laboratories.

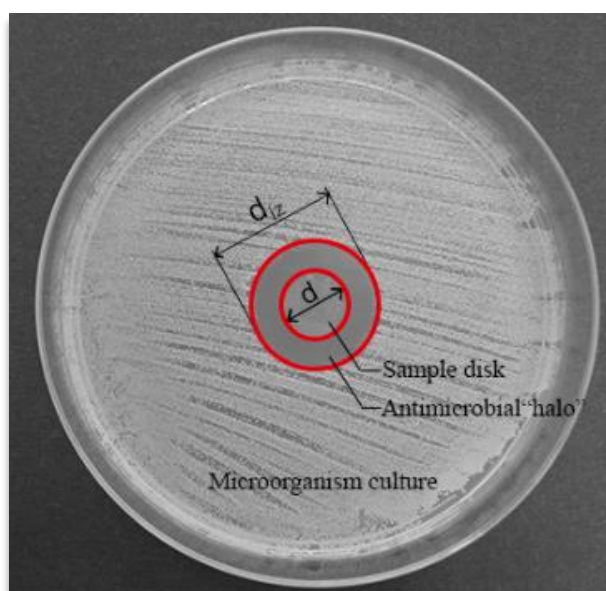


Figure II.17. Principle of disc method (bacterial activity).

II.2.10.2. Antioxidant activity

Antioxidant capacity (AC) is typically measured by a combination of complementary methods due to the wide variety of antioxidant compounds, their mechanisms of action, and the radical species involved. Antioxidant molecules can donate electrons and hydrogen atoms (H), which are transferred to neutralize the free radicals. The antioxidant can "prevent" the oxidation of other chemicals by undergoing oxidation themselves and are stabilized through mesomerism (delocalization of the unpaired electron). Based on the type of chemical reaction involved, all approaches used to measure AC can be classified into two main classes: single electron transfer (SET)-based assays, hydrogen atom transfer (HAT)-based assays. Some tests may involve both mechanisms, however the dominant pathway depends on factors, such as properties of the antioxidant structure, solubility, partition coefficient and the nature of solvent in the system. Two critical factors that determine the mechanism and efficacy of antioxidants are bond dissociation energy and ionization potential (the minimum energy needed to remove an electron from an atom) [42, 43]. An antioxidant can behave under different mechanisms and can respond differently based on the radical source. SET methods assess the ability of an antioxidant (AH) to reduce a radical species (R[•]) through electron (e⁻) donation. Since the reactivity of SET methods is dependent on deprotonation (loss of H⁺ ions related to acidity) and the ionization potential of the antioxidant's functional group, this means that SET measurements are pH-dependent. In contrast, HAT methods evaluate the ability of an antioxidant (AH) to quench free radicals through hydrogen atom (H) donation. The reactivity of these methods is determined by the dissociation energy of the antioxidant's hydrogen bonds and is therefore less dependent on pH. The oxidation principles of SET and HAT methods are provided in according to the following mechanism:



(1): electron transfer antioxidant (ETA).

(2): proton transfer antioxidant (PTA).

R[•]: radical; **AH:** antioxidant.

The DPPH radical scavenging capacity (2,2-diphenyl-1-picrylhydrazyl) is a method developed by Blois [44]. In this assay, a synthetic DPPH[•] (purple in color) radical is reduced by an antioxidant (AH) that can either transfer a hydrogen atom or a singlet electron to stabilize it

in a reduced form (DPPH or DPPH-H), which is yellow in color and can be measured at 517 nm (see Figure II.18).

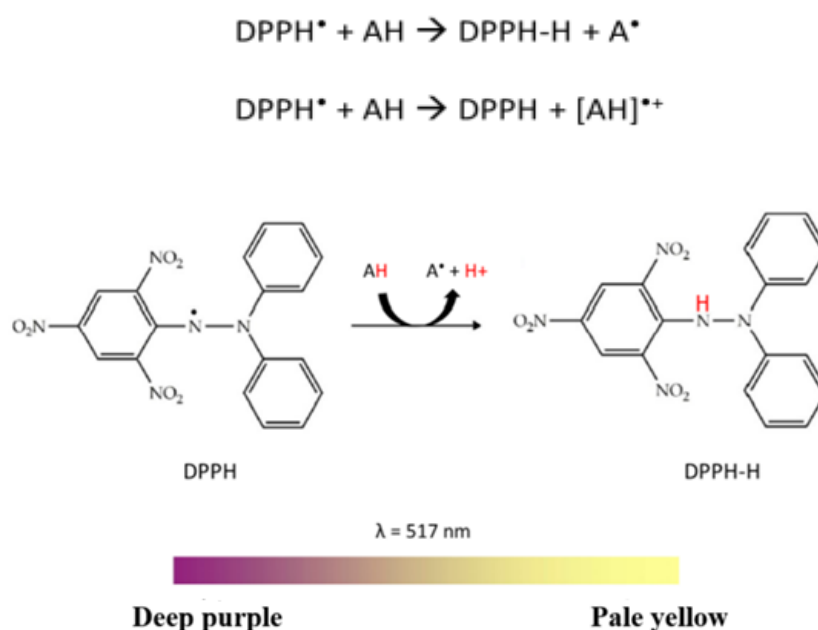


Figure II.18. Representation of Mechanism of the DPPH radical scavenging at 517 nm.

Part 2: Experimental Methods

1,10-Phenanthroline (1,10-phen) is among the most important bidentate ligands in coordination chemistry, particularly because it forms stable chelate complexes due to the two adjacent nitrogen donor atoms in its heteroaromatic ring system [45]. The stable, planar, and rigid nature of the ligand structure and strong π -acceptor character allow for strong complex stability with several transition metal ions [46]. Because of these properties, 1,10-phenanthroline has been extensively used in coordination chemistry, photophysical and electrochemical studies, and in the design of metal-based drugs and catalysts.

In this work, a series of coordination complexes (**C1-C6**) containing 1,10-phenanthroline and benzoic acid ligands were successfully synthesized and investigated. In the present study, the complexes **C1**, **C2**, and **C3** represent newly synthesized compounds prepared by a solution-based method, involving the reaction of divalent metal salts with 1,10-phenanthroline and benzoic acid in controlled stoichiometric ratios under reflux conditions. The synthesis was carried out in a mixed aqueous–ethanolic medium, and slow evaporation of the solution yielded

well-formed crystals suitable for structural characterization.

In this contrast, complexes **C4**, **C5**, and **C6** correspond to previously reported analogues in the literature, showing similar coordination environments around the central metal ion [47-51]. In all complexes, the metal centers are coordinated by the bidentate 1,10-phenanthroline ligand via the two nitrogen atoms (N, N') and by benzoate anions through oxygen atoms, leading to octahedral or slightly distorted octahedral geometries [52].

The stability of these complexes arises from the strong chelating ability of 1,10-phenanthroline and the carboxylate bridging function of benzoic acid, which together stabilize the metal center. The success of the synthetic procedure was confirmed by spectroscopic and crystallographic analyses, revealing consistent features within the series and confirming the novelty of **C1–C3** compared with the known compounds **C4–C6** Figure II.19.

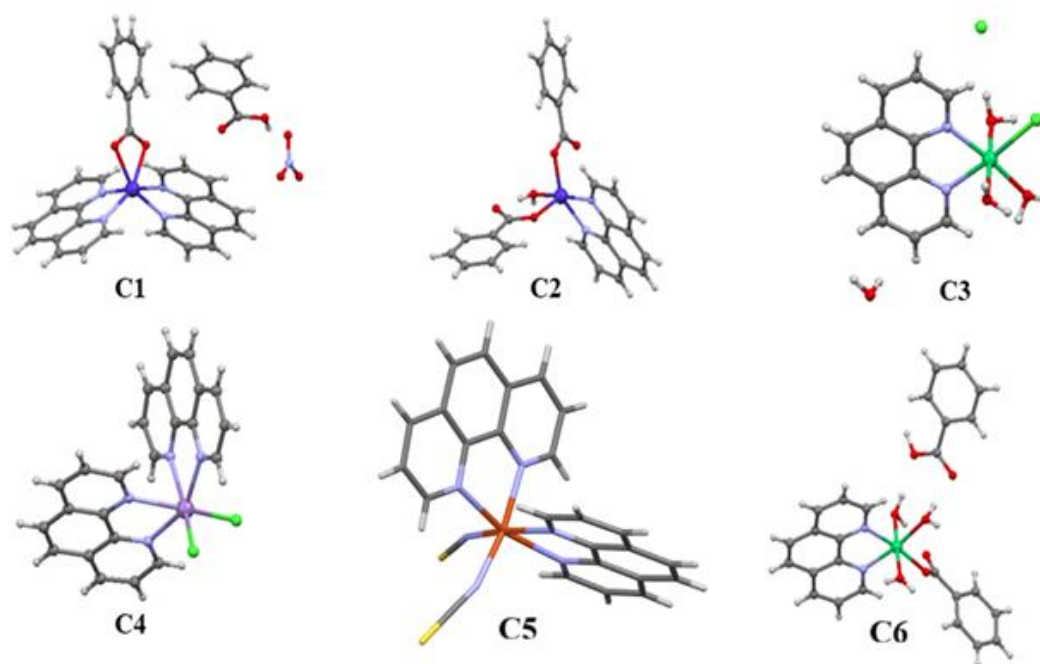
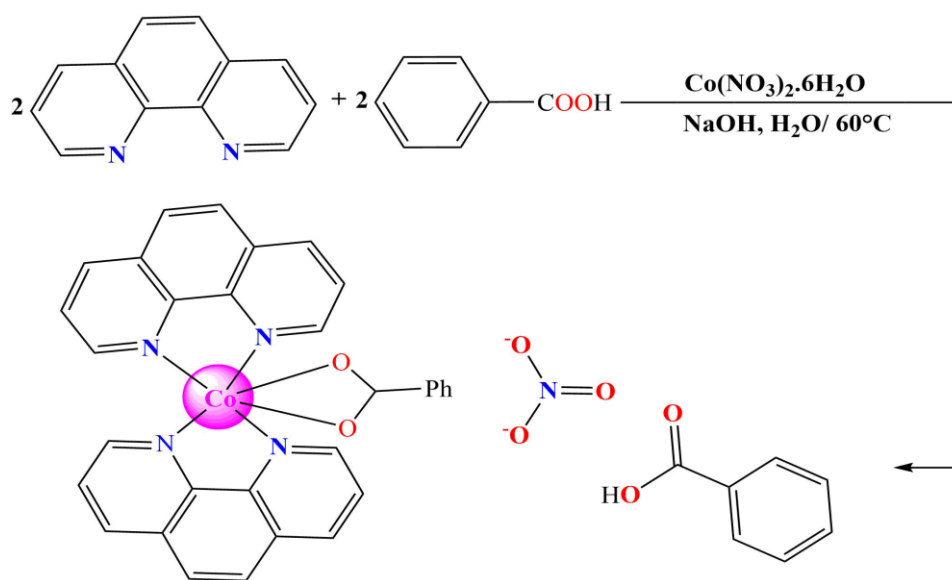


Figure II.19. Structural representation of the synthesized metal–phenanthroline (**C1–C6**) complexes.

II.3. Experimental Method for the Synthesis of Complexes

II.3.1. The synthesis of $[\text{Co}(\text{Phen})_2(\text{bz})] \cdot \text{bzH} \cdot \text{NO}_3$ complex (C1)

The brick red crystals were synthesized by mixing the benzoic acid (4.5 mmol, 0.55 g) and 0.2 g NaOH dissolved in 20 mL of distilled water with the metal salt $\text{Co}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ (2.4 mmol, 0.5 g) solubilized in 20 mL of distilled water, then agitated at room temperature for 1 h. To the mixture solution, 1,10 phenanthroline chloride monohydrate (2.4 mmol, 0.4 g) dissolved in 25 ml of ethanol was added and stirred at 60°C for 30 minutes. The solid crystals that formed with 80% yield after two days were rinsed with ethanol and then distilled water and dried in the air. Scheme 1 schematically shows the synthesis of the cobalt (II) complex.

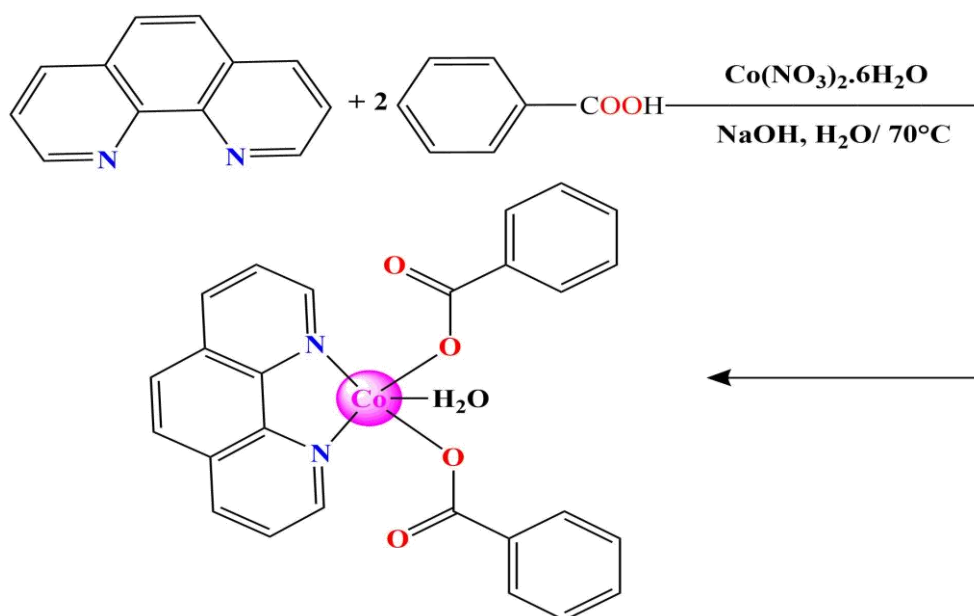


Scheme 1. Reaction pathway for the synthesis of the cobalt (II) complex $[\text{Co}(\text{Phen})_2(\text{bz})] \cdot \text{bzH} \cdot \text{NO}_3$ (C1).

II.3.2. The synthesis of $[\text{Co}(\text{Phen})(\text{bz})_2\text{H}_2\text{O}]$ complex (C2)

Single crystals of the $[\text{Co}(\text{Phen})(\text{bz})_2\text{H}_2\text{O}]$ were synthesized using the reflux method. The ethanolic solution (20 ml) of 1,10 phenanthroline chloride monohydrate (0.24 g, 1 mmol) and an aqueous solution (20 ml) of benzoic acid (0.24 g, 2 mmol) with (0.16g) NaOH were added to the solution of $\text{Co}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ (0.291 g, 1 mmol) in 20 ml of absolute ethanol. The mixture was magnetically stirred under reflux for two hours at 70°C . After reflux, the resulting solution was cooled to room temperature. Finally, the red distorted square-pyramidal single crystals were formed with 60 % yield after 2 months by removing excess filtrate with slow

evaporation. Then the crystals were washed with ethanol solvent several times and dried in the air. [Scheme 2](#) illustrates the synthesis of the cobalt (II) complex.

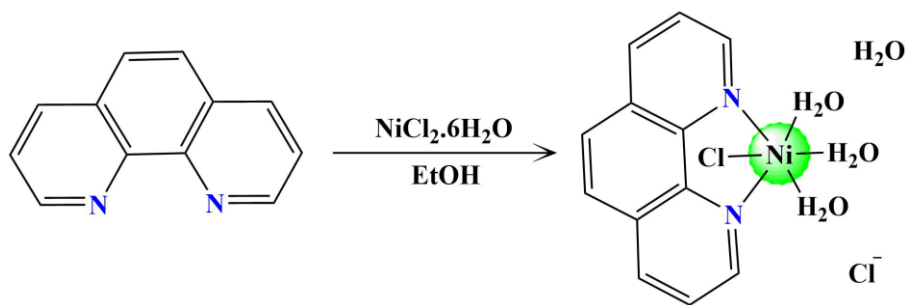


Scheme 2. Synthesis of the cobalt (II) complex [Co (phen- κ^2 N, N') (bz- κ O) $_2$ H $_2$ O] (**C2**).

The method of experimentation (synthetic method) is critical in identifying the nature of the complexes synthesized (**C1**, **C2**), even if the original starting materials are the same. Experimental conditions such as temperature, reaction time, evaporation of solvent, and crystallization method of the final product all will affect the stoichiometry, coordination geometry, and the crystalline form of the final product. Therefore, we can combine the same metal salts and ligands together to ultimately obtain a different complex, depending on the synthetic method (reflux, slow evaporation, diffusion, etc.) that was employed.

II.3.3. The synthesis of [Ni(Phen) (H $_2$ O) $_3$ Cl] · H $_2$ O · Cl complex (**C3**)

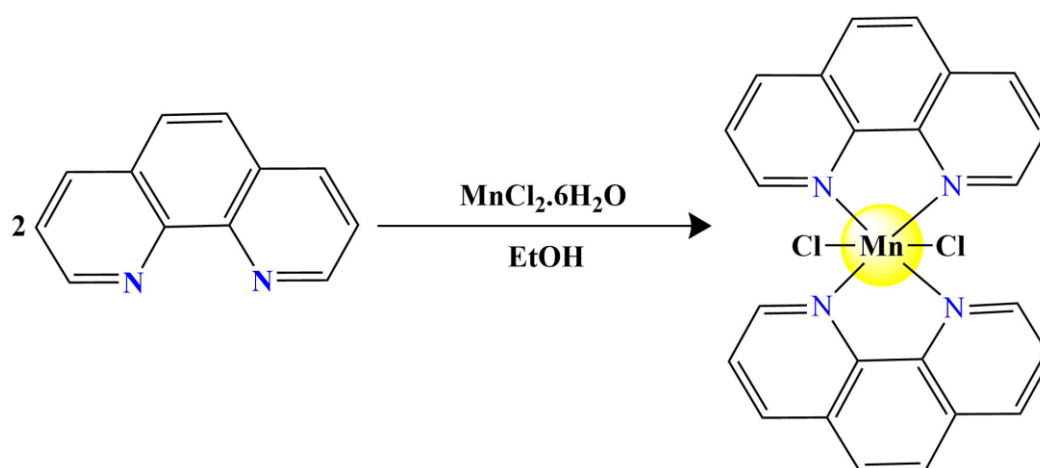
The solid crystals of [Ni (Phen) (H $_2$ O) $_3$ Cl] · H $_2$ O · Cl were synthesized by mixing the metal salt Ni (Cl) $_2$ · 6H $_2$ O (0.237 g, 1 mmol) and 1,10-phenanthroline chloride monohydrate (0.234 g, 1 mmol) in ethanol (25 mL), and the resulting solution was mechanically agitated at room temperature for 3 hrs. The blue stable crystals were formed with an 80% yield after a few weeks, which were collected and then washed with ethanol and air-dried. [Scheme 3](#) illustratively shows the synthesis of the nickel (II) complex.



Scheme 3. Detailed reaction showing the synthesis of the nickel (II) complex $[\text{Ni}(\text{phen})(\text{H}_2\text{O})_3\text{Cl}] \cdot \text{H}_2\text{O} \cdot \text{Cl}$ (C3).

II.3.4. The synthesis of $[\text{Mn}(\text{Phen})_2(\text{Cl})_2]$ complex (C4)

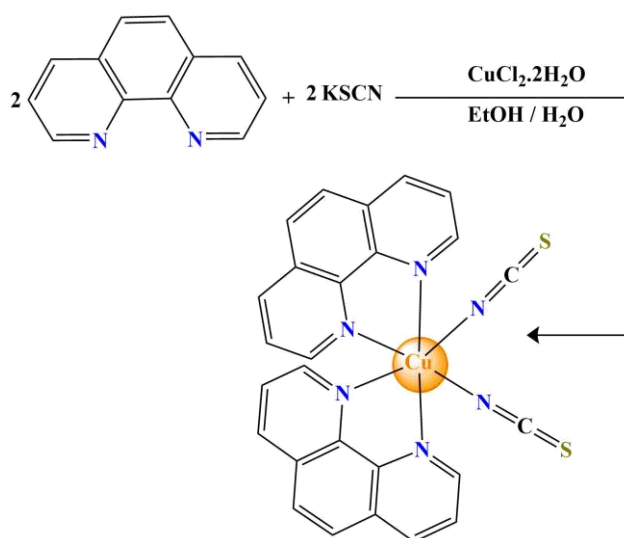
The complex dichloro-bis (1,10-phenanthroline-N, N') manganese(II) was prepared with few modifications to the report procedure by adding 25 mL of ethanolic solution of 1,10 phenanthroline chloride monohydrate (0.468 g, 2 mmol) ligand to metal salt $\text{MnCl}_2 \cdot 6\text{H}_2\text{O}$ (0.233 g, 1 mmol) in 20 ml ethanol under continuous stirring at laboratory temperature for 3 hours. A yellow-colored precipitate formed of the compound with 80% yield. It was isolated by filtration, then rinsed with ethanol several times, followed by distilled water washing. The final product was dried air. while the solid complex was dissolved in DMSO solvent to obtain suitable single crystals for X-ray analysis through slow evaporation after more than two months. The synthesis of the manganese (II) complex as presented in Scheme 4.



Scheme 4. Reaction mechanism through synthesis of manganese (II) complex $[\text{Mn}(\text{Phen})_2(\text{Cl})_2]$ (C4).

II.3.5. The synthesis of [Cu (Phen)₂(NCS)₂] complex (C5)

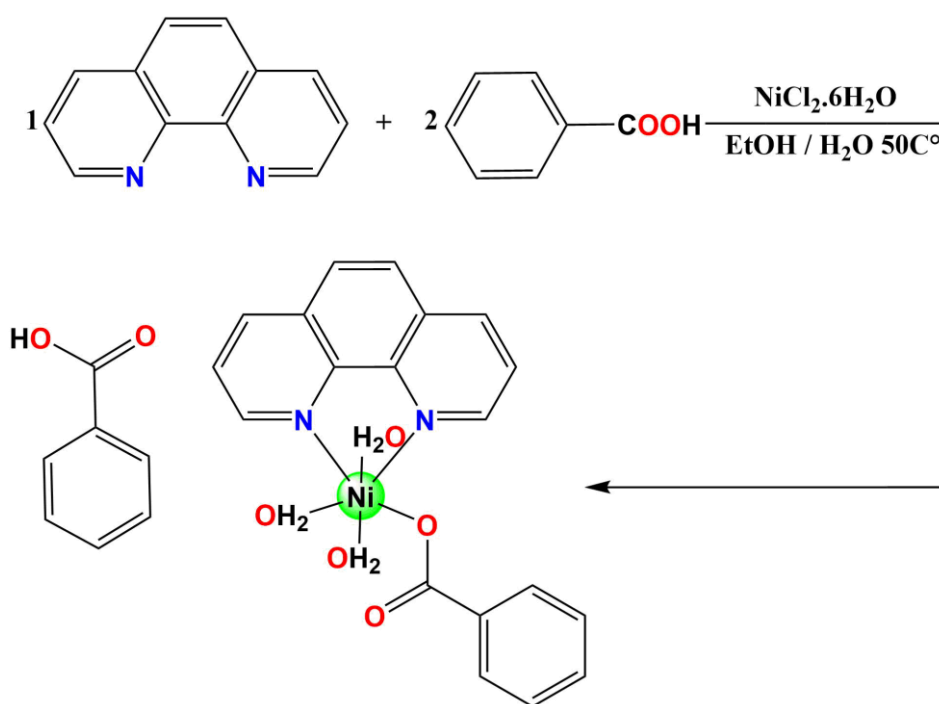
According to the literature, with a modified procedure method, a mixed ligand complex diisothiocyanato bis (1,10-phenanthroline-κ²N, N') copper (II) was synthesized by mixing the solution of 1,10 phenanthroline (0.468 g, 2 mmol) in ethanol (50 ml) with a magnetically agitated ethanolic solution (10 ml) of metal salt CuCl₂·2H₂O (0.17 g, 1 mmol). The resulting mixture was agitated for one hour at laboratory temperature. Then the aqueous solution of KSCN (1.94 g, 2 mmol) was added with continuous stirring for 2 hours. Therefore, the solid complex was formed and washed with distilled water, then air-dried. It was then dissolved in DMSO to form stable green crystals for X-ray analysis with 50% yield through the slow evaporation method of solvent over two months. Scheme 5 presents the reaction pathway of a copper (II) complex.



Scheme 5. Synthesis of copper (II) complex [Cu (Phen)₂(NCS)₂] (C5).

II.3.6. The synthesis of [Ni (Phen)(bz) (H₂O)₃. bzH] complex (C6)

The green prism crystals of the [Ni (Phen)(bz) (H₂O)₃. bzH] complex was synthesized by mixing the benzoic acid (0.24 g, 2 mmol) and 0.16 g of NaOH dissolved in 20 mL of warm distilled water with the metal salt Ni (Cl)₂·6H₂O (0.24 g, 1 mmol) solubilized in 20 mL of water. The resulting solution was agitated at 50°C for 1 h. Then the ethanolic solution (25 ml) of 1,10 phenanthroline chloride monohydrate (0.234 g, 1 mmol) was added with continuous stirring for 30 min. The suitable crystals for X-ray analysis formed with 87% yield after 24 days, then were washed with ethanol three times and dried in the air. Scheme 6 schematically illustrates the synthesis of the nickel (II) complex.



Scheme 6. Detailed reaction showing the synthesis of $[\text{Ni}(\text{Phen})(\text{bz})(\text{H}_2\text{O})_3]$. bzH complex (C6).

II.4. Conclusion

This chapter dives into the main experimental and theoretical tools researchers use to study metal-organic complexes. The details of the crystal structures were determined by single-crystal X-ray diffraction (SCXRD). In this work we explain the principles of each technique to characterize and identify molecular structures as well as their reactivity and stability in three-dimensional systems. The cooperation between these modern methods contributes to advancements in identifying the psycho-chemical parameters of organic, inorganic, and metal complex materials, as well as improvements in drug discovery and its effective manufacturing mechanisms.

References

- [1] Vollmer, M. (2013). Infrared. *European Journal of Physics*, 34(6), S49.
- [2] Helburn, R., Nolan, K. (2022). Characterizing biological macromolecules with attenuated total reflectance–Fourier transform infrared spectroscopy provides hands-on spectroscopy experiences for undergraduates. *Biochemistry and Molecular Biology Education*, 50(4), 381-392.
- [3] Takouachet, R. Hybrid compounds and amine-based organometallic (Doctoral dissertation, University of Khenchela-Abbas Laghrour).
- [4] Akram, D. A. (2023). Synthesis, Structural Characterization, and Biological activities of new transition metal-based complexes (Doctoral dissertation, University of Khenchela-Abbas Laghrour).
- [5] Berthomieu, C., Hienerwadel, R. (2009). Fourier transform infrared (FTIR) spectroscopy. *Photosynthesis research*, 101(2), 157-170.
- [6] Paiva, E. M., Hyttinen, E., Dönsberg, T., Barth, D. (2025). Biological contaminants analysis in microalgae culture by UV–vis spectroscopy and machine learning. *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy*, 330, 125690.
- [7] Maurice, A. A., Quintero, A. E., Vera, M. (2024). A comprehensive guide for measuring total vanadium concentration and state of charge of vanadium electrolytes using UV–Visible spectroscopy. *Electrochimica Acta*, 482, 144003.
- [8] Capocasa, G., Sessa, F., Tavani, F., Monte, M., Olivo, G., Pascarelli, S., D’Angelo, P. (2019). Coupled x-ray absorption/uv–vis monitoring of fast oxidation reactions involving a nonheme iron–oxo complex. *Journal of the American Chemical Society*, 141(6), 2299-2304.
- [9] Singhal, A., Saini, U., Chopra, B., Dhingra, A. K., Jain, A., Chaudhary, J. (2024). Uv-visible spectroscopy: a review on its pharmaceutical and bio-allied sciences applications. *Current Pharmaceutical Analysis*, 20(3), 161-177.
- [10] Ghosh, S., & Nandi, S. (2024). A Comprehensive Review on UV-Visible Spectroscopy and Its application. *Int. J. All Res. Education Sci. Methods*, 12, 1501-1507.
- [11] Patel, S., Raulji, A., Patel, D., Panchal, D., Dalwadi, M., Upadhyay, U. (2022). A review on UV visible spectroscopy. *Int. J. Pharm. Res. Appl*, 7(10), 1144-1151.
- [12] Oshina, I., Spigulis, J. (2021). Beer–Lambert law for optical tissue diagnostics: current state of the art and the main limitations. *Journal of biomedical optics*, 26(10), 100901-100901.

- [13] Wathudura, P., Pham, H., Siriwardana, K., Athukorale, S., Jayasundara, U., Gunatilake, S. R., Zhang, D. (2025). Expanding the Horizons of UV–vis Spectroscopy Education: Beyond the Beer–Lambert Law. *Journal of Chemical Education*, 102(6), 2389-2397.
- [14] Spackman, P. R., Turner, M. J., McKinnon, J. J., Wolff, S. K., Grimwood, D. J., Jayatilaka, D., Spackman, M. A. (2021). CrystalExplorer: a program for Hirshfeld surface analysis, visualization and quantitative analysis of molecular crystals. *Applied Crystallography*, 54(3), 1006-1011.
- [15] Spackman, M. A., Jayatilaka, D. (2009). Hirshfeld surface analysis. *CrystEngComm*, 11(1), 19-32.
- [16] Tan, S. L., Jotani, M. M., Tiekink, E. R. (2019). Utilizing Hirshfeld surface calculations, non-covalent interaction (NCI) plots and the calculation of interaction energies in the analysis of molecular packing. *Structure Reports*, 75(3), 308-318.
- [17] Jelsch, C., Ejsmont, K., Huder, L. The enrichment ratio of atomic contacts in crystals, an indicator derived from the Hirshfeld surface analysis. *IUCrJ*, 2014, 1 (2), 119-128.
- [18] Turner, M. J., McKinnon, J. J., Jayatilaka, D., Spackman, M. A. (2011). Visualisation and characterisation of voids in crystalline materials. *CrystEngComm*, 13(6), 1804-1813.
- [19] Ouakkaf, A. (2017). New hybrid compounds synthesis and structural study by X-ray diffraction.
- [20] Bragg, W. H., Bragg, W. L. (1913). The reflection of X-rays by crystals. *Proceedings of the Royal Society of London. Series A, Containing Papers of a Mathematical and Physical Character*, 88(605), 428-438.
- [21] Ahmed, M. (2012). Ultra high-resolution crystallography of small molecules and proteins (Doctoral dissertation, Université de Lorraine).
- [22] Benali-Cherif, R. (2014). *Polymorphism, structural analysis, and optical properties of semi-organic compounds based on amino acids* (Doctoral dissertation, University of Khenchela).
- [23] Hohenberg, P., Kohn, W. (1964). Inhomogeneous electron gas. *Physical review*, 136(3B), B864.
- [24] Kohn, W., Sham, L. J. (1965). Self-consistent equations including exchange and correlation effects. *Physical review*, 140(4A), A1133.
- [25] Schrödinger, E., Works, C. (1926). SCHRÖDINGER 1926C. *Annalen der Physik*, 79, 734.
- [26] Frisch, M. J. E. A. (2009). gaussian 09, Revision d. 01, Gaussian. Inc, Wallingford CT, 201.

- [27] Chaudhary, M. K., Srivastava, A., Singh, K. K., Tandon, P., Joshi, B. D. (2020). Computational evaluation on molecular stability, reactivity, and drug potential of frovatriptan from DFT and molecular docking approach. *Computational and Theoretical Chemistry*, 1191, 113031.
- [28] Parr, R. G., Szentpály, L. V., Liu, S. (1999). Electrophilicity index. *Journal of the American Chemical Society*, 121(9), 1922-1924.
- [29] Lakshminarayanan, S., Jeyasingh, V., Murugesan, K., Selvapalam, N., Dass, G. (2021). Molecular electrostatic potential (MEP) surface analysis of chemo sensors: An extra supporting hand for strength, selectivity & non-traditional interactions. *Journal of Photochemistry and Photobiology*, 6, 100022.
- [30] Tiéba, T. N., Charles, K. K., Stéphane, D. G., Bibata, K., Doh, S., Guillaume, K. C., Nahossé, Z. (2023). Theoretical Study of Reactivity and Stability of a Thiazine Derivative Series by the Density Functional Theory (DFT) Method. *Journal of Materials*, 11(1), 1-7.
- [31] Becke, A. D., Edgecombe, K. E. (1990). A simple measure of electron localization in atomic and molecular systems. *The Journal of chemical physics*, 92(9), 5397-5403.
- [32] Lu, T., Chen, F. (2012). Multiwfn: A multifunctional wavefunction analyzer. *Journal of computational chemistry*, 33(5), 580-592.
- [33] Humphrey, W., Dalke, A., Schulten, K. (1996). VMD: visual molecular dynamics. *Journal of molecular graphics*, 14(1), 33-38.
- [34] Turner, M. J., McKinnon, J. J., Jayatilaka, D., Spackman, M. A. (2011). Visualisation and characterization of voids in crystalline materials. *CrystEngComm*, 13(6), 1804-1813.
- [35] Morrison, J. L., Breitling, R., Highamb, D. J., Gilberta, D. R. A Lock-and-Key Model for Protein-Protein Interactions-Supplementary Material. *Homo*, 2384(2866), 21.
- [36] Jagtap, M., Girnar, G., Ahuja, V. (2025). Computational Approaches to Molecular Docking and Protein Modeling in Drug Discovery. *Journal of Drug Delivery & Therapeutics*, 15(6).
- [37] Calderone, R., Sun, N., Gay-Andrieu, F., Groutas, W., Weerawarna, P., Prasad, S., Li, D. (2014). Antifungal drug discovery: the process and outcomes. *Future microbiology*, 9(6), 791-805.
- [38] Romero-Reyes, M., Arman, S., Teruel, A., Kumar, S., Hawkins, J., Akerman, S. (2023). Pharmacological management of orofacial pain. *Drugs*, 83(14), 1269-1292.
- [39] Butt, S. S., Badshah, Y., Shabbir, M., Rafiq, M. (2020). Molecular docking using chimera and autodock vina software for no bioinformaticians. *JMIR Bioinformatics and*

Biotechnology, 1(1), e14232.

[40] Nicholson, W. L., Munakata, N., Horneck, G., Melosh, H. J., Setlow, P. (2000). Resistance of *Bacillus* endospores to extreme terrestrial and extraterrestrial environments. *Microbiology and molecular biology reviews*, 64(3), 548-572.

[41] Ibrahim, D., Lee, C. C., Sheh-Hong, L. (2014). Antimicrobial activity of endophytic fungi isolated from *Swietenia macrophylla* leaves. *Natural product communications*, 9(2), 1934578X1400900229.

[42] Prior, R. L., Wu, X., Schaich, K. (2005). Standardized methods for the determination of antioxidant capacity and phenolics in foods and dietary supplements. *Journal of agricultural and food chemistry*, 53(10), 4290-4302.

[43] Huang, D., Ou, B., Prior, R. L. (2005). The chemistry behind antioxidant capacity assays. *Journal of agricultural and food chemistry*, 53(6), 1841-1856.

[44] Blois, M. S. (1958). Antioxidant determinations by the use of a stable free radical. *Nature*, 181(4617), 1199-1200.

[45] Zhang, Y., Qin, Y., Sun, Y., Liu, X., Wang, Z. (2024). Synthesis, characterization and anticorrosion performance of a new corrosion inhibitor based on cobalt-phenanthroline-p-hydroxybenzoic acid ternary complex. *Materials Today Communications*, 41, 110362.

[46] Eni, D. B., Yufanyi, D. M., Nono, J. H., Tabong, C. D., Agwara, M. O. (2020). Synthesis, characterization and thermal properties of 1, 10-phenanthroline mixed-ligand complexes of cobalt (II) and copper (II): metal-mediated transformations of the dicyanamide ion. *Chemical Papers*, 74(9), 3003-3016.

[47] Pan, T. T., Xu, D. J. (2005). A polymorph of cis-dichlorobis (phenanthroline-κ²N, N') manganese (II). *Structure Reports*, 61(4), m740-m742.

[48] McCann, S., McCann, M., Casey, M. T., Jackman, M., Devereux, M., McKee, V. (1998). Syntheses and X-ray crystal structures of cis-[Mn (bipy) 2Cl₂] · 2H₂O · EtOH and cis-[Mn (phen) 2Cl₂](bipy= 2, 2'-bipyridine; phen= 1, 10-phenanthroline); catalysts for the disproportionation of hydrogen peroxide. *Inorganica chimica acta*, 279(1), 24-29.

[49] Parker, O. J., Aubol, S. L., Breneman, G. L. (1996). cis-Diisothiocyanatobis (1, 10-phenanthroline) copper (II), [Cu (NCS)₂(C₁₂H₈N₂)₂]. *Crystal Structure Communications*, 52(1), 39-41.

[50] Kabešová, M., Kožíšková, Z. (1992). Bis (1, 10-phenanthroline) copper (II) Complexes. Refinement of the Crystal Structure of the Dithiocyanato-bis (1, 10-phenanthroline) copper (II) Complex. *Collection of Czechoslovak chemical communications*, 57(6), 1269-1277.

[51] JIN, J., LI, D., LI, L., SHI, Z. F., LIU, D. W., NIU, S. Y., ZHANG, G. N. (2011). Syntheses, Structures and Surface Photo-electric Properties of A Series of Ni (II) Coordination Supramolecules. *Acta Chimica Sinica*, 69(18), 2108.

[52] Saha, U., Dutta, D., Nath, H., Franconetti, A., Frontera, A., Bhattacharyya, M. K. (2019). Supramolecular association in Cu (II) coordination complexes involving energetically significant NO $\cdots$ NO π -hole interaction and cooperative π -stacked ternary assembly: Experimental and theoretical studies. *Inorganica Chimica Acta*, 488, 159-169.

Chapter III

Results and discussion

III.1. Introduction

Phenanthroline is a highly effective N-donor heterocyclic ligand and chelating agent that is both rigid and planar, featuring appropriate functional aromatic groups that form stable complexes with transition metal ions in solution [1]. Cobalt and Nickel are well-known transition metals, and the significance of coordination in chemical compounds arises from their strong nucleophilicity. Additionally, benzoic acid, with its specific function groups capable of coordinating with transition metals, is widely used in organometallic complexes due to the carboxylate-binding sites playing a major role as beneficial hydrogen bond donors in the formation of supramolecular architecture [2].

In this chapter we synthesized three novel complexes: the (benzoate)-bis (1,10-phenanthroline)-cobalt (II) nitrate benzoic acid (**C1**), the Aqua-bis(benzoato- κ O) (1,10-phenanthroline- κ^2 N, N') cobalt (II) (**C3**), and the Triaqua (chlorido)(1,10-phenanthroline- κ^2 N,N') nickel(II) chloride monohydrate (**C3**). The molecular structures of these complexes were determined using single-crystal X-ray diffraction analysis and characterized through spectroscopic (FTIR, UV-Vis) techniques. In addition, through Hirshfeld surface analysis, the intermolecular interactions with their contributions were identified and summarized. To determine the best molecular geometric shape and to visualise the location of HOMO and LUMO as frontier orbitals, a theoretical study was performed by density functional theory (DFT) calculations. Molecular Electrostatic Potential (MEP) was generated to determine the electrophilic and nucleophilic sites, while Reduced Gradient density (RGD) [3], Electron Localization Function (ELF), and Localized Orbital Locator (LOL) analyses were conducted to explain the density distribution, predict chemical behavior, and evaluate the rigidity and stability of the three novel complexes [4].

For each of the compounds synthesised, simulations were conducted on their potential biological activity via molecular docking onto two different sets of receptor proteins. The two sets of receptor proteins that were used as docking reference points were selected based on the *Klebsiella pneumoniae* receptor (PDB ID = 6RD3) and the dihydrofolate reductase (PDB ID = 5E8Q). The data obtained from the molecular docking simulations demonstrate strong molecular interaction between the synthesised compounds and their respective target enzymes. This supports the assumption that these compounds may possess potential therapeutic properties.

Part 1: Structural characterization of the synthesized compounds

III.2. Study of novel (benzoato)-bis(1,10-phenanthroline)-cobalt (II) nitrate benzoic acid complex (C1)

III.2.1. Crystallographic study of new complex (C1)

The crystal structure analysis revealed that the cobalt (II) complex (C1) crystallizes in the monoclinic system, space group $I2/a$, with the corresponding crystallographic details summarized in Table III.1. The cobalt center is coordinated by one benzoate ligand and two phenanthroline ligands, with the latter acting in a bidentate coordination mode. The Co(II) ion adopts a distorted octahedral geometry (Figure III.1), as confirmed by the bond lengths and angle values listed in Table III.2. The metal center is six-coordinate, with the equatorial plane formed by two symmetric oxygen atoms from the coordinated benzoate ligand and two nitrogen atoms (N, N') from the phenanthroline molecules. The axial positions are occupied by the second pair of nitrogen atoms from the phenanthroline ligands.

During refinement, the crystal structure indicated a disorder at the C5 atom of the coordinated benzoate. The positive charge of the cationic complex $[\text{Co}(\text{Phen})_2(\text{bz})]^+$ is balanced by a nitrate ion (NO_3^-), while the free benzoic acid molecule (bzH) remains neutral.

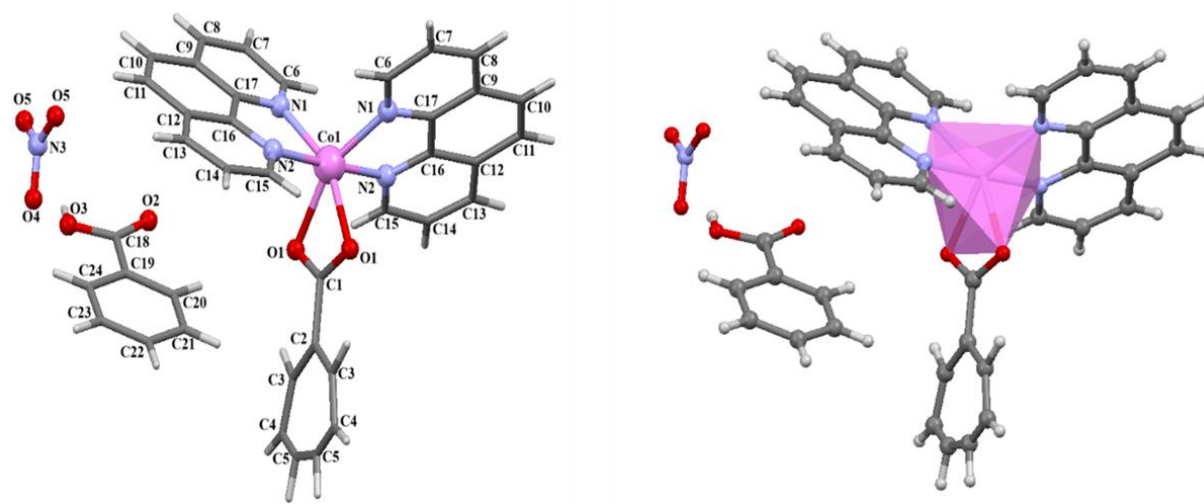


Figure III.1. Molecular structure of complex (C1) with an octahedral coordination environment.

Table III.1. Selected crystallographic data and structure refinement parameters for compound (C1).

Data collection	Compound (C1)
CCDC N°	2366740
Chemical Formula	C ₃₈ H ₂₇ Co N ₅ O ₇
Formula weight (g/mol)	724.60
Diffractometer	Xcalibur, Eos
Radiation type	Mo K α ($\lambda=0.71073$ Å)
Temperature (K)	295(2)
Density (Calculated) (Mg/m ³)	1.332
Crystal system, Space group	Monoclinic, <i>I2/a</i>
a (Å), b (Å), c (Å)	13.0418 (19), 19.9959 (16), 16.640 (2)
β (°)	112.231 (17)
Cell Volume (Å ³)	4017.0 (10)
Z	4
μ (mm ⁻¹)	0.49
Crystal size (mm)	0.52 $\times$ 0.29 $\times$ 0.22
No. of measured, independent and observed	12867, 3808
[$I > 2\sigma(I)$] reflections	2842
$R_{\text{(int)}}$	0.032
Refinement	
$R[F^2 > 2\sigma(F^2)]$, $wR(F^2)$, S	0.047, 0.111, 1.04
No. of unique reflections	3808
No. of parameters	279
$\Delta\rho_{\text{max}}$, $\Delta\rho_{\text{min}}$ (e Å ⁻³)	0.17, -0.32

The single crystal x-ray diffraction analysis of Co (II) complex (C1) revealed the presence of various hydrogen bands, C—H $\cdots$ O non-covalent interactions, and ring π – π interactions, which consequently formed the fantastic one-dimensional supramolecular arrangement illustrated in Figure III.2. Since the two-week contacts C—H8 $\cdots$ O1 and C—H10 $\cdots$ O1 are due from the same accepted oxygen atom of binding benzoate, this allowed the hydrogen-band motifs $R_2^1(6)$ to be created [5,6]. Notably, the lengths of O1 $\cdots$ H8 and O1 $\cdots$ H10 are 2.682(1) Å and 2.492(1) Å, respectively. Additionally, the 1D supramolecular architecture indicates that the pattern of π – π stacking interactions intermediate the neighboring phenanthroline rings results in a centroid separation of 3.730 Å. Highlighting that the stability of this crystalline arrangement is reinforced by the presence of a specific hydrogen band, C—H $\cdots$ O, that is formed by connecting two oxygen (O5) atoms of NO₃[−] anions with the coordinate benzoate (*bz*),

resulting in the design of an $R_2^2(7)$ hydrogen band motifs (Figure III.2).

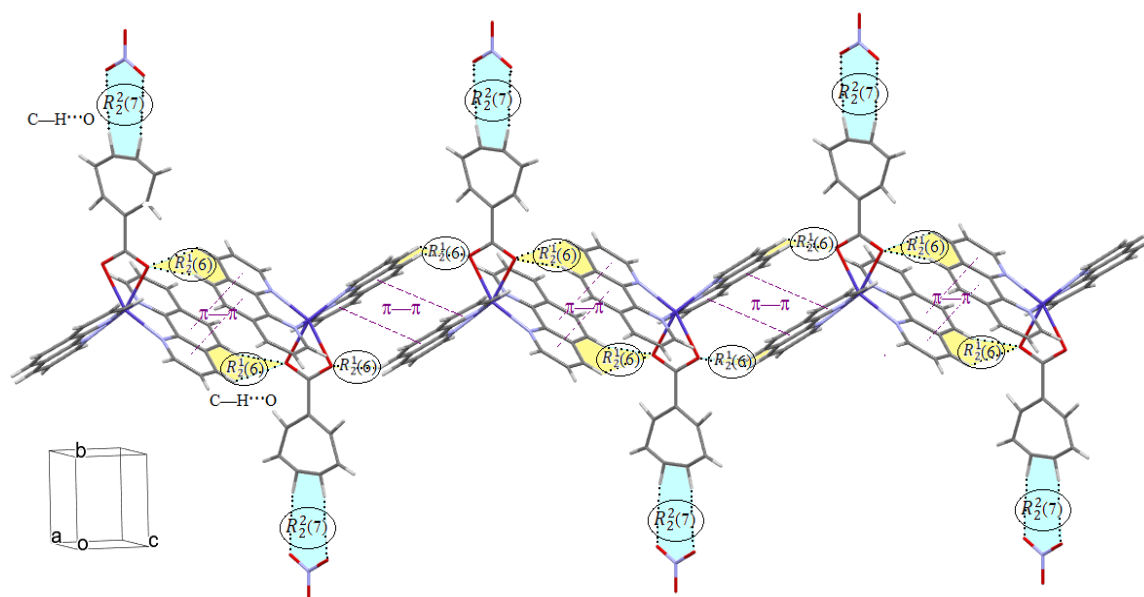


Figure III.2. 3D view of the 1D supramolecular architecture of complex (C1), highlighting the π - π stacking interactions and C—H $\cdots$ O hydrogen bonds that result in the formation of two types of graph-set motifs, $R_2^2(7)$ and $R_2^1(6)$.

Table III.2. Highlights of both bond lengths and bond angle values of complex (C1).

Bond distances (Å)		DFT	Bond angles (°)		DFT
Co1—O1	2.1680 (17)	2.1678	O1 ⁱ —Co1—O1	60.15 (9)	59.92
Co1—O1 ⁱ	2.1679 (17)	2.1678	N1 ⁱ —Co1—O1	97.25 (7)	97.24
Co1—N1 ⁱ	2.096 (2)	2.096	N1—Co1—O1	154.20 (7)	154.20
Co1—N1	2.096 (2)	2.096	N1 ⁱ —Co1—O1 ⁱ	154.20 (7)	154.20
Co1—N2	2.113 (2)	2.113	N1—Co1—O1 ⁱ	97.25 (7)	97.24
Co1—N2 ⁱ	2.113 (2)	2.113	N1 ⁱ —Co1—N1	107.25 (11)	107.24
			N1 ⁱ —Co1—N2	100.49 (8)	100.49
			N1—Co1—N2 ⁱ	100.50 (8)	100.49
			N1 ⁱ —Co1—N2 ⁱ	78.54 (8)	78.54
			N1—Co1—N2	78.54 (8)	78.54
			N2—Co1—O1	89.34 (7)	89.33
			N2 ⁱ —Co1—O1 ⁱ	89.34 (7)	89.33
			N2 ⁱ —Co1—O1	92.04 (7)	92.04
			N2—Co1—O1 ⁱ	178.40 (11)	178.40

The multiparty composition of the molecular structure of complex **C1** will account for the variety of geometric orientations that occur in the crystal lattice. Notably, the $R_6^4(26)$ hydrogen-bond motifs, illustrated in Figure III.3, were formed through two hydrogen bonds involving the same oxygen atom (O4) of the nitrate anion and the O3–H3A group of free benzoic acid, with an H3A···O4 distance of 2.108 Å. Additionally, the second carboxylic oxygen atom (O2) of the free benzoic acid (*bzH*) participates in a C22–H22···O2 interaction with an H22···O2 distance of 3.293 Å. Furthermore, the combination of four benzoic acid molecules (*bzH*) and two nitrate anions (NO_3^-) generate a remarkable chair-like supramolecular architecture within the crystal lattice through hydrogen bonding (Figure III.4) [7]. The chair-shaped architecture, stabilized by various non-covalent interactions, contributes significantly in improving both the strength and stability of the layered frameworks in complex (**C1**).

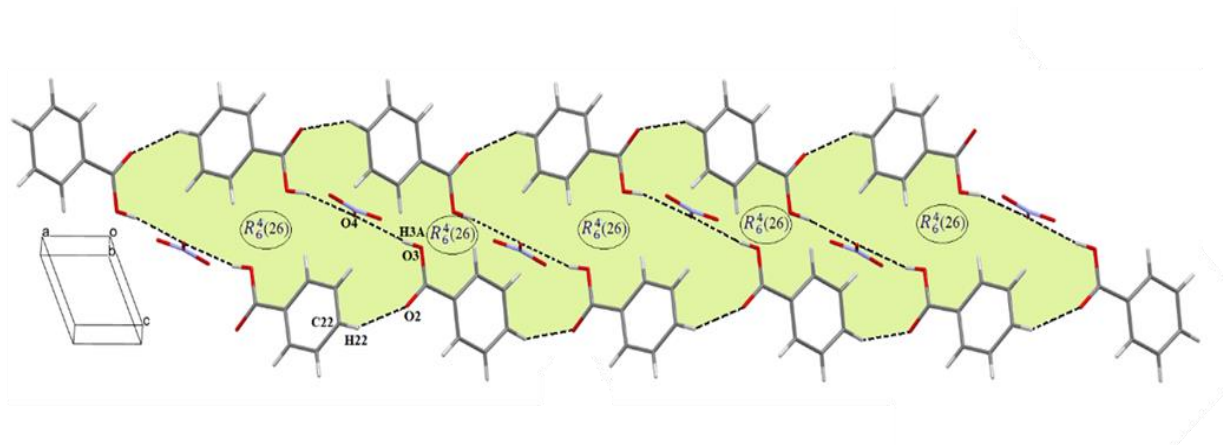


Figure III.3. Representation of $R_6^4(26)$ supramolecular motifs formed by C22–H22···O2 and O3–H3A···O4 non covalent interactions.

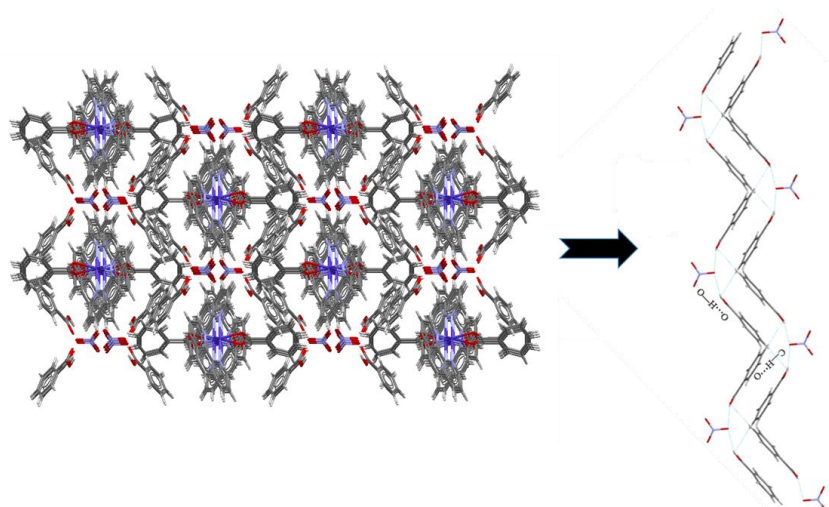


Figure III.4. Packing view showing the chair-like supramolecular pattern within the crystal lattice.

Crystallographic analysis of complex (C1) revealed the presence of a lone pair– π (lp– π) non-covalent interaction within its molecular structure. This supramolecular interaction is formed between the lone electron pair located on the oxygen atom (O2) of the benzoic acid molecule and the aromatic π -system of the coordinated phenanthroline ligand, with spacing of 3.614 Å (Figure III.5). The C–H $\cdots\pi$ contacts play a crucial role in the organization of the crystal lattice, contributing to the filling of void spaces within molecular layers and enhancing both the stability and rigidity of the crystal structure [8,9]. Additionally, the *bzH* molecules interact with the phenyl rings of phenanthroline ligands through a different class of π – π stacking interactions, further reinforcing the supramolecular assembly of the Co (II) complex (Figure III.5).

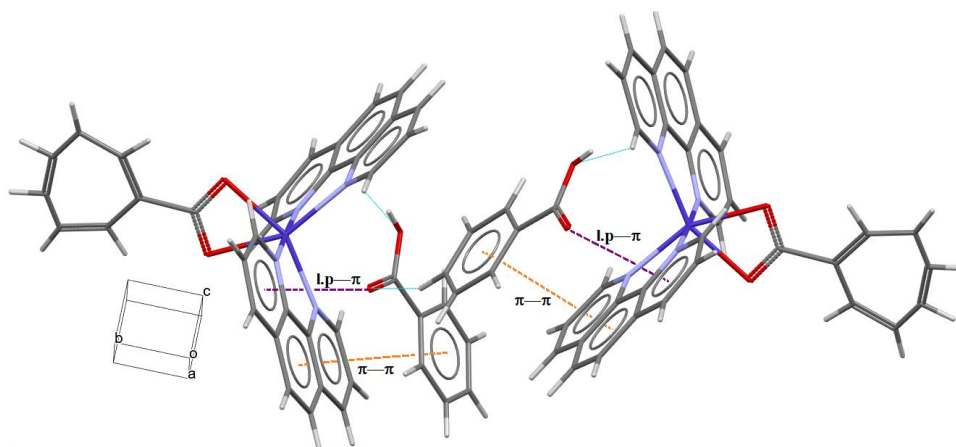


Figure III.5. lp– π and π – π stacking interactions highlighted in the supramolecular assemblies of the Co(II) complex (C1), formed between (*bzH*) molecules and coordinated phenanthroline moieties.

III.2.2. Full interaction maps of Co (II) complex (C1)

Full Interaction Maps (FIM) is a method of 3D visualization for the representation and examination of intermolecular interactions within molecules that was produced utilizing Mercury software. The analyses of FIMs are based on scatterplots specific interactions employing the IsoStat library feature switched on in the mercury program [10]. The principle of the construction of these 3D scatterplot models is that two adaptive functional groups come together to produce a specific interaction.

In order to analyze the results of the FIM analysis, reference colors are used in distinguishing the molecular surface: the red areas indicate hydrogen bond acceptor interactions, the blue areas define hydrogen bond donor interactions and the brown areas indicate the π – π stacking atoms within supramolecular architectures.

In this study, the FIM map of the new compound (C1) is shown in Figure III.6, which shows

the red hotspots indicating the spaces in which O–H···O and C–H···O non-covalent interactions are localized in the crystalline lattice, formed via the oxygen atom probes from the benzoate ligands and the NO₃[−] anions. The blue hotspots signify the uncharged N nitrogen atoms of the phenanthroline coordinate ligands. Furthermore, note that the translucent surfaces indicate the weak interactions in the crystal ultimately arising from the π – π aromatic stacking of phenanthroline molecules. Lastly, all information obtained through this 3D-colored mapping helped to understand the stability and reactivity of the Co(II) complex.

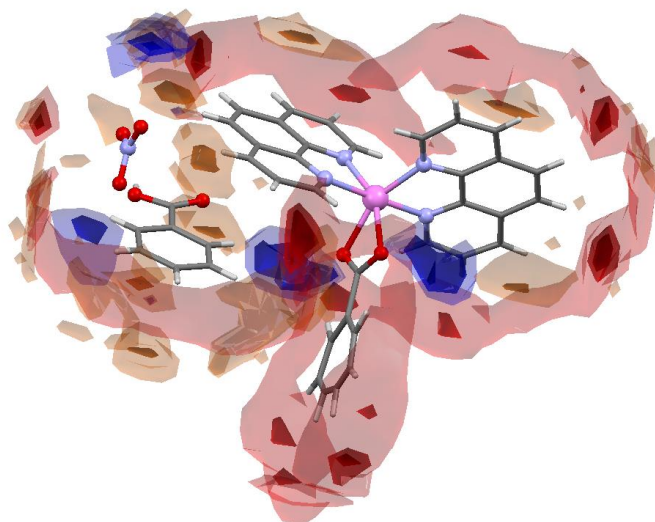


Figure III.6. A 3D-colored map of non-covalent interactions surrounding the molecular structure of cobalt complex (C1).

III.2.3. Hirshfeld surface analysis of cobalt (II) complex (C1)

The Hirshfeld surface approach allows for a quantitative analysis of intermolecular interactions of compounds, enhancing our understanding of the supramolecular arrangement within crystal molecules. The three-dimensional Hirshfeld surface mapping utilizes various models, including the d norm, shape index, curvedness, and fragment patch, to visualise the types and natures of contacts using the coloured codes and specific shapes. This method facilitates a description of 3D molecular structure. Figure III.7, 8 and 9 showcase the three-dimensional HS calculations of (benzoate)-bis (1,10-phenanthroline)-cobalt (II) nitrate benzoic acid (C1), obtained from single-crystal x-ray data using CrystalExplorer17.

The normalized contact distance (d_{norm}) map of complex (C1) (Figure III.7) revealed the bright red spots denote the strong interaction as O–H···O hydrogen bonding, which plays a vital role in the rigidity and stability of the crystal in the solid state, as will the light red regions

signifying C–H···O moderate contacts that are important in the formation of supramolecular architecture within the monoclinic crystal structure of cobalt complex (C1). Notably, all non-covalent interactions with the neighboring molecules surrounding the surface of the central molecular structure are illustrated in Figure III.8.

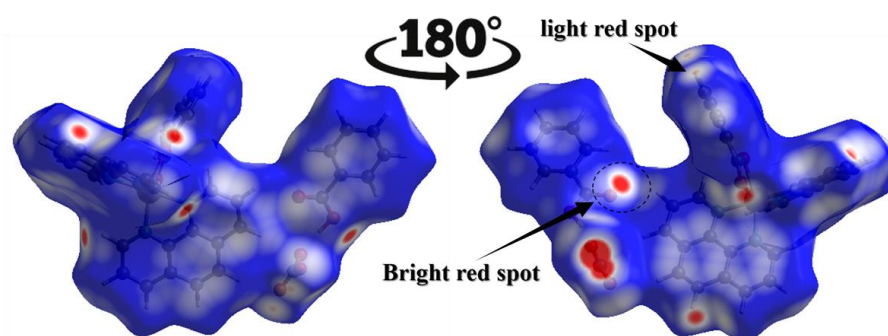


Figure III.7. The 3D Hirshfeld surfaces plotted over the $dnorm$ function of $[\text{Co}(\text{Phen})_2(\text{bz})] \cdot \text{bzH} \cdot \text{NO}_3$ (C1) in the range of -0.15 to 0.6.

Additionally, the shape index map exhibited the presence of π – π stacking interactions resulting from the supramolecular organization of two Phen rings and the aromatic contacts between benzoate molecules and the coordinated phenanthroline ligands, as demonstrated by the opposite triangles with blue and red color appearances on the surface of the crystal complex (Figure III.9). These intriguing aromatic non-covalent interactions evaluated the stability of the design structure in the overall packing of the complex (C1). Notably, the flat regions characterized by low curvature, as illustrated in the curvedness surface mapping, confirmed the position of interactions identified by the shape index surface (Figure III.9).

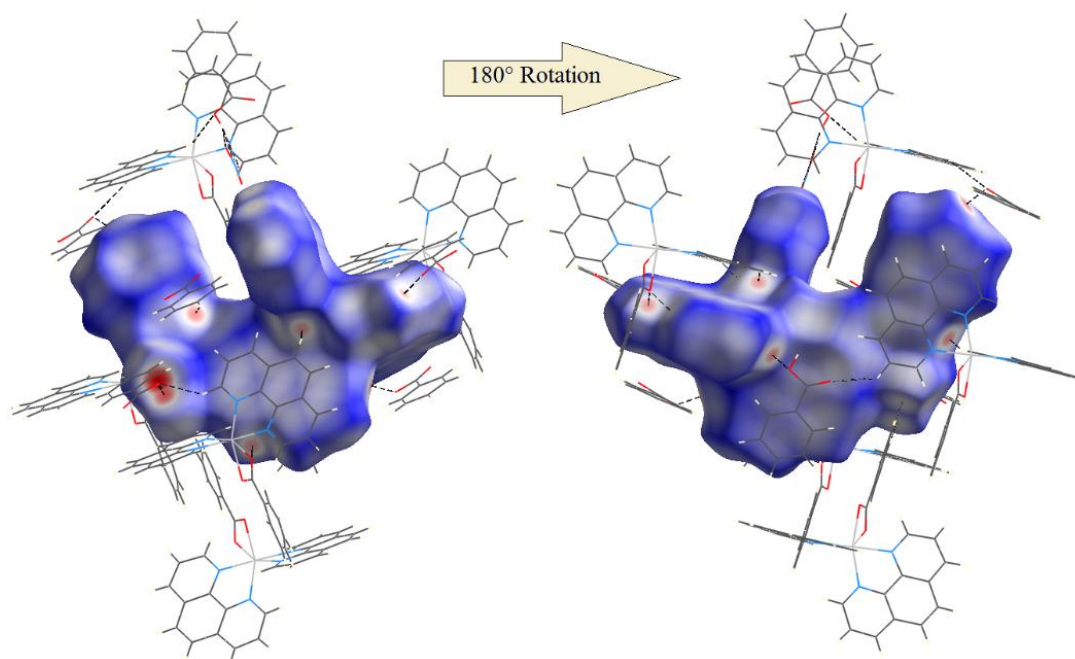


Figure III.8. The illustration of the two orientations of the *dnorm* Hirshfeld surface for complex 1 in 0.5 to 1.5 Å surrounded by the strong O–H···O hydrogen bonds and moderate C–H···O hydrogen contacts.

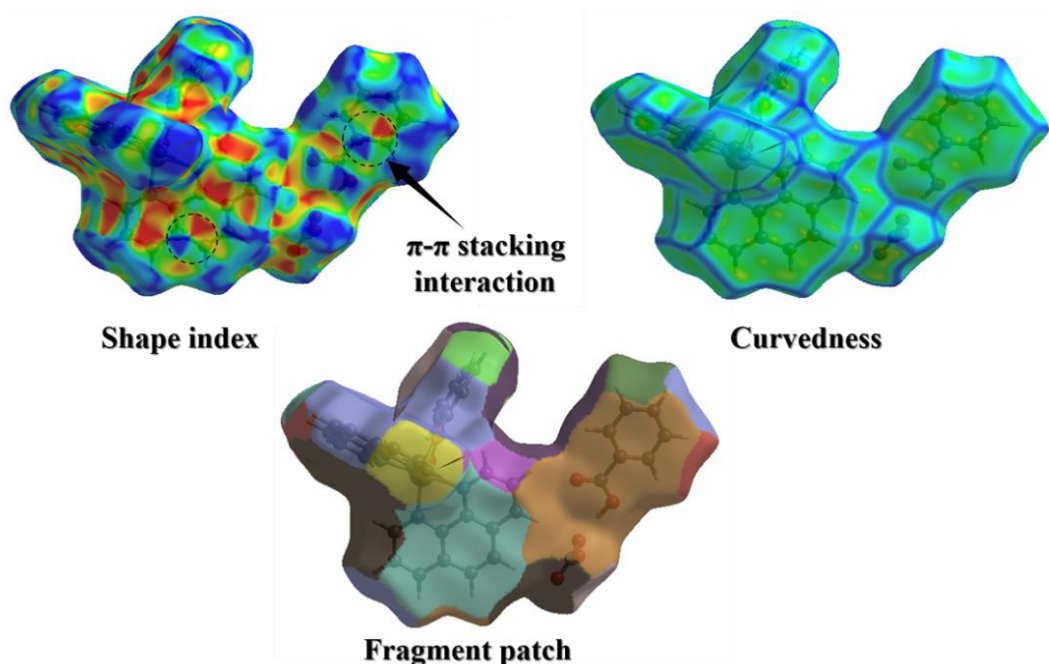


Figure III.9. Representation of *HSs* mapped over via shape index in the range -0.8 at 0.7 Å, curvedness surface in -0.4 at 0.2 Å and fragment patch in 0 at 29 Å for noval compound (C1).

III.2.4. Infrared spectroscopy analysis of complex (C1)

The molecule (benzoate)-bis(1,10-phenanthroline)-cobalt (II) nitrate benzoic acid was characterized using Fourier-transform infrared (FT-IR) spectroscopy, which confirmed the most important functional groups in this mixed complex and is complementary to the primary X-ray diffraction study. Figure III.10 presents the FT-IR spectrum of compound C1, taken from 400 - 4000 cm^{-1} . The peak at 3473 cm^{-1} is the O–H stretching associated with the benzoic acid molecule. The C–H stretching in the aromatic C–H bonds are found at the peaks 3064 cm^{-1} and 2923 cm^{-1} . The asymmetric and symmetric stretch of the (COO^-) carboxylate of the benzoate ligand was evident at 1597 cm^{-1} and 1333 cm^{-1} , respectively. The distance between these bands, $\Delta\nu = 264 \text{ cm}^{-1}$, is consistent with the benzoate ligand being bidentate in compound (C1) [11]. The strong absorption at 1713 cm^{-1} , characteristic of the uncomplexed C=O of free benzoic acid, [12] along with the evidence of the band found at 1519 cm^{-1} , confirms *bzH* within the crystal lattice. The NO_3^- anion is identified by the absorption peak found at 1428 cm^{-1} [13]. Bands at 647 and 505 cm^{-1} correspond to metal–oxygen vibrations [14]. Finally, a peak at 422 cm^{-1} provided evidence of the coordination between the metal center and the nitrogen atoms of the phenanthroline ligands.

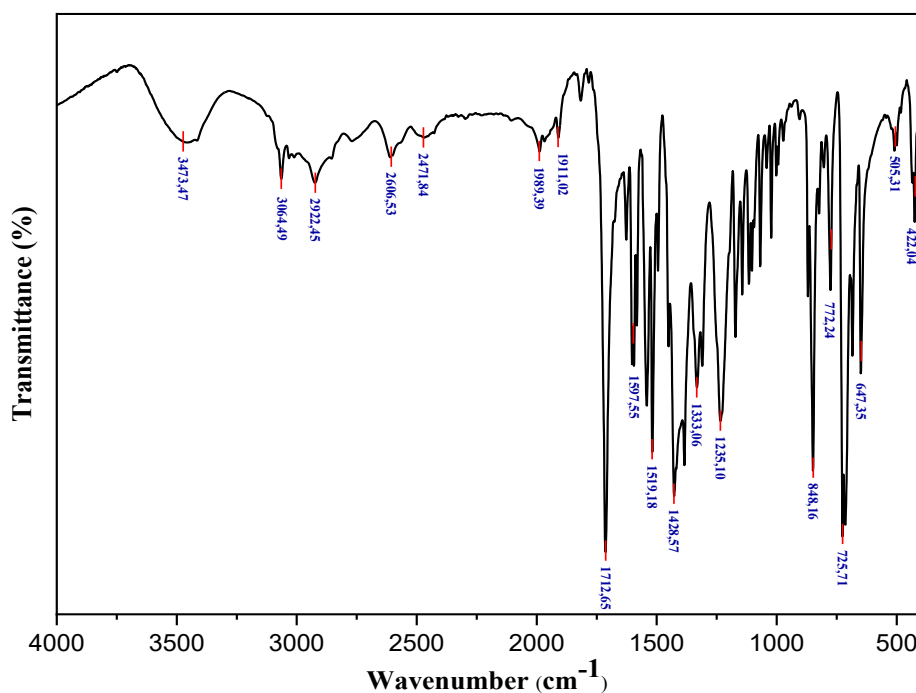


Figure III.10. FT-IR spectrum of title complex (C1).

III.2.5. Ultraviolet-visible (UV-Vis) spectroscopy of complex (C1)

The electronic spectrum of the mixed-ligand complex (C1) was obtained in the 200–800 nm range in DMSO as the solvent, shown in Figure III.11. The spectrum shows a broad absorption band at $\lambda = 238$ nm, which can be assigned to the $\pi \rightarrow \pi^*$ transitions of the aromatic rings [15]. The second band at 294 nm can be attributed to the $n \rightarrow \pi^*$ transition. In addition to this, at 656 nm there is a broad absorption band, attributable to the ${}^2E_g \rightarrow {}^2T_{2g}$ transition, indicative of Co(II) coordination in the prepared (benzoate)-bis(1,10-phenanthroline)-cobalt(II) nitrate benzoic acid complex, which is consistent with a distorted octahedral coordination geometry [16].

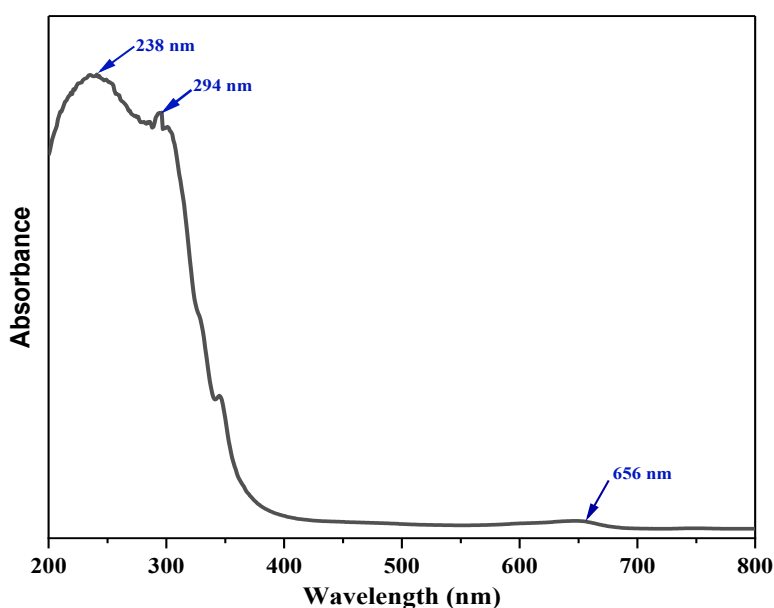


Figure III.11. Ultraviolet–visible (UV-Vis) spectrum of the Co (II) complex (C1).

III.2.6. Theoretical investigations

III.2.6.1. Geometric optimization of complex (C1)

Computational calculations were carried out using density functional theory (DFT) with the Gaussian 09W software program for complex (C1) with the novel molecular structure transition metal. As for the purposes of the current work, DFT/B3LYP in combination with a 3-21G basis set was used to optimize the structure of $[\text{Co}(\text{Phen})_2(\text{bz})] \cdot \text{bzH} \cdot \text{NO}_3$ (C1). The optimized structure of title compound is presented in Figure III.12, which is the lowest energy conformation and indicates a stable configuration.

Theoretical structural parameters, including bond lengths and bond angles, were obtained from the fully optimized geometry and compared to experimental values derived from the crystal structure (CIF file). This CIF file also served as the initial input for all theoretical

calculations. The high level of agreement observed between the calculated and experimental data particularly for the Co–N and Co–O bond lengths, with only minor deviations can be attributed to the influence of chemical conditions and the presence of diverse non-covalent interactions within the crystal lattice.

These results confirm the preservation of the distorted octahedral geometry around the cobalt center in complex (C1) and demonstrate the effectiveness of computational methods in crystallographic studies. All key measurements are summarized in Table III.2. The computational analysis of the (benzoate)-bis(1,10-phenanthroline)-cobalt (II) nitrate benzoic acid complex highlights that the central cobalt(II) ion maintains six coordination sites, consistent with the experimentally determined geometry. It is coordinated by two bidentate phenanthroline ligands and one bidentate benzoate ligand. The accuracy of the theoretical results closely matching experimental observations is largely due to the appropriate selection of functional methods and basis sets in the DFT calculations.

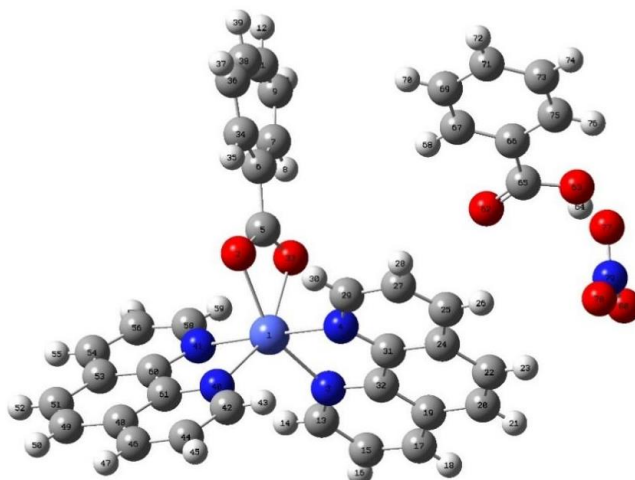


Figure III.12. Optimization molecular structure of Co (II) complex (C1).

III.2.6.2. Frontier Molecular orbital analysis of complex (C1)

The Figure III.13 shows the frontier molecular orbitals (FMOs) of the cobalt (II) complex, comprising HOMO-1, HOMO, LUMO, and LUMO+1, along with their relevant energy levels in electron volts (eV). These orbitals were generated with density functional theory (DFT) calculations using the B3LYP functional with the 3-21G basis set. The HOMO (–2.947 eV) and HOMO^{–1} (–3.218 eV) orbitals are mostly distributed on the central cobalt metal ion and the coordinated phenanthroline ligands, indicating significantly strong metal–ligand π -interactions. LUMO (–2.649 eV) is seen to be delocalized over the benzoate ligand, but it also showed partial

delocalization over the ring system of phenanthroline ligands indicating that it is likely the major electron acceptor during excitation. In this case LUMO+1 (-2.406 eV) is seen to show considerable delocalization over the benzoic acid and nitrate units, suggesting the presence of uncoordinated species which may also be involved in potential charge transfer as well. The results find that the calculated HOMO-LUMO energy gap is only 0.30 eV, while it finds that the gap is wider at 0.81 eV for HOMO-1 to LUMO+1 transitions. Furthermore, the energy gap (ΔE) explained the reactivity, physical properties and electronic distribution within compounds, while the lowest gap revealed the highest chemical reactivity and extra polarizability in metal-organic frameworks [17,18]. The comparatively small energy gaps suggest significant stabilizing delocalization of the electron enhancing potential for charge transfer to occur intramolecularly which supports evidence that the DFT/B3LYP method and the 3-21G basis set generates meaningful electronic properties for this cobalt complex. In this quantum analysis through the orbital energies, various electronic DFT parameter descriptions can be calculated, such as electrophilicity index (ω), chemical hardness (η), and chemical potential (μ), which play a vital role in comprehending the stability and rigidity of compounds Table III.3 [19-21].

Table III.3. Global reactivity descriptors for title complex (C1).

Complex	E_{HOMO} (eV)	E_{LUMO} (eV)	E_{gap} (eV)	χ (eV)	I (eV)	A (eV)	η (eV)	S (eV)
(C1)	-2.95	-2.65	0.30	2.80	2.95	2.65	0.15	3.37

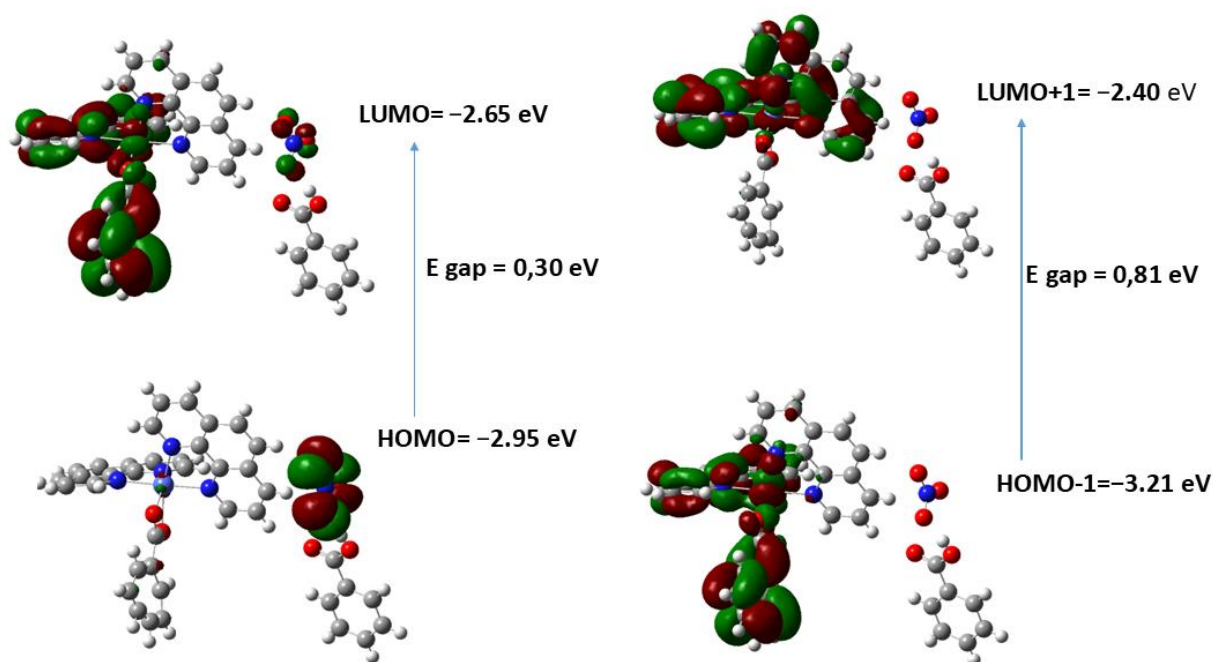


Figure III.13. Frontier orbitals HOMO-LUMO for complex (C1).

III.2.6.3. Molecular Electrostatic Potential analysis of complex (C1)

The (benzoate)-bis(1,10-phenanthroline)-cobalt (II) nitrate benzoic acid mixed-ligand complex (C1) has an MEP map shown in Figure III.14. The MEP map is an effective computational method for visualizing the electronic charge density found throughout the molecular surface and revealing electrophilic and nucleophilic reactive sites as well as regions where hydrogen-bonding interactions might occur. The MEP map is presented as a color-coded surface, which helps visualize these regions in terms of colors assigned to differences in electrostatic potential values (+288.8 kJ.mol⁻¹ for maximum positive potential to -288.8 kJ.mol⁻¹ for maximum negative potential). In the MEP map of the title complex the red-shaded regions localized about the nitrate (NO₃⁻) anion and the oxygen atoms in the benzoic acid (bzH) moiety depict electron-rich (nucleophilic) sites that are capable of electrophilic attack. This is consistent with previous work that observed the O–H···O and C–H···O hydrogen-bond interactions through single-crystal X-ray diffraction and on Hirshfeld surface analyses. Blue areas that mapping over top of the bidentate 1,10-phenanthroline ligand, especially about the nitrogen donor atoms and the cobalt (II) center are electron-poor (electrophilic) regions that would plausibly allow nucleophilic attack.

Finally, areas shown in green and yellow depict electrostatically neutral areas (or less reactive) on the molecular surface. In general, the MEP analysis offers a full picture of the chemical reactivity, tendencies for intermolecular interactions, and electrostatic stability of the

complex. Additionally, it acts as a predictive marker for potential biological activity, as the visualization of electron density distribution clarifies the predicted reactive sites and interaction pathways of the compound.

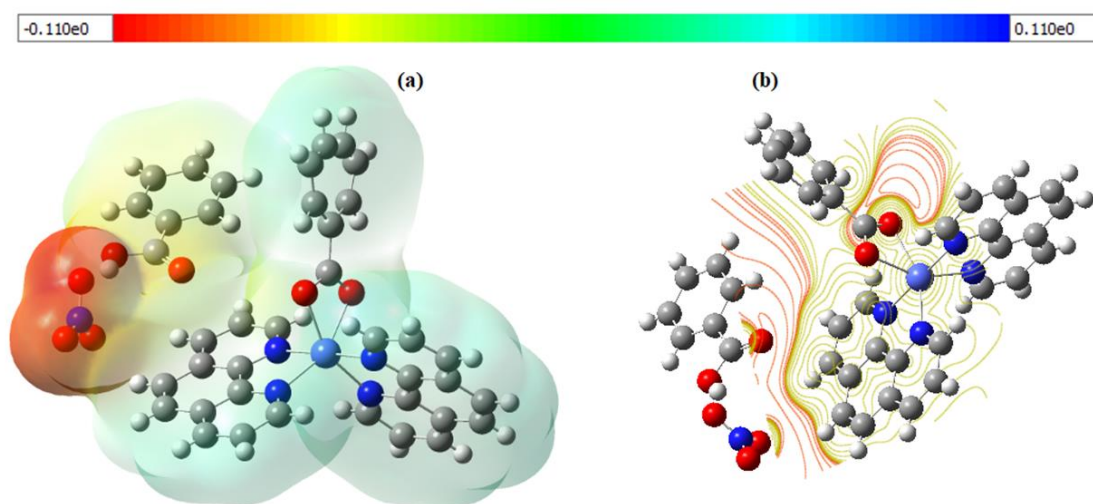


Figure III.14. Representation of MEP for complex (C1), (a) 3D map surface. (b) 2D contour plot.

III.2.6.4. ELF and LOL analyses for Cobalt complex (C1)

Figure III.15 shows the Electron Localization Function (ELF) and Localized Orbital Locator (LOL) maps for the (benzoate)-bis(1,10-phenanthroline)-cobalt (II) nitrate benzoic acid complex (C1) calculated using Multiwfn 3.8 software. The ELF provides meaningful pictorial representation of para-cluster electron density that provides covalent bonding interactions, lone pairs, and transferal of electron density character in π systems in the structure of the molecule [22]. The LOL, derived from the kinetic energy density, provides more clarity on the localized molecular orbitals. From the maps produced localized electron density is shown in blue, clearly shown in the C–H covalent bonds between phenanthroline species in addition to the Co–N and Co–O coordination bonds. The red colored regions represent delocalized electrons located in the hydrogen atoms and finally, the greens colored regions above each of the phenanthroline ligands represent the π systems that are responsible for π – π stacking in the crystal solid-state design of complex (C1). Combined, the ELF and LOL representations demonstrate electron interactions leading to supramolecular stabilization in the crystal lattice by showing π – π stacking and other non-covalent interactions while also showing local reactive centers and coordination environments of the organometallic bond.

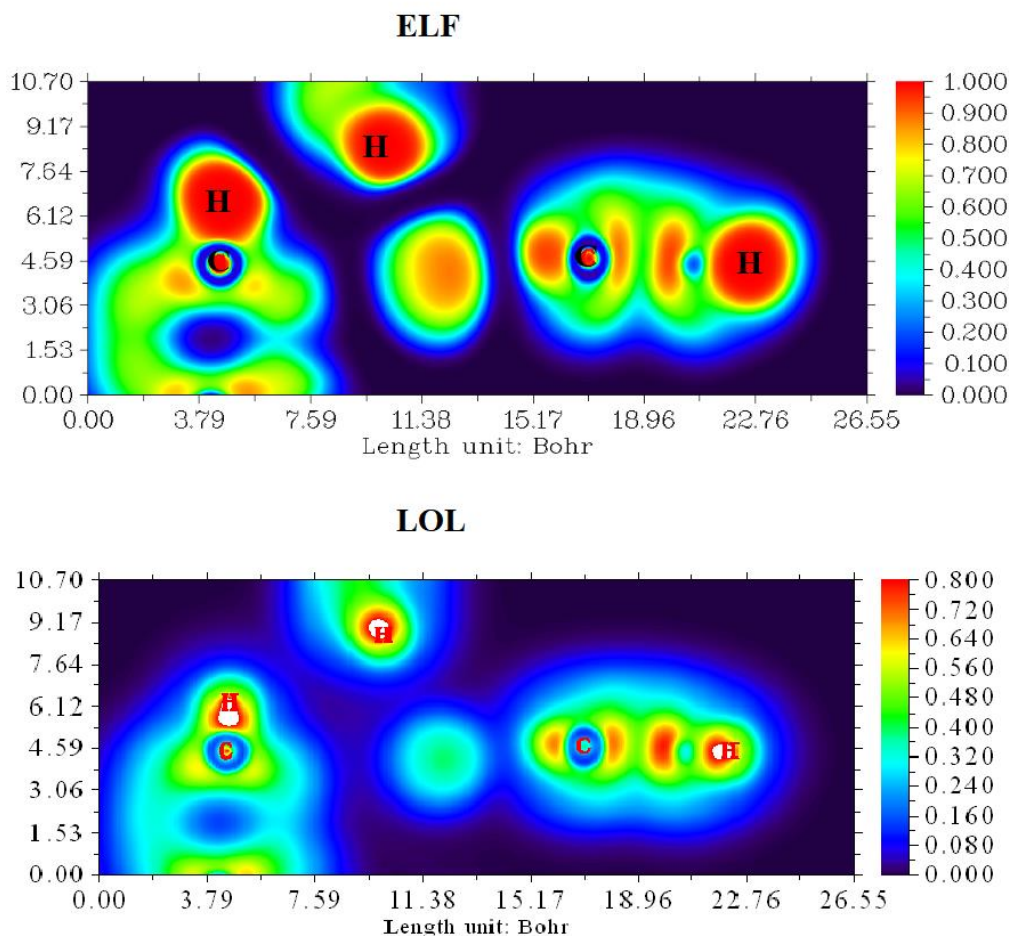


Figure III.15. The ELF and LOL maps for compound (C1).

III.2.6.5. Reduced density gradient (RDG) analysis of complex (C1)

The RDG analysis, shown in Figure III.16, for complex (C1) was prepared from a set of output files from a DFT calculation on B3LYP with the 3-21G basis set and analyzed with the Multiwfn 3.8 program [23]. This theoretical analysis using the reduced density gradient (RDG) method allows for the visualization and classification of various specific types of non-covalent interactions (NCI) observed in the molecule. The possible NCI discussed here include van der Waals interactions, hydrogen-bonding interactions (both inter- and intramolecular), halogen contacts, and steric repulsion forces. The RDG plots are interpreted via the $\text{sign}(\lambda_2)\rho$ descriptor, where λ_2 is the second eigenvalue of the Hessian matrix of electron density and ρ is the value of electron density [24]. The blue region ($\text{sign}(\lambda_2)\rho < 0$) corresponds to the attractive interaction (in this case hydrogen bonding), the green region ($\text{sign}(\lambda_2)\rho \approx 0$) indicates areas of weak van der Waals contacts, and the red region ($\text{sign}(\lambda_2)\rho > 0$) suggest areas of repulsive steric interactions.

The RDG plot of the title complex (C1) shows large blue spikes, which indicate the existence of O–H···O and C–H···O hydrogen-bonding interactions in the crystal. Conversely, the red regions indicate that the structural crowding caused by the bidentate ligands (phenanthroline) around the Co (II) center is leading to steric repulsive effects. The green surfaces correspond to weak van der Waals interactions due to close contacts between benzoic acid molecules and the nitrate anion which contributes to supramolecular stabilization. To summarize the crystallography, electronic results and RDG analysis, they provide a clear understanding of the delicate, non-covalent interactions that give rise to structural stability, molecular packing, and ultimately molecular reactivity, in supramolecular assemblies such as complex (C1).

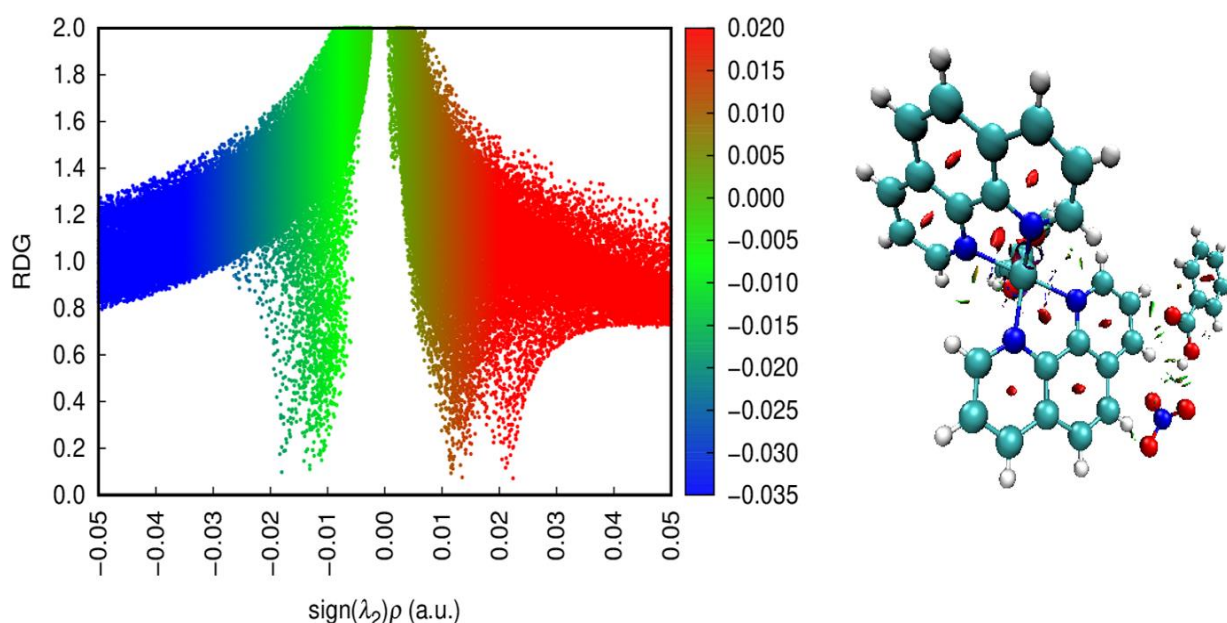


Figure III.16. The RDG scatter plots of cobalt (II) complex (C1).

III.3. Study of complex Aqua-bis(benzoato-κO) (1,10-phenanthroline-κ²N, N') cobalt (II) (C2)

III.3.1. Crystal structure analysis of complex (C2)

The crystalline molecular structure of complex (C2) is shown in Figure III.17. The complex [Co(Phen)(bz)₂(H₂O)] crystallizes in the monoclinic system in space group P2₁/c with the corresponding crystallographic details summarized in Table III.4. The Co(II) ion presents a distorted square-pyramidal geometry with five coordination sites, as represented in Figure III.18 and confirmed by the bond lengths and angle values listed in Table III.5. The cobalt is

surrounded via the two oxygen atoms O3 of one monodentate benzoate and the O1W oxygen atom of a water molecule with lengths [Co—O1W = 2.1010 Å, Co—O3 = 1.9956 Å] and two N atoms (N1 and N2) of a 1,10-phenanthroline bidentate ligand [Co—N1 = 2.0979 Å, Co—N2 = 2.1609 Å]; these atoms indicate the equatorial plane of the crystal geometry. The axial position is occupied by another oxygen atom from the benzoate molecule with distance Co—O1 = 2.0368. This crystal geometry has been proved through similar studies with other transition metal complexes [25, 26].

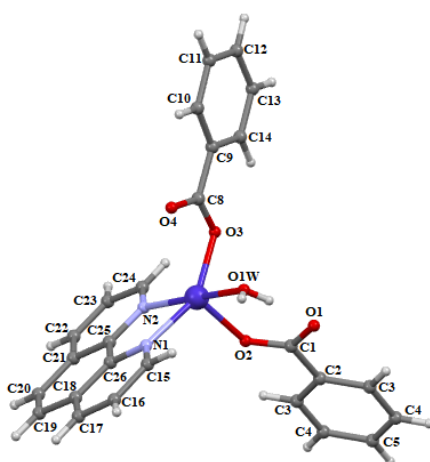


Figure III.17. Crystal structure of compound (C2).

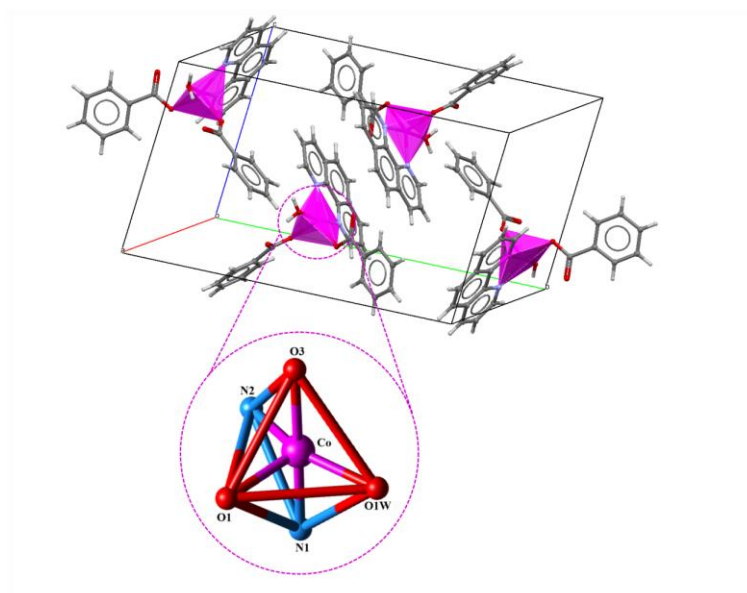


Figure III.18. The crystal packing with the polyhedral representation clearly exhibits the distorted square-pyramidal geometry.

Table III.4. Crystal data and structure refinement for complex (C2).

Crystal data	Complex (C2)
Chemical formula	C ₂₆ H ₂₀ CoN ₂ O ₅
Molecular weight (g/mol)	499.37
Temperature	298
Crystal system	Monoclinic
Space group	P2 ₁ /c
a, b, c (Å)	10.6228(2), 21.0600(3), 11.1847(2)
α , β , γ	90, 116.429(2), 90
Cell Volume/Å ³	2240.68(7)
Radiation type	CuK α (λ = 1.54184)
D _{calc} g/cm ³	1.480
μ (mm ⁻¹)	6.358
F (000)	1028.0
Z	4
Crystal size (mm)	0.20 x 0.15 x 0.10
No. of measured, independent and observed	23769, 4834
[$I > 2\sigma(I)$] reflections	4329
$R_{(int)}$	0.05
Refinement	
Final R indices [$F^2 > 2\sigma(F^2)$], $wR(F^2)$, S	0.043, 0.117, 1.041
No. of unique reflections	4834
No. of parameters	314
$\Delta\rho_{max}$, $\Delta\rho_{min}$ (e Å ⁻³)	0.48, -0.33

The X-ray crystallographic analysis demonstrates a one-dimensional supramolecular arrangement (Figure III.19) that is formed through C–H $\cdots$ O hydrogen bonding and π – π stacking interactions. This crystal architecture revealed the neighboring two aromatic (*Phen*) rings contacting two centroid-centroid with a split distance of 4.18 Å, while the shortest distance between conjugated planes is 4.103 Å between C19–C24. Additionally, the C19–H19 $\cdots$ O4 interactions result between aromatic C19–H19 carbon via the length (0.931 Å) of the phenanthroline molecule and the carbonyl oxygen O4 atom of one benzoate ligand with significant distance [O4 $\cdots$ H19 = (2.668 Å)]. Specifically, Figure III.20 highlights the graph-set descriptor $R_2^2(24)$ of these hydrogen bonds in crystal packing [27, 28].

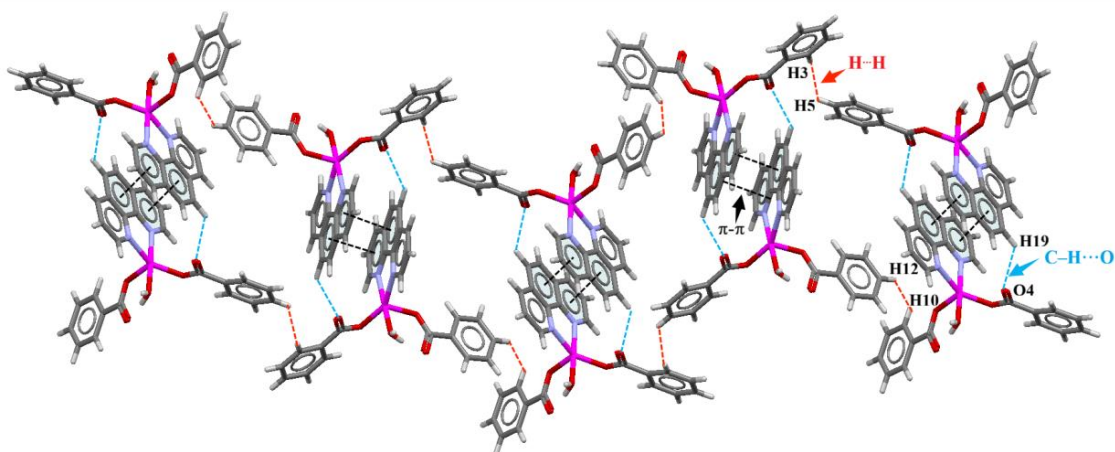


Figure III.19. Illustration of the one-dimensional supramolecular network in compound (C2), showing the C–H···O hydrogen bonds, H···H weak contacts, and π – π stacking interactions.

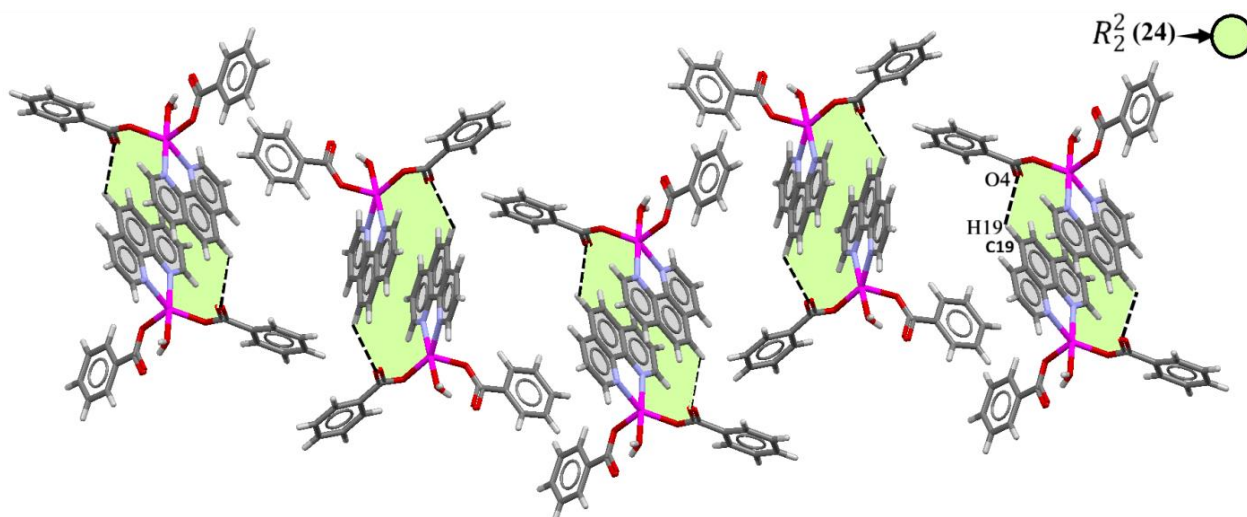


Figure III.20. View of intermolecular $R_2^2(24)$ graph-set motifs created through C19–H19···O4 interactions of (C2).

Table III.5. Representative bond lengths (Å) and bond angles (°) for complex (C2).

Bond distances (Å)			Bond angles (°)		
		DFT			DFT
Co—O1W	2.1010(15)	2.1010	O1W—Co—N2	175.07 (6)	175.07
Co—O1	2.0368(14)	2.0367	O1—Co—O1W	92.53 (6)	92.53
Co—O3	1.9956(16)	1.9957	O1—Co—N1	105.71(6)	105.70
Co—N1	2.0979(15)	2.0976	O1—Co—N2	90.30 (6)	90.29
Co—N2	2.1609(17)	2.1609	O3—Co—O1W	93.52 (7)	93.51

O3—Co—O1	99.92 (8)	99.91
O3—Co—N1	151.51(8)	151.50
O3—Co—N2	89.97(7)	89.96
N1—Co—O1W	97.53 (6)	97.52
N1—Co—N2	77.81 (6)	77.80

In addition, the two-dimensional supramolecular assembly network is stabilized with strong O—H...O hydrogen-bonding interactions. In particular, there are two important hydrogen bonds, O1W—H2W...O2 and O1W—H1W...O4, with short contact distances of 1.874 Å and 1.989 Å, respectively, which result for both forming $R_2^2(12)$ and $S_1^1(6)$, presented in Figure III.21. These strong hydrogen bonds are essential for sustaining the crystal lattice and make a significant contribution to the structural stability of the metal-organic complex in the solid state [29, 30]. Noteworthy, the mixed ligands present in the molecular structure of complex (C2) afford a characteristic three-blade fan-like crystal habit, which is clear in the two-dimensional packing diagram in Figure III.22.

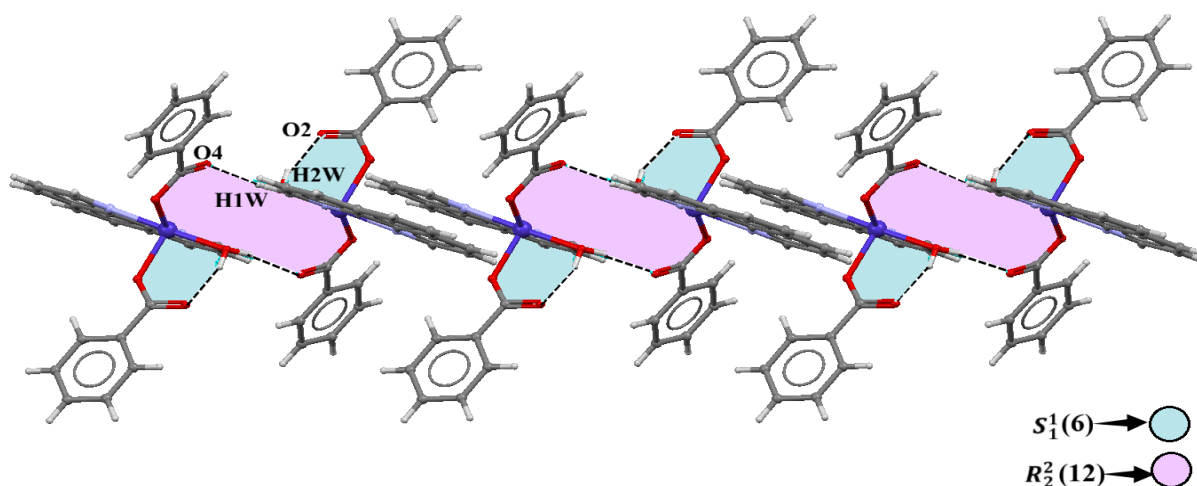


Figure III.21. Visualization of $R_2^2(12)$, $S_1^1(6)$ hydrogen-bonding motifs created through O—H...O strong hydrogen bonds in 2D supramolecular arrangement.

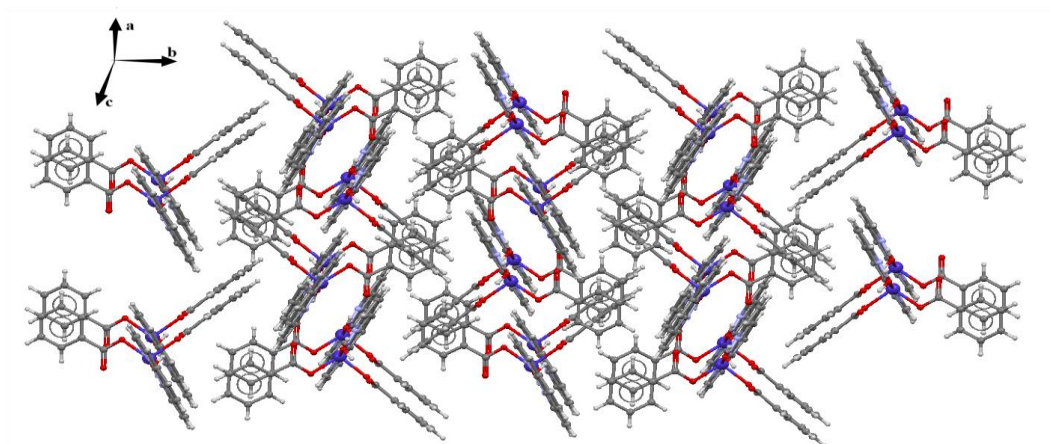


Figure III.22. Two-dimensional packing arrangement views of compound (C2).

III.3.2. Full interaction maps of complex (C2)

The Full Interaction Map (FIM) is a crystallographic tool that has been predicted and visualized through the use of the MERCURY software package [31]. FIM analysis visualizes interaction site preferences within the molecular structure, providing visualization of spatial regions of the molecular structure in which non-covalent interactions are most likely to occur. The basis on which the 3D map is the molecule fragmented into function groups that form scatterplots, then each pair scatterplots of fragments is related together to obtain the full map shape of specific interactions around a crystal molecular. knowing that the scatterplots are available in the Isostar data taken from CSD [32].

In this research, color maps of probes selected with CSD materials are used to determine the areas of probable non-covalent interactions in the complex molecule, as illustrated in (Figure III.23). The dark red hotspots indicate the carbonyl oxygen of the two benzoates and water oxygen probes acceptors with a higher propensity. The opaque blue hotspots represent the probe uncharged NH nitrogen donors for the 1,10-phenanthroline ligand. The brown hotspots illustrate proximity of hydrophobic interactions, and there are some of the more transparent hotspots (blue, red and brown) denote weak active interactions around the whole molecule. In addition, the analysis of the maps may inform regarding crystal packing, and the organization of supramolecular assembly of solid states, and also describe the structure chemical crystallography properties.

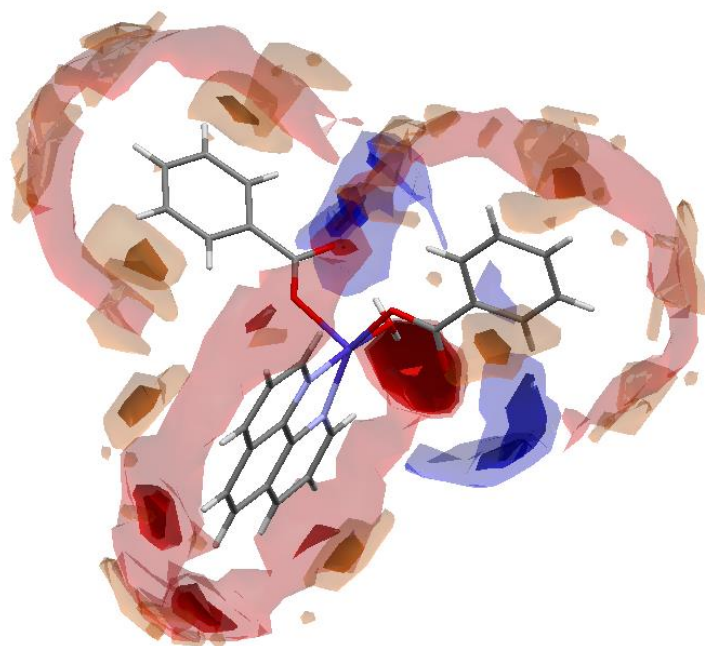


Figure III.23. Full Interaction Map (FIM) illustrating the non-covalent interaction regions around the Cobalt (II) complex (C2).

III.3.3. Hirshfeld surface analysis of Complex (C2)

The intermolecular interactions which are assessed using the Hirshfeld surface method are crucial to understanding the interactions relating to the crystal packing and the overall stability of the compound. Several mapped properties were used to yield high-resolution 3D Hirshfeld surfaces for the mixed-ligand complex as d_{norm} , shape index, curvedness and fragment patch surfaces, and each was displayed on a fixed color scale of -0.2 to 0.5 Å (red to blue), -0.7 to 0.7 Å, -0.3 to 0.3 Å, and 0 to 19 Å (Figure III.24). The normalized contact distance map of crystalline was used to investigate the types of intermolecular interactions with the bright red spots appearing O–H...O and C–H...O contacts. It also, identifying all regions of significant importance to non-covalent interactions in the solid state of the compound C1 is illustrated in Figure III.25. Moreover, the surface defined by the shape-index provides clear evidence of π – π stacking interactions, as evidenced through the pair of opposites triangles with red and blue colors that were located on the aromatic ring systems. This observation further validates the presence of a planar packing mode between neighboring phenanthroline ligands in the crystal lattice (Figure III.24). The curvedness mapping further indicates the presence of π – π stacking through the smooth green flat regions corresponding to low surface curvature features, which relate to layered aromatic contacts.

III.3.4. The two-dimensional fingerprint plots

The two-dimensional fingerprint (FP) plot analysis presents the total contact distribution in Figure III.27 (a), while the percentage contributions of the main intermolecular interactions, including $\text{H}\cdots\text{H}$, $\text{H}\cdots\text{C}/\text{C}\cdots\text{H}$, $\text{H}\cdots\text{O}/\text{O}\cdots\text{H}$, $\text{C}\cdots\text{C}$, $\text{H}\cdots\text{N}/\text{N}\cdots\text{H}$, and $\text{C}\cdots\text{N}/\text{N}\cdots\text{C}$, are depicted in Figure III.27 (b-g), respectively. The dominant non-covalent interactions are $\text{H}\cdots\text{H}$ contacts, contributing 42.1% to the surface with a broad tip at $d_e = d_i = 1.02$ Å, reflecting the high abundance of hydrogen atoms and confirming their major role in crystal packing. $\text{H}\cdots\text{C}/\text{C}\cdots\text{H}$ are the second most significant interactions in complex equal to 30.5% with the tips at $d_e + d_i = 3.1$ Å. The pair of spikes from the $\text{H}\cdots\text{O}/\text{O}\cdots\text{H}$ interactions make up 17.3% of the HS with peaks at $d_e + d_i = 1.8$ Å; this contact plays a major role in the stability of the compound. In addition, the $\text{C}\cdots\text{C}$ interactions represent a few scattered points in the center of the 2D fingerprint plots with a percentage of 6.8%. Lastly, the $\text{H}\cdots\text{N}/\text{N}\cdots\text{H}$ and $\text{C}\cdots\text{N}/\text{N}\cdots\text{C}$ contacts concerning 1.9% and 1.4% weak contributions to the overall crystal packing. In this case study, the 2D fingerprints approach allowed the precise regions and area zones associated with specific important interactions of the single crystal to be shown for the $\text{H}\cdots\text{H}$, $\text{H}\cdots\text{C}/\text{C}\cdots\text{H}$, and $\text{H}\cdots\text{O}/\text{O}\cdots\text{H}$ on the Hirshfeld surface in Figure III.26, respectively.

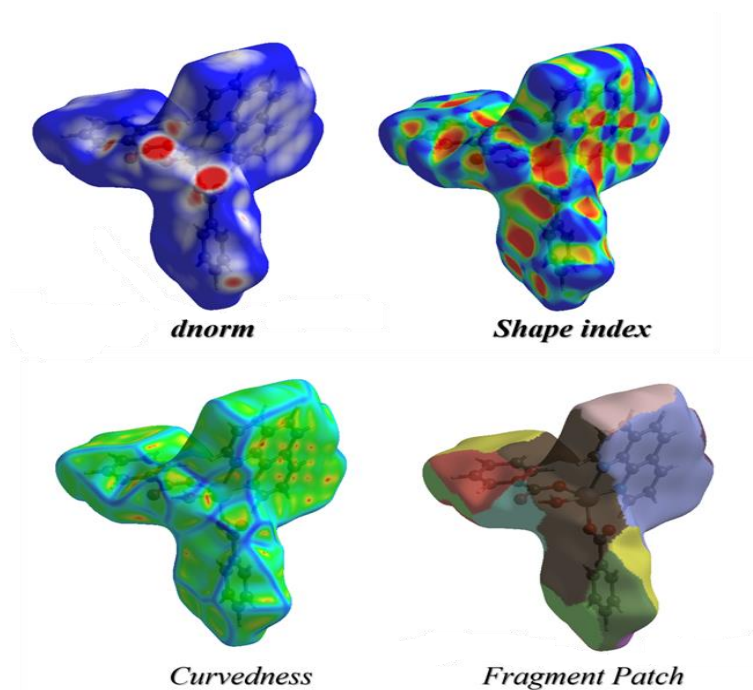


Figure III.24. 3D Hirshfeld surfaces for compound (C2) were visualized by mapping d_{norm} (−0.2 to 0.5 Å), shape index (−0.7 to 0.7 Å), curvedness (−0.3 to 0.3 Å), and fragment patch (0 to 19 Å).

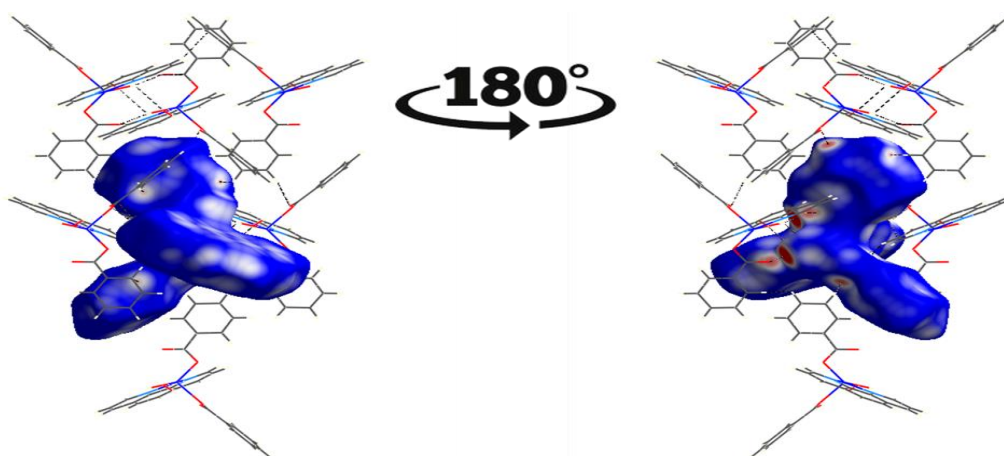


Figure III.25. Two different orientations of the three-dimensional Hirshfeld surface mapped over d_{norm} for cobalt (II) complex (**C2**), highlighting the key intermolecular interactions.

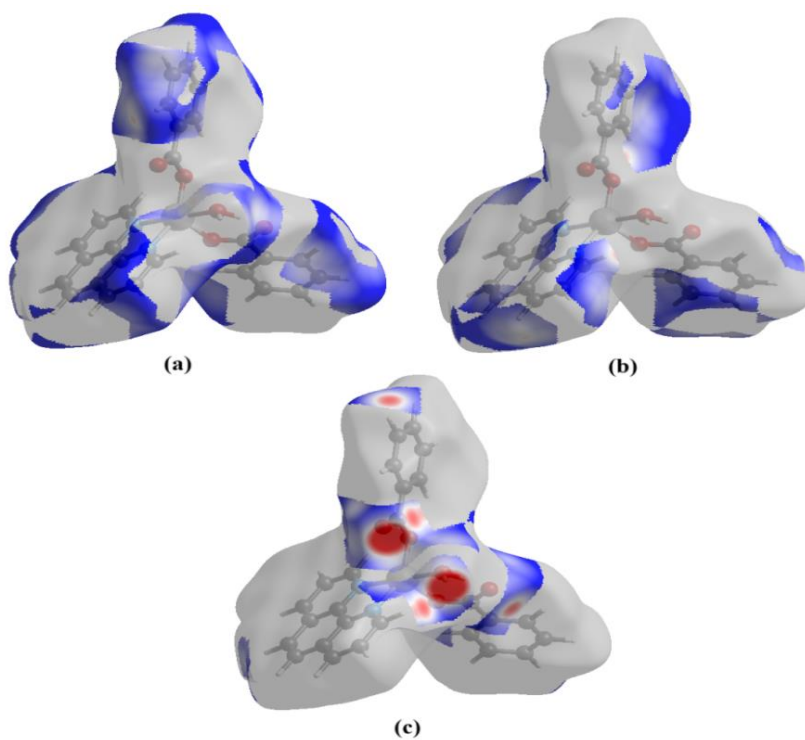


Figure III.26. Representation of the contacts zones plotted onto surface for (a) $H\cdots H$, (b) $H\cdots C/C\cdots H$, and (c) $H\cdots O/O\cdots H$ interactions.

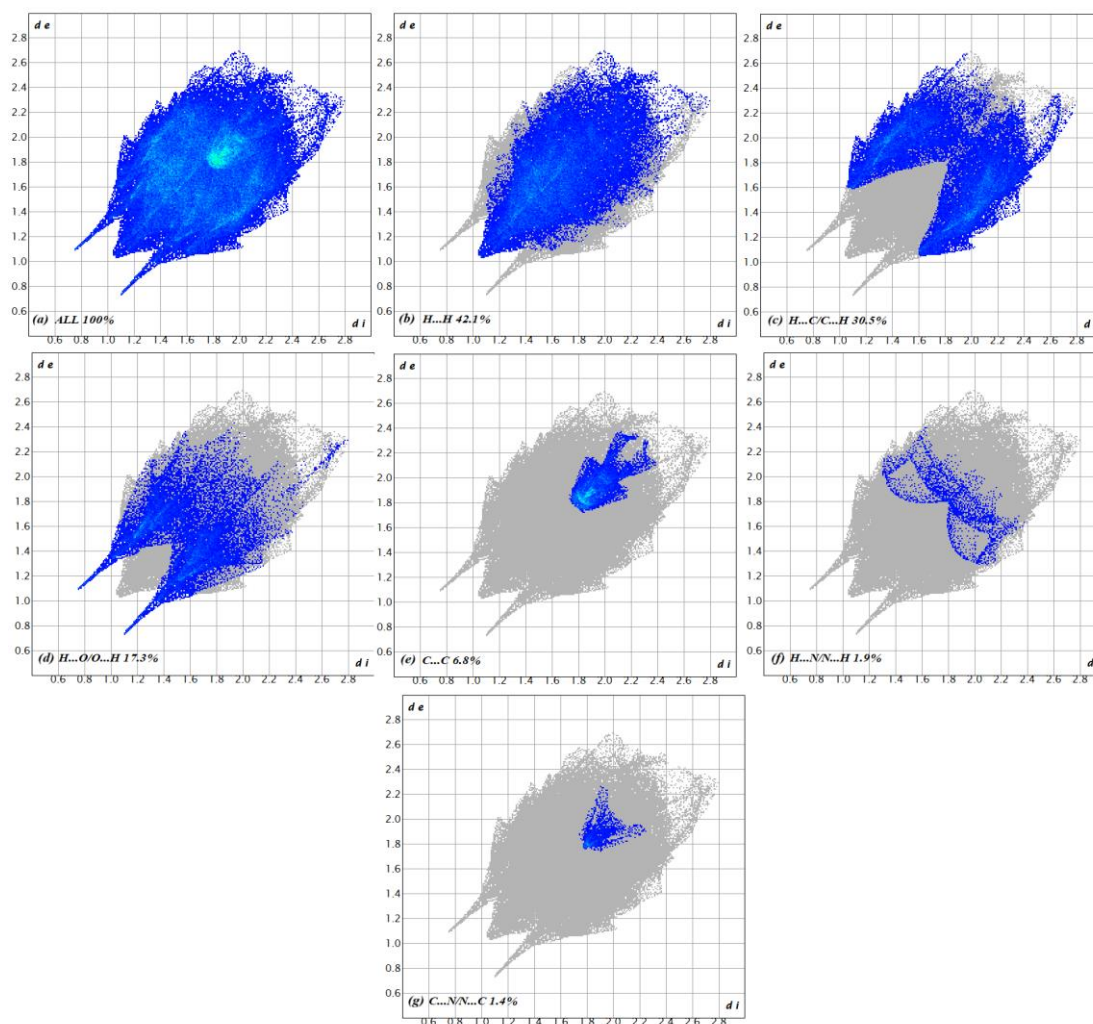


Figure III.27. The 2D fingerprint plots for complex (C2) illustrate all intermolecular contacts (a), with their respective percentage contributions displayed separately: (b) H $\cdots$ H (42.1%), (c) H $\cdots$ C/C $\cdots$ H (30.5%), (d) H $\cdots$ O/O $\cdots$ H (17.3%), (e) C $\cdots$ C (6.8%), (f) H $\cdots$ N/N $\cdots$ H (1.9%), and (g) C $\cdots$ N/N $\cdots$ C (1.4%).

III.3.5. Crystal Voids Analysis of Complex (C2)

The void surface approach is capable of discussing the proprietary mechanical force of structure in single crystal packing [33]. It also reflects the effect of the electron density distribution on the structural design of the compound. Figure III.28 shows that the volume is 202.21 Å³ and the percentage of this empty space is 9.02%, calculated using the *CrystalExplorer* software. Consequently, the crystal packing display is a compact arrangement that significantly increases the overall stability. This small unoccupied space is a result of the strength and the virulence of intermolecular interactions.

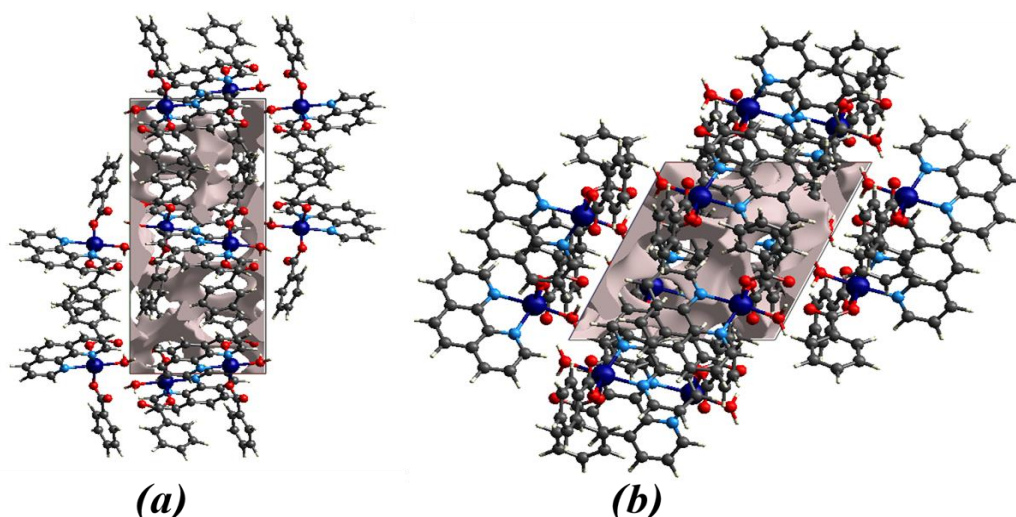


Figure III.28. Graphical representation of the voids in the crystal packing of compound (C2): (a) viewed along the c-axis and (b) viewed along the b-axis.

III.3.6. Infrared spectroscopy of complex (C2)

The experimental IR spectrum of the cobalt (II) complex (C2), depicted in Figure III.29, validates the coordination environment surrounding the Co (II) center. Two expected stretching vibration bands at 475 and 440 cm^{-1} were assigned to the Co–N and Co–O bonds, respectively, validating not only the successful coordination of the bidentate 1,10-phenanthroline ligand through nitrogen atoms but also the coordination of the monodentate benzoate ligand through one oxygen atom. The carboxylate group vibrations are observed as strong bands at 1633 cm^{-1} (ν_{asym}) and 1429 cm^{-1} (ν_{sym}) with a separation of $\Delta\nu = 204 \text{ cm}^{-1}$ consistent with the monodentate coordination mode of the benzoate ligand. Furthermore, the band at 1519 cm^{-1} was attributed to the C=N stretching vibration of the coordinated phenanthroline ligand [34]. A broad absorption band around 3411 cm^{-1} was attributed to O–H stretching, confirming the presence of a coordinated water molecule bound to the cobalt ion.

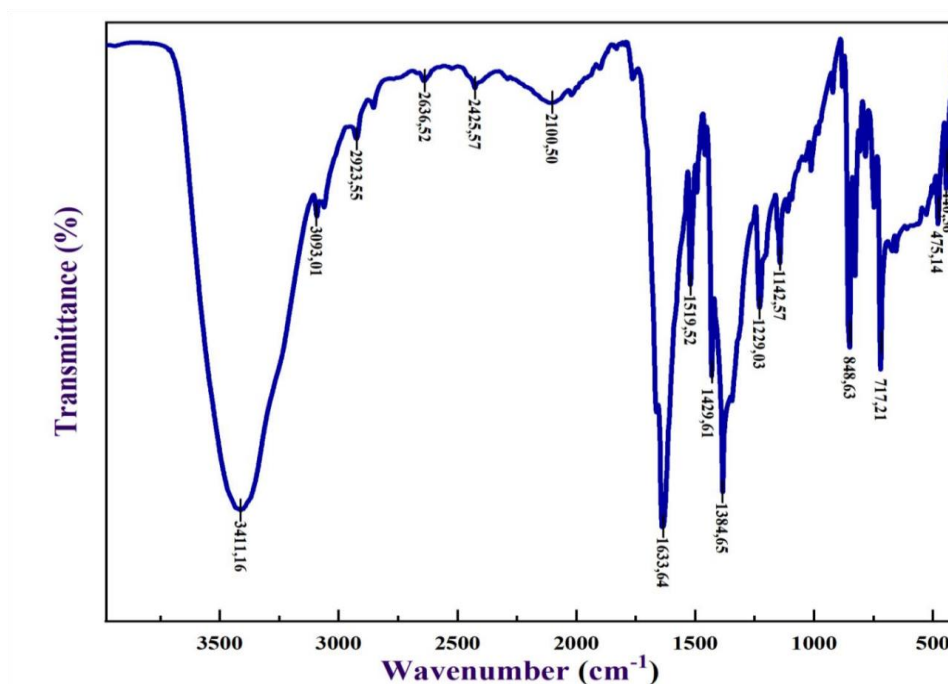


Figure III.29. Experimental FT-IR spectrum of compound (C2).

III.3.7. Ultraviolet-Visible spectroscopy analysis of complex (C2)

The experimental Ultraviolet-Visible spectrum (Figure III.30) of the Aqua-bis(benzoato- κ O) (1,10-phenanthroline- κ^2 N, N') cobalt (II) complex (C2) was recorded in DMSO as a solvent, which illustrates the three absorption bands at 239 nm, 294 nm, and 501 nm. The bond absorption at 239 nm is due to the electronic transition $\pi \rightarrow \pi^*$ in the 1.10 phenanthroline and benzoate ligand. Next, the weaker electronic absorption at 294 nm is attributed to an $n \rightarrow \pi^*$ charge transfer transition corresponding to lone pair- π interactions resulting from the pair electrons of the carboxylate group in the benzoate ligand interacting with phenyl rings of phenanthroline ligands. In addition, the broadness of the absorption peak at 501 nm indicates a spin-allowed d-d transition on the transition metal Cobalt (II), which exhibits a square pyramidal geometry [35].

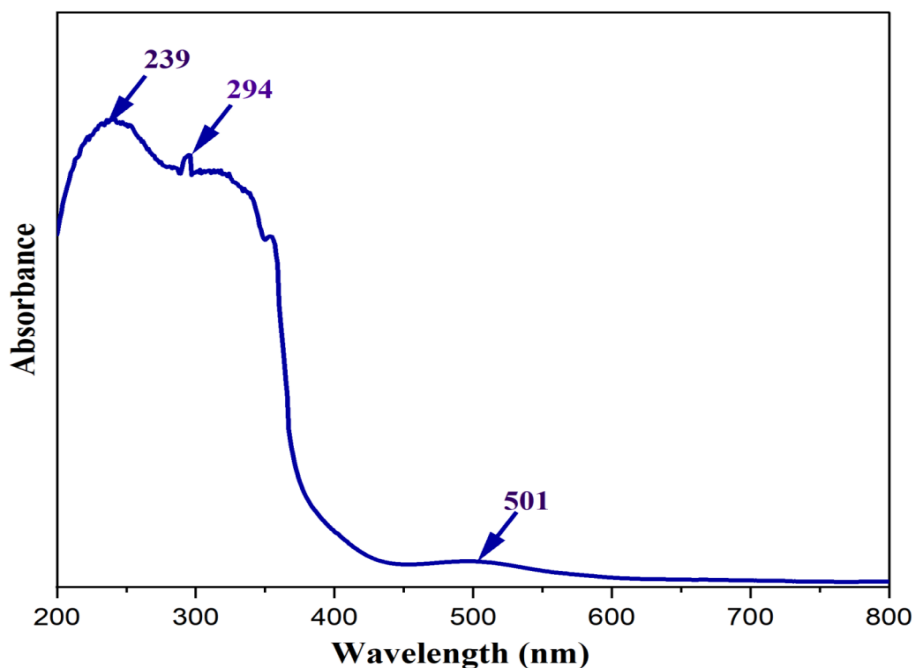


Figure III.30. The experimental UV-Vis spectrum of compound (C2).

III.3.8. Theoretical investigations

III.3.8.1. Geometric optimization of complex (C2)

The aqua-bis(benzoato- κ O) (1,10-phenanthroline- κ^2 N, N') cobalt (II) complex (C2) (Figure III.31), in its fully optimized geometry, has been derived using a density functional theory (DFT) approach through PBE0 hybrid functional. The LANL2DZ basis set was used on the Co (II) center in the Gaussian 09W software package. The optimized structure confirms a distorted square-pyramidal coordination sphere around the cobalt ion, which can be indirectly validated by its excellent correspondence to the experimental crystallographic data. In fact, the theoretical bond distances and angles are in excellent agreement with those obtained by single-crystal X-ray diffraction, helping to further validate the integrity of this model of the cobalt complex's geometry. The optimized geometry also supports coordination of Co (II) to five donor atoms, including two nitrogen atoms, which are donated from a bidentate 1,10-phenanthroline ligand, two oxygen atoms from monodentate benzoate groups, and one water-coordinated oxygen atom. Together, this arrangement supports the cobalt complex as being stable at its true minimum energy geometry.

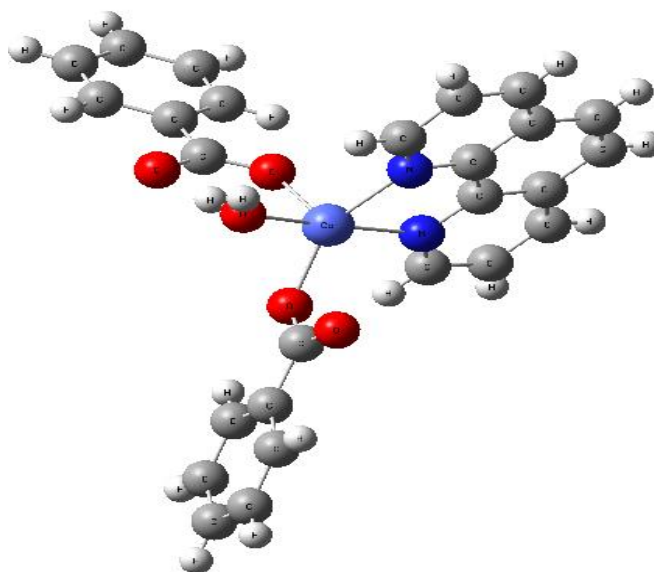


Figure III.31. Theoretical geometry optimization of compound (**C2**) obtained using DFT calculations.

III.3.8.2. Frontier Molecular orbitals analysis of compound (**C2**)

The DFT/PBE0 method with the LANL2DZ basis set was utilized to simulate and optimize the structural geometry of the complex (**C2**) to obtain the geometry bond angles, bond lengths, and electronic parameters (EHOMO, ELUMO and MESP) of the complex. The electronic structure of complex (**C2**) was also investigated via its frontier molecular orbitals shown in [Figure III.32](#). The HOMO can be found to be delocalized across the cobalt center and the aromatic benzoate ligands; the LUMO was found to be localized on the ligands with antibonding π^* character, suggesting a characterization of metal-to-ligand charge transfer (MLCT). The calculated HOMO–LUMO energy gap of 0.84 eV can be interpreted as indicating a high degree of reactivity and polarizability. Similarly, the HOMO-1 and LUMO+1 orbitals are situated on the aromatic ligands, again offering insights into the higher energy electronic transitions associated with UV excitation processes. This indicates the importance of the ligand π -systems in determining the electronic and photochemical behavior of the complex. The relatively small HOMO-LUMO gap and high softness (S) parameter suggests increased chemical reactivity, perhaps contributing to biological activity. The calculated values of the reactivity descriptor parameters (ionization potential (I), electron affinity (A), absolute electronegativity (χ), absolute hardness (η), and softness (S)), for complex (**C2**), were evaluated at the same theoretical level as summarized in [Table III.6](#).

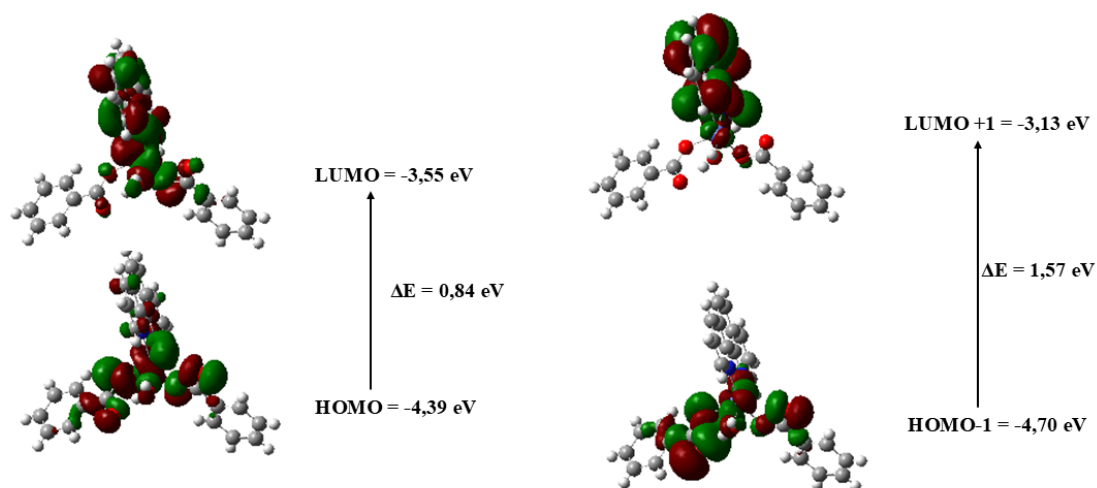


Figure III.32. Frontier molecular orbitals of complex (C2) were calculated at the DFT level using the PBE0 functional with the LANL2DZ basis set.

Table III.6. Global reactivity descriptors for title complex (C2).

Complex	E_{HOMO} (eV)	E_{LUMO} (eV)	E_{gap} (eV)	χ (eV)	I (eV)	A (eV)	η (eV)	S (eV)
(C2)	-4.39	-3.55	0.84	3.97	4.39	3.55	0.42	2.38

III.3.8.3. Molecular Electrostatic Potential analysis of compound (C2)

The molecular electrostatic potential (MEP) evaluation of aqua-bis(benzoato- κ O) (1,10-phenanthroline- κ^2 N, N') cobalt (II) compound C2 (Figure III.33) revealed a potential range exciting from -0.08592 to $+0.08592$ a.u. (-2.34 to $+2.34$ eV), indicating great electronic polarization about the complex. The regions of negative potential about the oxygen atoms of the benzoate and aqua ligands indicate the presence of electron-rich sites that are conducive to electrophilic attack. While positive potential regions near the Co (II) center are electron-deficient surfaces that are suitable for nucleophilic attack. The intermediate potentials surrounding the 1,10-phenanthroline ligand structure do indicate partial charge delocalization through both its aromatic system and nitrogen donor. Generally, the electrostatics indicate a highly polarized coordination environment typical of a mixed-ligand cobalt (II) species.

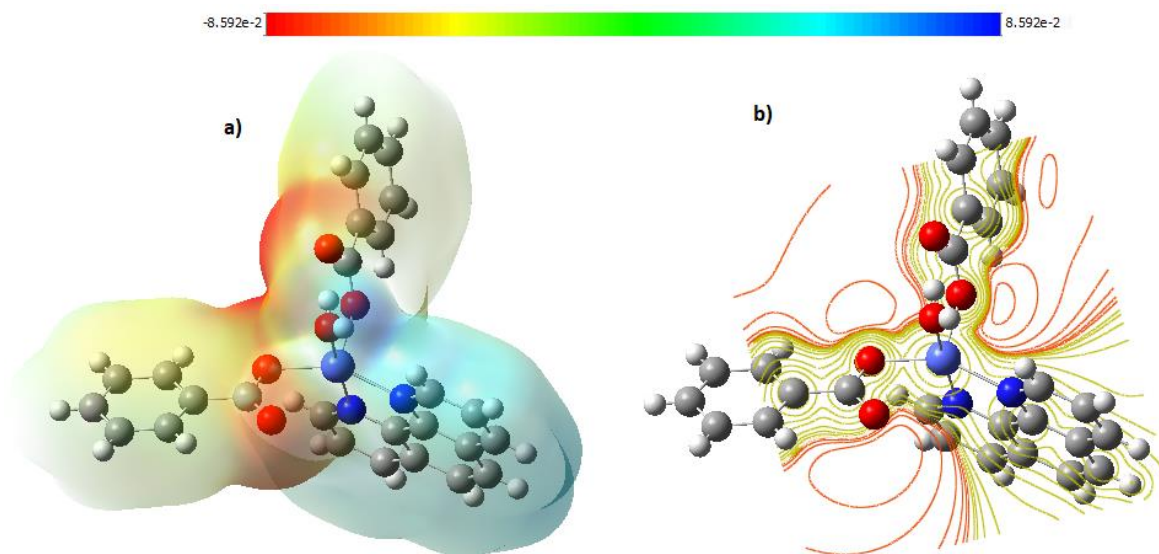


Figure III.33. Molecular electrostatic potential (MEP) maps of cobalt (II) complex (C2) showing (a) surface potential distribution and (b) electrostatic potential contour plot.

III.3.8.4. ELF and LOL analyses for Cobalt complex (C2)

Figure III.34 illustrates the results from Electron Localization Function (ELF) and Localized Orbital Locator (LOL) investigations of the complex (C2). The ELF plot (left side) shows apparent areas of electron localization adjacent to the nitrogen of the phenanthroline ligand and the oxygen of the aqua ligand, where these electrons co-localize with the associated Co–N and Co–O bonds, respectively, consistent with studies of Co–phenanthroline systems [36]. As indicated earlier, localized lobes between the cobalt center and the benzene ligand provide evidence of metal– π interactions, which show a combination of σ -donation from the π -system of benzene, in partnership with π -back-donation from the cobalt d orbitals [37].

In contrast, the LOL map (right) (Figure III.34) displays a smoother distribution of electron density indicative of greater orbital delocalization within the π -framework of the benzene ring, which is consistent with the Born–Oppenheimer-type character of LOL [38], based on kinetic energy density. The LOL maxima are lower than ELF maxima due to some degree of bonding character delocalization characterizing metals and π -type interactions. The combination of ELF and LOL further supports a mix of localized coordinate bonds (Co–N and Co–O) and delocalized metal– π interactions (Co–Bz) within cobalt's coordination sphere. the results from Electron Localization Function (ELF).

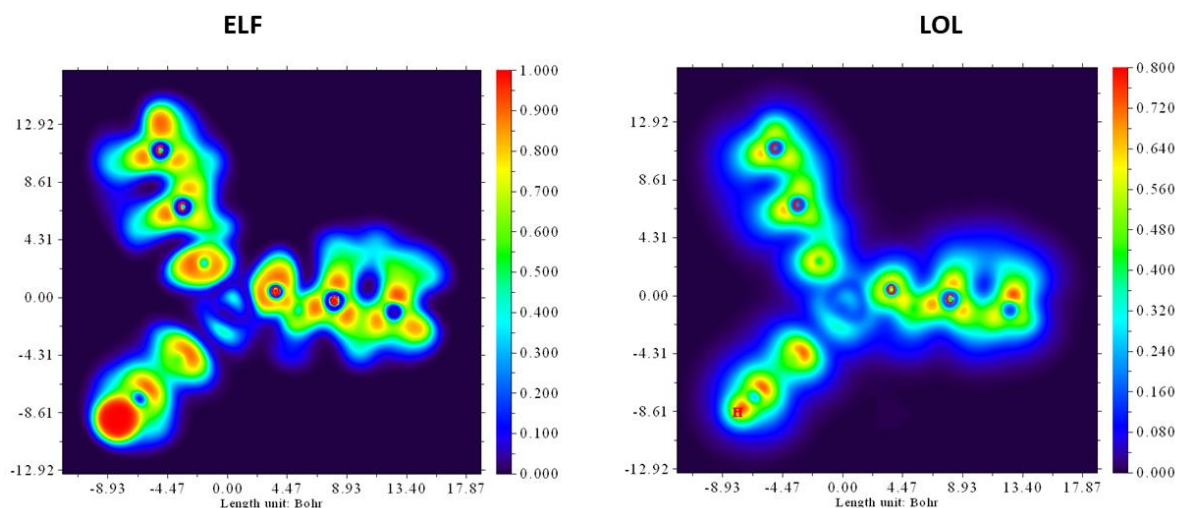


Figure III.34. ELF (Electron Localization Function) and LOL (Localized Orbital Locator) plots for the Co (II) complex (C2).

III.3.8.5. Topological analysis using RDG (Reduced Density Gradient)

The reduced density gradient (RDG) analysis (Figure III.35) has been performed to explore the noncovalent interactions in the cobalt (II) complex (C2). The RDG function λ_2 is a function of the density $\rho(r)$ and its gradient $\nabla\rho(r)$ [39]. The sign of $\lambda_2\rho$ provides for distinguishing attractive ($\lambda_2 < 0$) from repulsive ($\lambda_2 > 0$) interactions. As shown in the RDG scatterplot, there are a number of spikes in the range of -0.05 to $+0.05$ a.u., confirming that there are a number of weak interactions in the complex (C2). The negative sign (λ_2) ρ (blue areas) refers to attractive interactions like hydrogen bonding, while positive (λ_2) ρ values (red areas) correspond to steric repulsion. The isosurface of RDG show that there are blue regions between O1W–H2W $\cdots$ O2 and O1W–H1W $\cdots$ O4. This is indicative of strong hydrogen bonding interactions between the coordinated water molecule and the O-atoms of the benzoate. Furthermore, there is a blue-green isosurface between C19–H19 $\cdots$ O4, revealing the presence of a weaker C–H $\cdots$ O hydrogen bond that also proves stabilizing in molecular packing. The green areas surrounding the phenanthroline and benzoate ligands are indicative of van der Waals interactions and further provide notable supramolecular stability. Conversely, red fusiform patches near the aromatic rings and Co–O coordination atoms show steric repulsion due to elastic density overlaps. These RDG features of the corresponding interactions provide proof that the stability and geometry of the cobalt (II) complex rely on an equilibrium of hydrogen bonding, van der Waals interactions, and sterics.

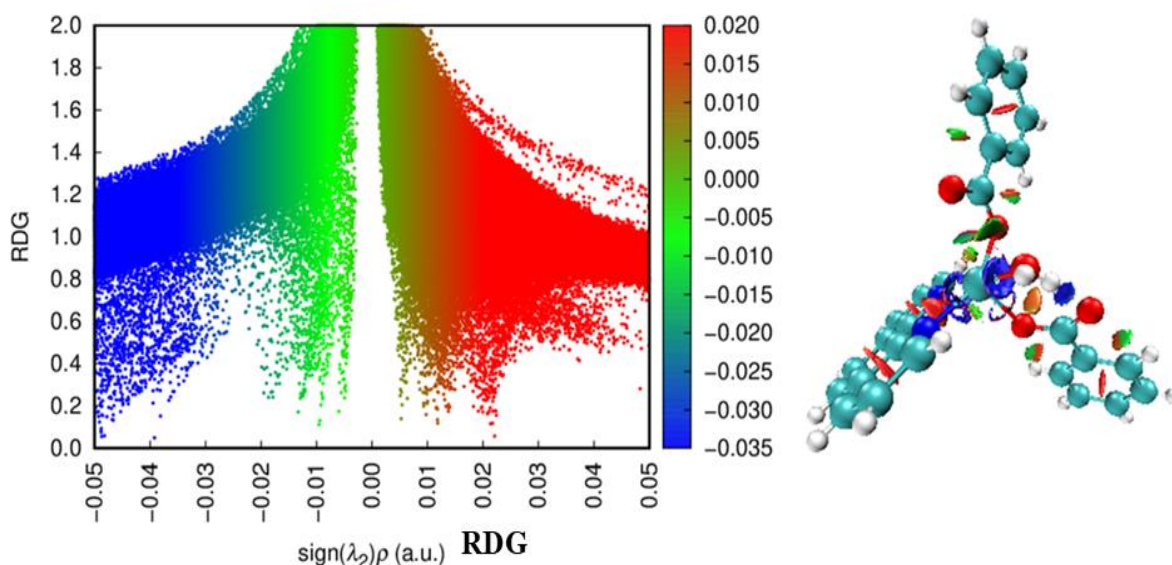


Figure III.35. The RDG scatter plots of Cobalt (II) complex (C2).

III.4. Study of new complex Aqua-chloro(1,10-phenanthroline- κ^2N, N') nickel (II) chloride monohydrate (C3)

III.4.1. Crystal structure analysis of complex (C3)

The molecular structure of complex **C3** (shown in Figure III.36) crystallizes in the monoclinic system, with a 2_1 screw axis running parallel to the b-axis and an n-glide plane corresponding to the space group $P2_1/n$. The main crystallographic data and parameters for structure refinement for complex C3 are summarized in Table III.7. The Ni (II) ion is contained in a distorted octahedral geometry presenting six coordination (Figure III.36) [40, 41]. Geometric bond lengths and angles can be found in Table III.8. The coordination sphere is formed by two nitrogens of a bidentate 1,10-phenanthroline ligand, three aqua ligands, and one coordinate chloride (C11) atom. The Cl⁻ anion and the lattice water are coordinated by the strong intramolecular hydrogen bonds, specifically O1W—H $\cdots$ Cl2 and O2W—H $\cdots$ O4W, with the distances of [H $\cdots$ Cl2 = 2.29 Å and H $\cdots$ O4W = 1.93(1) Å]. The Cl⁻ anion also contributes to charge neutrality by acting as a counter ion for the cationic complex unit [Ni (Phen)(H₂O)₃ (Cl)]⁺ present in the structure.

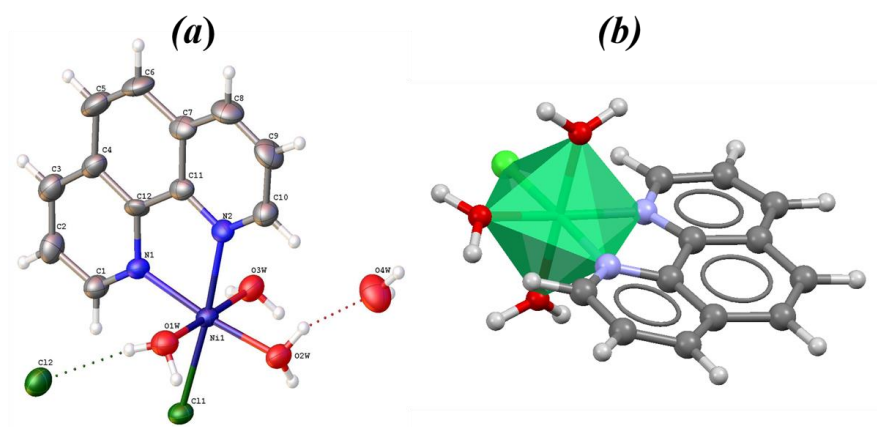


Figure III.37. (a) Molecular view and fragment of the optimized structure of complex (C3), (b) emphasizing the geometry around the Ni (II) metal center.

Table III.7. Crystal data and structure refinement parameters for Nickel (II) complex (C3).

Crystallographic data	Complex (C3)
Chemical formula	C ₁₂ H ₁₆ Cl ₂ N ₂ NiO ₄
<i>M_w</i> (g/mol)	381.88
Temperature (K)	294(2)
Crystal system	Monoclinic
Space group	P2 ₁ /n
a, b, c (Å)	7.5763(18), 12.3382(12), 16.849(5)
α, β, γ (°)	90, 102.27(3), 90
V (Å ³)	1539.0(6)
Z	4
P _{calc} (cm ³)	1.648
μ (mm ⁻¹)	1.623
Crystal size (mm ³)	0.395 × 0.184 × 0.153
Radiation	Mo Kα (λ = 0.71073)
2θ range for data collection (°)	5.95 to 51.358
Index ranges	-7 ≤ h ≤ 9, 0 ≤ k ≤ 15, -20 ≤ l ≤ 6
Reflections collected	2921
Data/restraints/parameters	2921/0/196
Goodness-of-fit on F ²	1.125
Final R indexes [I ≥ 2σ (I)]	R ₁ = 0.0751, wR ₂ = 0.1895
Final R indexes	R ₁ = 0.0868, wR ₂ = 0.1974
Δρ _{max} , Δρ _{min} (e Å ⁻³)	1.40/-0.83

Table III.8. Main bond distances and bond angles for the compound (**C3**).

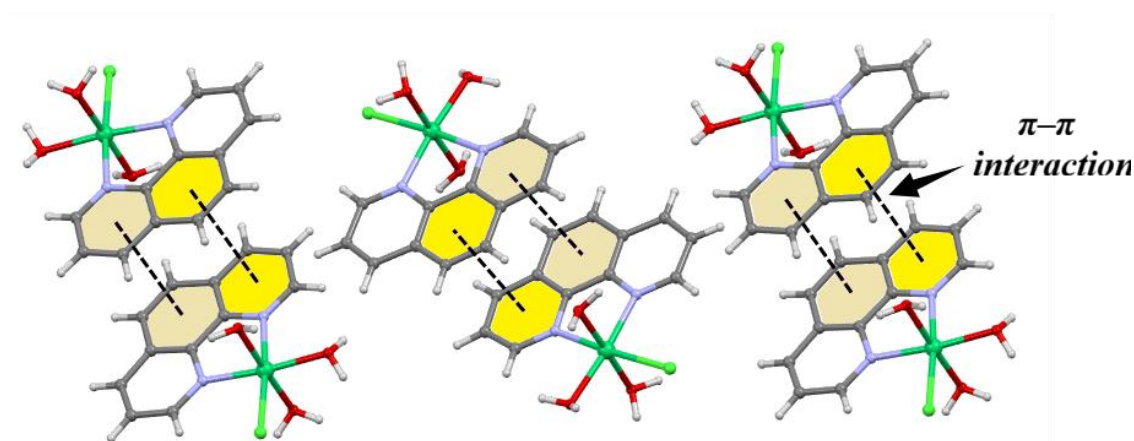
Bond distances (Å)		DFT	Bond angles (°)		DFT
Ni—O1W	2.050 (7)	2.050	O1W—Ni—O2W	89.3 (3)	89.9
Ni—O2W	2.058 (5)	2.059	O1W—Ni—O3W	177.8 (2)	177.8
Ni—O3W	2.059 (7)	2.057	O1W—Ni—N1	90.4 (3)	90.3
Ni—N1	2.062 (6)	2.061	O1W—Ni—N2	88.1 (3)	88.1
Ni—N2	2.101 (6)	2.100	O1W—Ni—Cl1	90.7 (19)	90.7
Ni—Cl1	1.353(9)	1.361	O2W—Ni—O3W	90.0 (3)	90.0
			O2W—Ni—N1	173.2 (2)	173.2
			O2W—Ni—N2	92.5 (2)	92.5
			O2W—Ni—Cl1	92.2 (17)	92.2
			O3W—Ni—N1	90.1 (3)	90.3
			O3W—Ni—N2	89.8 (3)	89.8
			O3W—Ni—Cl1	91.3 (19)	9.3
			N1—Ni—N2	80.7 (2)	80.6
			N1—Ni—Cl1	94.5 (17)	94.5
			N2—Ni—Cl1	175.0 (18)	175.0

The molecular framework of complex (**C3**) is stabilized through various non-covalent interactions. Single-crystal X-ray diffraction confirms the presence of both O—H $\cdots$ Cl and O—H $\cdots$ O intermolecular hydrogen bonds, which are summarized in Table III.9. The coordinated oxygen water O1W—H1WA forms the donor-acceptor strong interaction with the coordinate Cl1 atom. Together, the O2W—H2WB, O3W—H3WA, and O4W—H4WA coordinate water molecules binding with the Cl2 anion unit to create three other H-Bond contacts. In addition, two hydrogen bonds were formed by the interaction of the O3W—H3WB and O4W—H4WB of lattice water with the Cl coordinate atom. The aim of these hydrogen bindings is to determine and describe the supramolecular arrangement of the crystal structure and reinforce its rigidity and chemical properties [42, 43]. In addition, the Ni(II) metal-organic complex displays remarkable π – π stacking interactions between neighboring 1,10-phenanthroline groups, as shown in Figure III.38. The centroid-to-centroid distance between the two stacked aromatic rings (C4, C5, C6, C7, C11, C12) and (C9, C10, N2, C11, C7, C8) is 3.770 Å, while the shortest C $\cdots$ C contact is 3.714 Å (C5 $\cdots$ C10). These π – π interactions are important for enhancing the structural integrity of the complex in the supramolecular architecture [44, 45].

Table III.9. Summary of Hydrogen bonds present in Nickel (II) complex **C3**.

D—H...A	d(D—H)/Å	d(H...A)/Å	d(D-A)/Å
O1W—H1WA...Cl2	0.87	2.29	3.142(7)
O1W—H1WB...Cl1 ¹	0.87	2.32	3.151(7)
O2W—H2WA...O4W	0.85	1.93	2.704(10)
O2W—H2WB...Cl2 ¹	0.85	2.71	3.267(6)
O3W—H3WA...Cl2 ²	0.85	2.31	3.105(7)
O3W—H3WB...Cl1 ³	0.85	2.32	3.142(7)
O4W—H4WA...Cl2 ⁴	0.85	2.39	3.177(7)
O4W—H4WB...Cl1 ³	0.85	2.66	3.296(8)

Symmetry codes : ¹1-x,2-y,-1-z; ²1+x,+y,+z; ³-x,2-y,-1-z; ⁴1/2+x,3/2-y,-1/2+z

**Figure III.38.** Visualization of π - π stacking interactions in the 1D supramolecular architecture within the complex (**C3**).

III.4.2. Full interaction map for the Nickel (II) complex (**C3**)

The interaction map for the Nickel (II) complex (**C3**) is illustrated in Figure III.39. The *MERCURY* program [31] was used to generate the full interaction map through analysis and visualization of the interactions surrounding the whole structure. This tool, represented by colored hotspot regions, indicates areas of non-covalent interactions present within the crystal lattice. In this study, the red hotspots represent donor zones corresponding to the oxygen atoms from coordinated and lattice water molecules, which are crucial for the formation of strong O—H...O hydrogen bonds, as well as for the presence of O—H...Cl non-covalent interactions. The opaque green hotspots highlight the acceptor regions associated with the coordinated chlorine atoms and the chloride anion. The blue regions reveal the NH nitrogen for the bidentate

phenanthroline ligand. Additionally, the transparent brown, green, and blue zones surrounding the molecule prove the existence of the aromatic C-H carbon and highlight the weak interactions, such as π - π stacking and C-H $\cdots$ π contacts within the whole molecule of metal-organic complex (C3).

Overall, this 3D interaction map effectively enhances the identification and understanding of the intermolecular interaction regions within the crystal lattice, thereby contributing to the evaluation of the stability of the compound in the solid state.

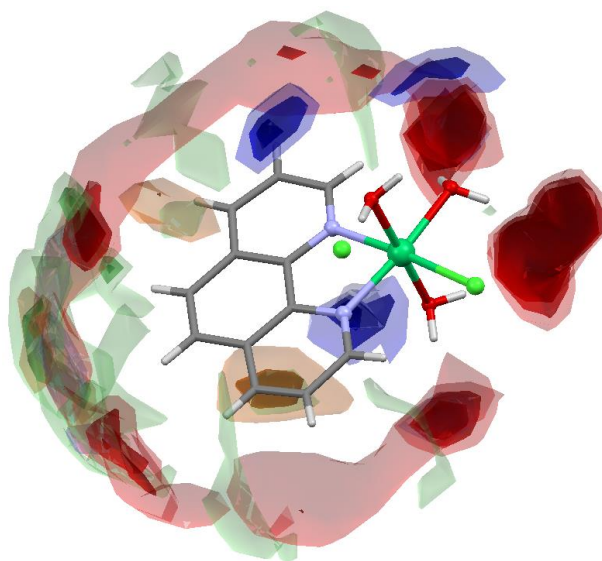


Figure III.39. The Full Interaction Map of the Nickel (II) complex (C3) visualizes the regions of intermolecular interactions.

III.4.3. Hirshfeld surface analysis of Nickel (II) complex (C3)

The Hirshfeld surface (*HS*) method is commonly utilized in crystallography to assess intermolecular interactions through the identification of close contact areas in the crystal lattice. Various three-dimensional surfaces with different representations were made transparently using CrystalExplorer software [46, 47]. The Hirshfeld surfaces of the crystal structure (C3), including d_{norm} , d_e , d_i , shape index, curvedness, and fragment patch, are displayed in (Figure III.40) and (Figure III.41). The normalized contact distance (d_{norm}) on the surface of the Nickel (II) complex (C3) displays values between -0.3 (red) to 0.4 (blue) a.u (Figure III.40). The d_{norm} surface emphasizes hydrogen-bonding interactions, with spots that are red indicating areas of strong contacts. Bright red spots near the chlorine and oxygen atoms represent strong O-H $\cdots$ O and O-H $\cdots$ Cl hydrogen bonds located in the molecule, while lighter red spots indicate the

weaker interactions. One notable weak hydrogen bond is indicated by a spot on the surface, C–H $\cdots$ O, located in the crystal packing between the hydrogen atom (H10) of the 1,10-phenanthroline ring and the oxygen (O4W) of the lattice water molecule. Moreover, Figure III.42 shows all important intermolecular contacts in the crystal arrangement to present a holistic picture of the interactions that stabilize the lattice.

Additionally, the shape index surface mapping from -0.7 to 0.7 a.u. showed oppositely red and blue triangles that represented the $\pi\cdots\pi$ stacking interactions of the bidentate phenanthroline ligands. The presence of these weak, planar interactions is further supported by the flat regions on the Curvedness surface that are mapped from -0.3 to 0.1 a.u. (Figure III.41).

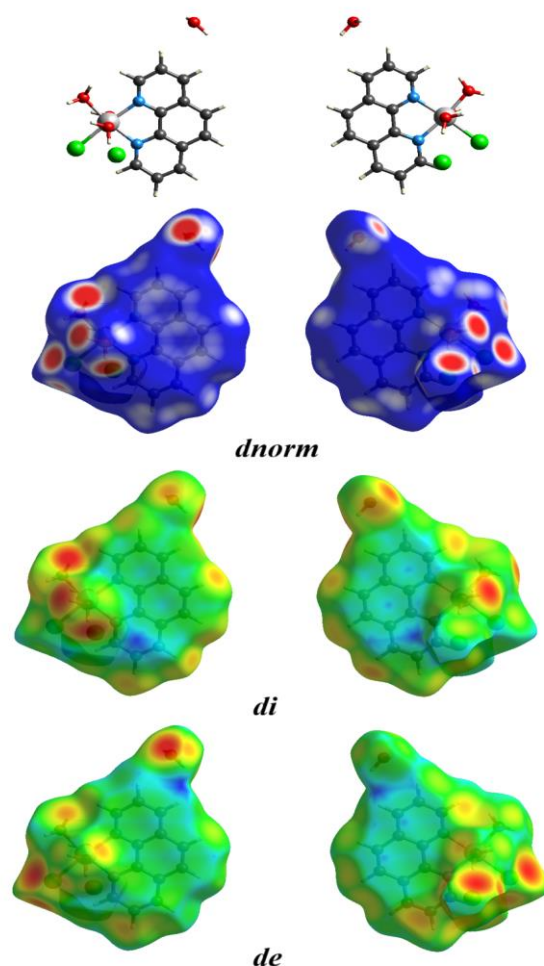


Figure III.40. Two views of the 3D Hirshfeld surfaces plotted over with *dnorm*, *di*, and *de* for Nickel (II) complex (C3).

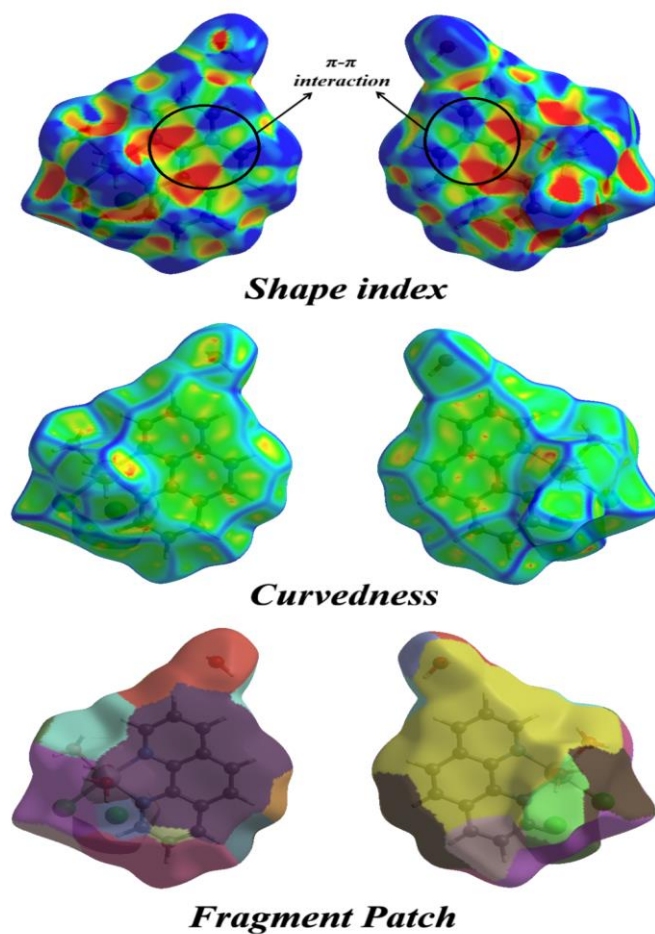


Figure III.41. Two perspectives of the Hirshfeld surfaces mapped over with Shape index, Curvedness, and Fragment patch of complex (C3).

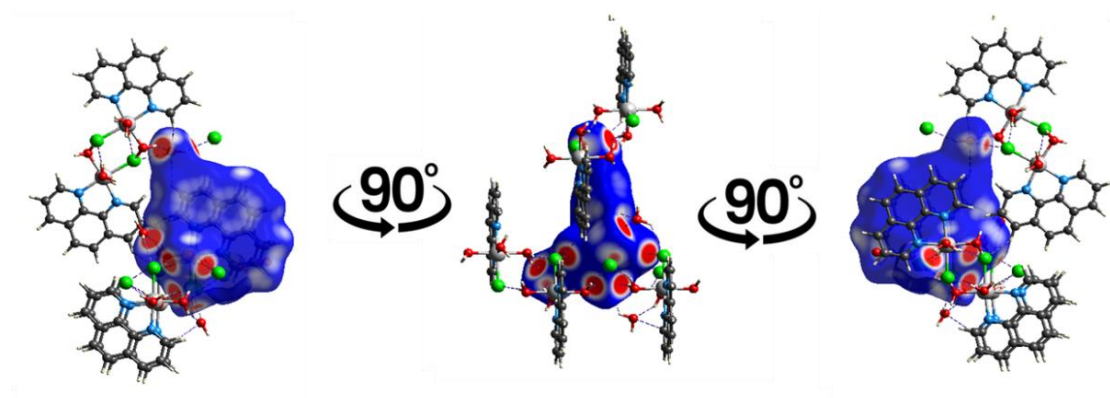


Figure III.42. 3D Hirshfeld surfaces of all intermolecular interactions for the Nickel (II) complex (C3), mapped over $dnorm$ in the range of -0.2 to 0.4 a.u.

III.4.4. 2D Fingerprint plots of complex (C3)

The two-dimensional fingerprint plots (2D-FPs) [48] provide a quantitative indication of all intermolecular interactions found in the Nickel (II) complex (C3), as seen in Figure III.43. These resulting 2D graphs of all close interactions included the reciprocal contacts. The dominant interactions are H $\cdots$ H contacts, representing van der Waals forces within the crystal lattice, which account for 36.8% of the total Hirshfeld surface area. This pattern indicates a high density of hydrogen atoms in the molecular structure, characterized by a distinct tip at $d_e = d_i = 1.2$ Å. The next most significant contributions arise from H $\cdots$ Cl/Cl $\cdots$ H interactions, attributed to hydrogen bonding, comprising 28.5% of the total surface and appearing as a pair of spikes with tips at $d_e + d_i = 2.20$ Å. The H $\cdots$ O/O $\cdots$ H interactions contribute 13.5%, visible as twin spikes at a close-contact distance of $d_e + d_i = 2.18$ Å. Meanwhile, the H $\cdots$ C/C $\cdots$ H interactions account for 10.8% of the total surface area. The C $\cdots$ C contacts contribute 8.8%, indicative of possible $\pi\cdots\pi$ stacking interactions. There are also additional weak intermolecular contacts, such as H $\cdots$ N/N $\cdots$ H, C $\cdots$ N/N $\cdots$ C, and C $\cdots$ Cl/Cl $\cdots$ C, that also contribute, but only to a minor extent, to the global Hirshfeld surface.

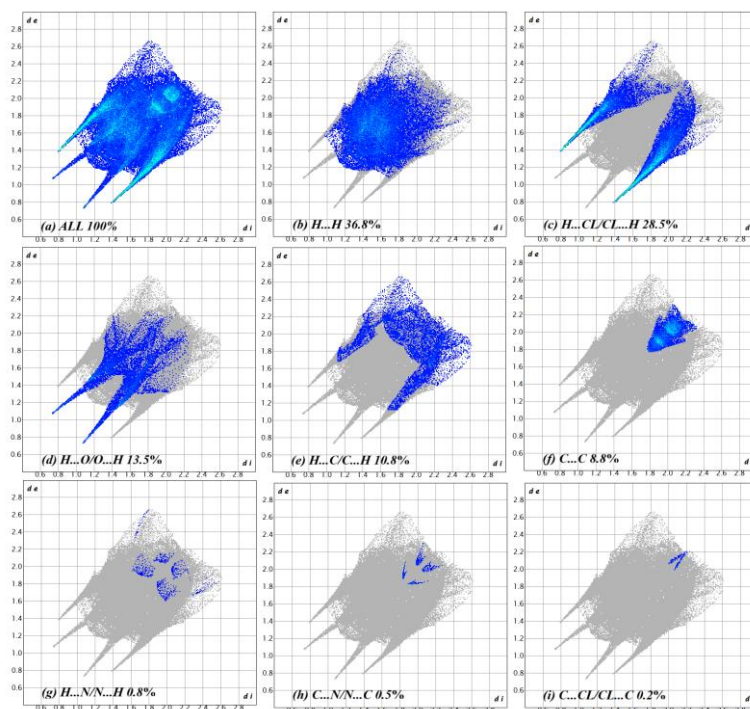


Figure III.43. The 2D fingerprint plots for complex C3, presented all interactions (a), which are divided into (b) H $\cdots$ H 36.8%, (c) H $\cdots$ Cl/Cl $\cdots$ H 28.5%, (d) H $\cdots$ O/O $\cdots$ H 13.5%, (e) H $\cdots$ C/C $\cdots$ H 10.8%, (f) C $\cdots$ C 8.8 %, (g) H $\cdots$ N/N $\cdots$ H 0.8%, (h) C $\cdots$ N/N $\cdots$ C 0.5%, and (i) C $\cdots$ Cl/Cl $\cdots$ C 0.2% contacts.

III.4.5. Crystal Void Analysis of Complex (C3)

The void surface of the nickel (II) complex **C3** (Figure III.44) was calculated using the *CrystalExplorer* program. This tool is widely used to determine the hardness of crystal packing and understand the mechanical properties of compounds. Void analysis allows for the calculation of both volume and percentage of unoccupied space in a crystal structure based on electron density distribution. In this study, the unoccupied volume within the unit cell complex (**C3**) was obtained at 124.16 Å³, and its percentage was calculated as 8.06% in the unit cell. This lower unfilled volume percentage reveals the rigidity and mechanical stability of the complex.

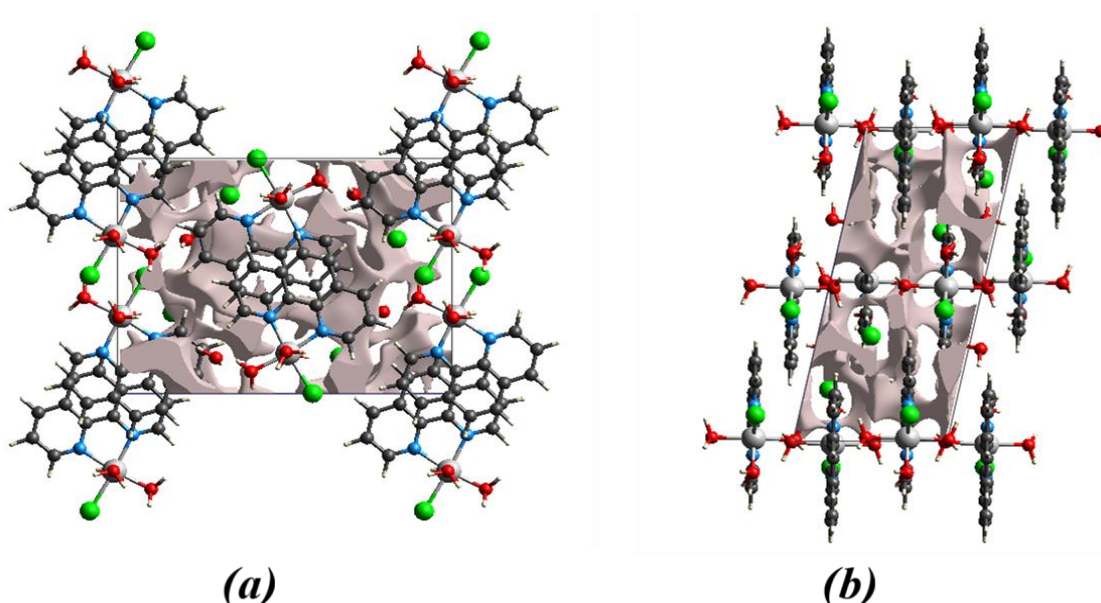


Figure III.44. Graphical representation of the voids within the crystal packing of the Nickel (II) complex (**C3**), viewed (a) along the *a*-axis and (b) along the *b*-axis.

III.4.6. Infrared spectroscopy of complex (C3)

Figure III.45 depicts the IR spectrum for Nickel (II) complex (**C3**), which was obtained in the range of 400–4000 cm⁻¹. The spectrum features a broad absorption band around 3369 cm⁻¹ from the O–H stretching vibrations of coordination and lattice water molecules, followed by peaks at 3053, 2830, and 2607 cm⁻¹ attributable to the aromatic C–H stretching vibrations from the phenanthroline (Phen) heterocycle ligand [49]. Peaks at 1585, 1512, 1427, and 1342 cm⁻¹ confirm that a 1,10 phenanthroline ligand is present in the coordination sphere. Specifically, the sharp bands at 1585 and 1512 cm⁻¹ correspond to C=N and C=C groups and revealed remarkable shifts compared to the $\nu(\text{C}=\text{N})$ and $\nu(\text{C}=\text{C})$ of the free phenanthroline molecule [50]. Peaks at 1427 and 1342 cm⁻¹ may indicate the C–H and C–N vibrations of phenanthroline,

confirming the binding of the nitrogen atoms to the nickel (II) ion in the complex **C3** [51]. The FTIR spectrum exhibits low-frequency bands at 477 and 637 cm^{-1} , which confirm the Ni–N and Ni–Cl stretching vibrations, respectively [52].

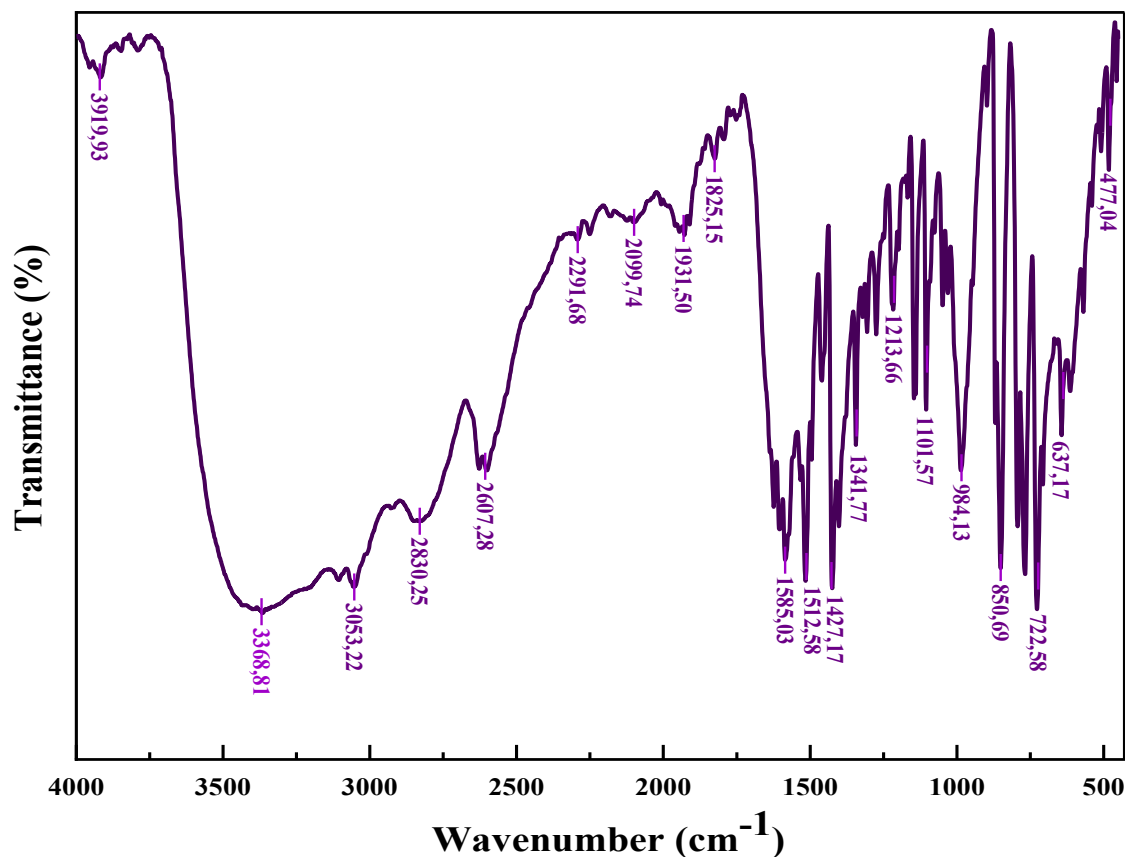


Figure III.46. IR spectrum of Nickel (II) complex (**C3**).

III.4.7. Theoretical Investigations

III.4.7.1. Geometrical optimization of complex (**C3**)

The structure of the Ni (II) complex (**C3**) was optimized using the DFT/B3LYP/6-311G+ (d, p) method. The optimized geometry of the Ni (II) complex is depicted in [Figure III.47](#). The Ni–O bond length (for the H_2O ligand) is approximately 2.05 Å. The Ni–Cl and Ni–N distances are about 2.42 Å and 2.10 Å, respectively. The full optimized structure confirms a distorted octahedral coordination geometry around the nickel ion. These bond distances indicate that the synthesized Nickel complex has a well-organized, symmetrical, and stable arrangement of atoms, which is indicating significant structural stability and potential biological activity.

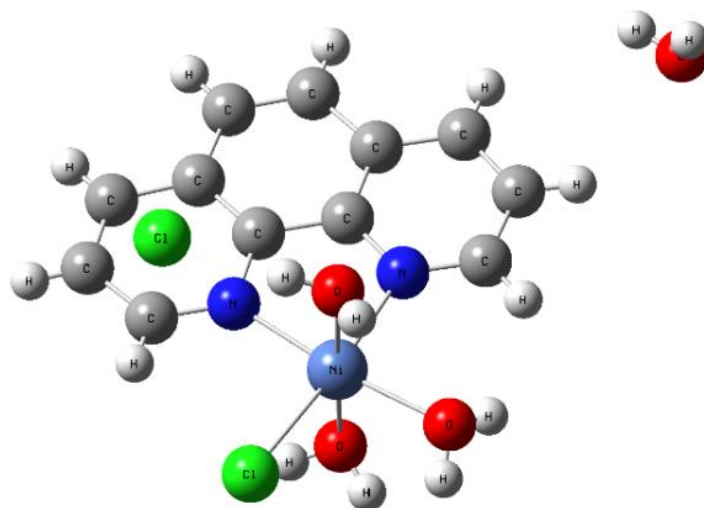


Figure III.47. Theoretical geometry optimization of compound (**C3**) obtained using DFT calculations.

This diagram (Figure III.48) shows the key molecular orbitals for the nickel complex (**C3**). The HOMO (highest occupied molecular orbital) mainly sits on the ligands, especially on the aromatic ring and the nitrogen and chlorine atoms. This means it's mostly a π -type ligand donor. The LUMO (lowest unoccupied molecular orbital), on the other hand, is mostly on the nickel metal and the oxygen and nitrogen atoms attached to it. This shows it's a metallic d-type and it accepts electrons. So, when an electron moves from the HOMO to the LUMO, it's like a charge is moving from the ligand to the metal (MLCT), and this takes 2.22 eV of energy. The HOMO-1 orbital is slightly lower than the HOMO, still decided upon the ligands. The LUMO+1, slightly higher than the LUMO, continues to have some presence both on the metal and the ligands. The energy gap between HOMO-1 and LUMO+1 (1.28 eV) is less than that of the usual HOMO-LUMO gap because, most probably, these are two orbitals of very similar nature (both π or d), hence their energies would be closer together. This describes that there will be a stronger electronic effect interacting with orbitals of parallel types rather than with a typical HOMO-LUMO pair where one is from a different electronic area (ligand to metal). This compound has a small HOMO-LUMO energy gap and thus is quite soft; it implies reactivity. This could make it work better with biological systems. We also figured out its ionization potential (I), electron affinity (A), electronegativity (χ), hardness (η), and softness (S). You can find those numbers for compound (**C3**) in Table III.10.

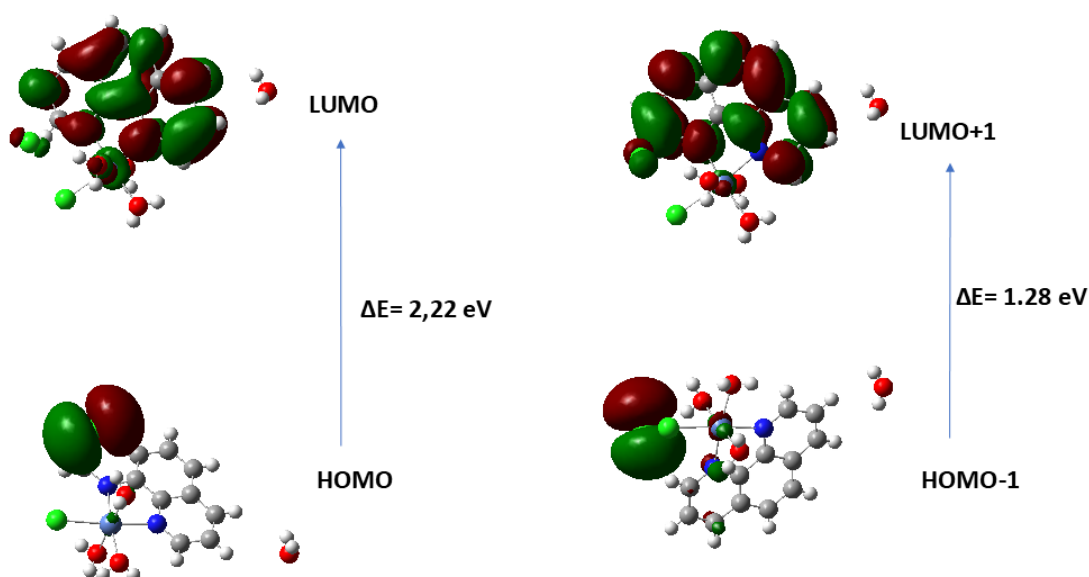


Figure III.48. Frontier molecular orbitals (HOMO, LUMO, HOMO-1, and LUMO+1) of the nickel complex and their corresponding energy gaps.

Table III.10. Global reactivity descriptors for title complex (C3).

Complex	E_{HOMO} (eV)	E_{LUMO} (eV)	E_{gap} (eV)	χ (eV)	I (eV)	A (eV)	η (eV)	S (eV)
(C3)	-3.50	-1.28	2.22	2.39	3.50	1.28	1.11	0.90

III.4.7.2. Molecular Electrostatic Potential analysis of compound (C3)

The molecular electrostatic potential (MEP) computed at the B3LYP/6-311+G (d, p) level demonstrates this clearly within the complex (C3). The data, shown in Figure III.49, shows areas of negative potential red and yellow primarily found around the oxygen atoms of the coordinated water molecules and the chloride group, suggesting these atoms can support an electrophilic attack. Areas of positive potential light blue are seen mostly on the ligand backbone hydrogen atoms, suggesting these could support a nucleophilic attack. The MEP distribution shows the overall highly electron-rich nature of the oxygen donor groups and the significant electron-deficient nature of the hydrogen atoms near the metal center more accurately supports them being the main reactive sites of the complex.

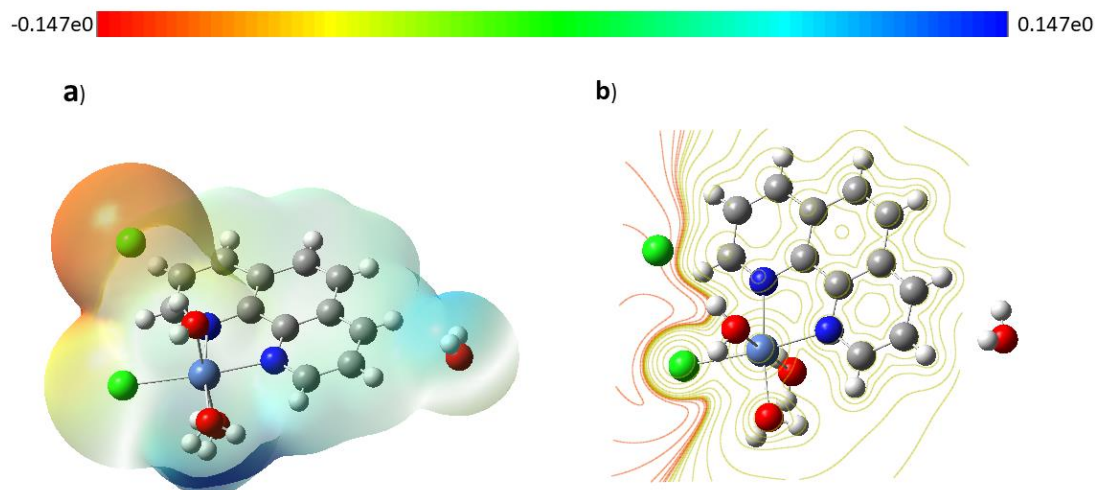


Figure III.49. Molecular electrostatic potential map (MEP) of complex (C3).

III.4.7.3. ELF and LOL analyses for Cobalt complex (C3)

The Electron Localization Function (ELF) analysis of complex (C3) reveals (Figure III.50) well-defined regions of electron localization around the nitrogen atoms of the phenanthroline ligand and the oxygen atom of the coordinated water molecule. These features correspond to the lone pairs of chloride ions and oxygen atoms of aqua ligands where strong electron localization is observed in ELF and LOL maps. In contrast, the electron density around nickel (II) is more diffuse, reflecting d-orbital-related delocalization and a partial covalency of the Ni–N, Ni–O, and Ni–Cl bonds. The phenanthroline ligand exhibits a sharp π delocalization in ELF, which gets more diffuse in LOL. Both maps thus confirm strongly localized lone pairs, moderately covalent metal-ligand bonds, and characteristic π delocalization of phenanthroline.

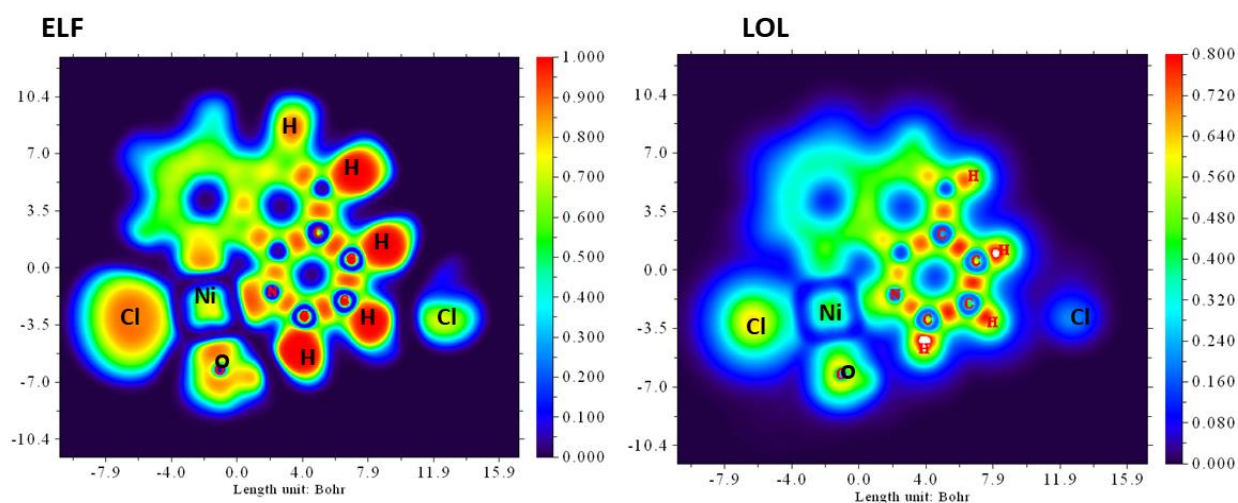


Figure III.50. ELF (Electron Localization Function) and LOL (Localized Orbital Locator) plots for the Ni (II) complex (C3).

III.4.7.4. Topological analysis using RDG of complex (C3)

In the RDG analysis for the complex Ni(II) (C3) (Figure III.51), different types of noncovalent interactions were characterized. The density function between -0.05 and $+0.05$ a.u. evidenced the presence of weak interactions. Regions of low density, or negative values of $\lambda_2\rho$, were depicted in blue, implying attractive interactions: strong hydrogen bonds between the coordinated water molecule and the chloride anion, and a stronger hydrogen bond of the type $O-H\cdots O$. Green color regions reveal the presence of van der Waal interactions which stabilize the supramolecular assembly. On the other hand, the red color regions close to the aromatic rings and coordinated O atoms indicate steric repulsions. The RDG thus proves that stability and geometry are due to a balance of hydrogen bonds, VdW interactions, and sterically effects.

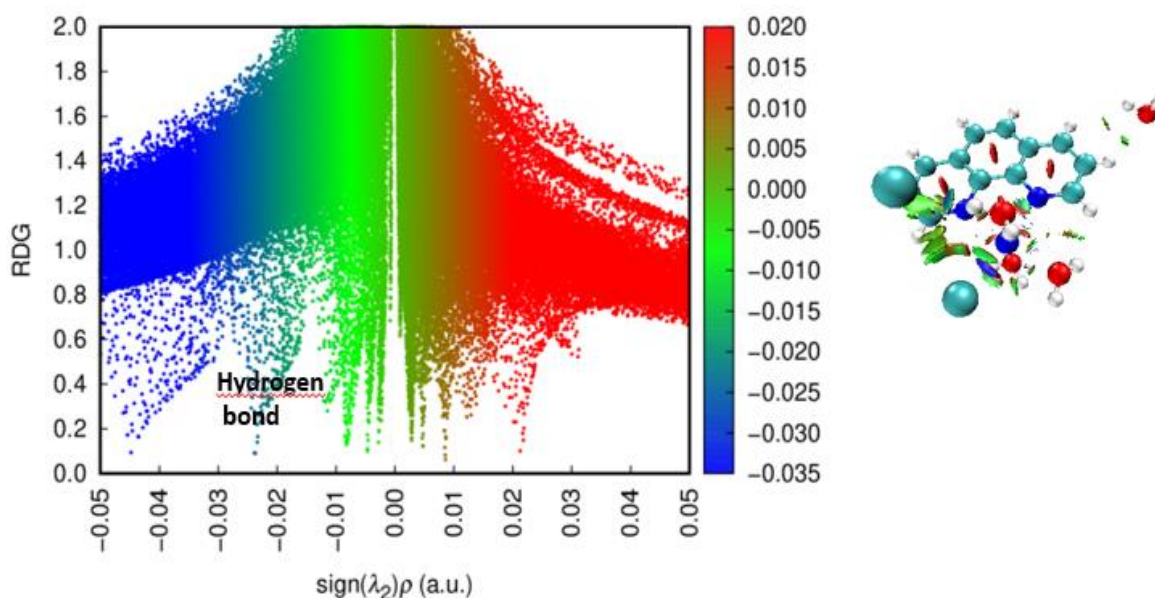


Figure III.51. The RDG scatter plots of Nickel (II) complex (C3).

Part 2: Biological Activities

III.5. Antibacterial activity

The antibacterial potency of compounds C1, C2 and C3 (Figure III.52) was assessed using the disc diffusion method on Mueller-Hinton (MH) agar medium. Bacterial strains were first reactivated on nutrient agar and incubated for 24 hours at $37\text{ }^{\circ}\text{C}$ [53, 54]. After incubation, several isolated colonies were suspended in physiological saline to obtain a homogeneous bacterial suspension, with the optical density adjusted between 0.08-0.10 at 620 nm. Using this standardized inoculum, MH agar plates were uniformly inoculated by swabbing the surface. Sterile Whatman paper discs were then placed on the agar and impregnated with 20 μl of the

synthesized compounds at different concentrations. A disc impregnated with dimethyl sulfoxide (DMSO) served as the negative control, while Cefoxitin (Fox, 30 µg/disc), Gentamicin (20 µg/disc), and Doxycycline (30 µg/disc) were used as positive controls. The plates were pre-incubated at room temperature for 20 minutes to allow diffusion of the compounds, followed by incubation at 37 °C for 24 hours. Antibacterial activity was evaluated by measuring the diameters of inhibition zones (mm). The activities of complexes (C1), (C2), and (C3) were evaluated by Inhibition Diameters (ID) at 10 mg/ml, and Minimum Inhibitory Concentration, (MIC) values ranging from 10 to 25mg/ml against *Escherichia coli* ATCC 25922, *Pseudomonas aeruginosa* ATCC 29222, and *Staphylococcus aureus* ATCC 25923. The Results obtained are summarized in [Table III.11](#).

DMSO, used as the negative control showed no inhibitory effect against any of the tested bacterial strains, confirming that observed activity is attributable to the tested compounds. The results indicate that all three metal complexes exhibit antibacterial activities against these strains.

Among them, complex **C3** exhibited the highest activity with the largest inhibition zones against *E. coli*, *P. aeruginosa*, and *S. aureus*, along with a low MIC (25 µg/mL). Complex **C1** exhibits moderate activity, whereas **C2** appeared to be the least active, particularly against *P. aeruginosa*. Comparison with standard antibiotics, **C3** exhibits an efficacy comparable to gentamicin and some cases superior to Cefoxitin, suggesting promising antimicrobial potential. In general, Gram-positive bacteria, especially *S. aureus*, were more susceptible to these complexes than Gram-negative bacteria. The superior performance of complex **C3** may be attributed to the presence of –OH groups, which likely enhance its bioactivity. Therefore, this complex can be considered a promising candidate for further pharmacological studies.

Table III.11. Antibacterial activity of synthesis complexes (C1-C3) using paper disc-diffusion method and microdilution test.

	Complex (C1)		Complex (C2)		Complex (C3)		DOX 30µg	FOX 30µg	GEN 20µg/ml
	ID	CMI	ID	CMI	ID	CMI			
<i>E. Coli</i>	15.33±0.33	50	18.33±0.33	50	29.66±0.33	25	37	20	35
<i>P. aeruginosa</i>	16.33±0.33	50	14.33±0.33	25	31.33±0.33	25	38	24	35
<i>S. aureus</i>	17.33±0.33	25	15.66±0.66	25	18.66±0.66	25	40	NA	35

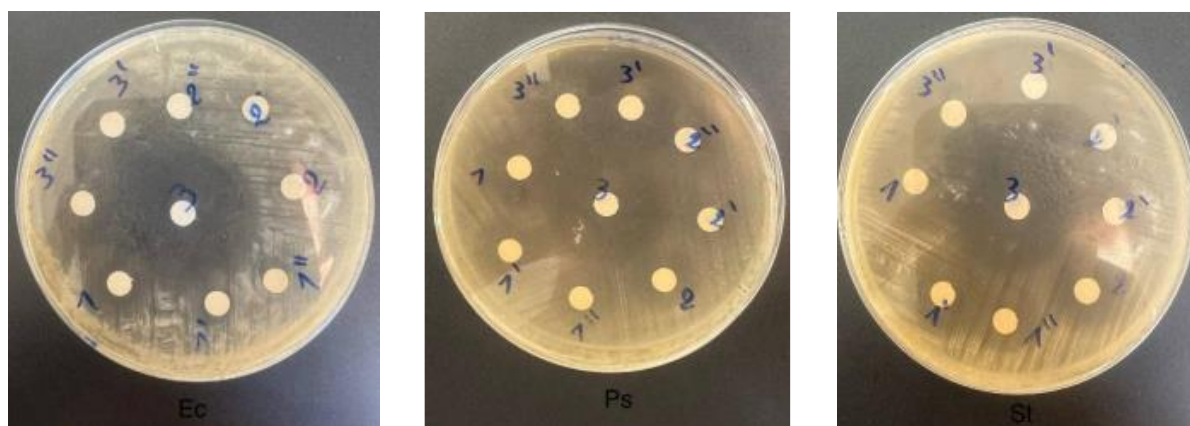


Figure III.52. Disk diffusion assay showing the antibacterial activity of compounds (C1), (C2), and (C3) against *E. coli*, *Pseudomonas*, and *Staphylococcus*.

III.6. Antioxidant activity

The examination of IC₅₀ values for the three compounds demonstrates significant differences in their antioxidant activity. Compound **C3** possesses the highest antioxidant activity, with an IC₅₀ value of approximately 301.49 µM; In contrast, compounds **C1** and **C2** showed higher IC₅₀ values (≈ 420.86 and ≈ 411.59 µM, respectively) indicating lower free

radical scavenging capacity. The improved antioxidant activity of **C3** may be attributed to the three coordinated H₂O molecules, which contribute a stabilization of the complex and facilitate electron or hydrogen-transfer processes. Additionally, these coordinated water molecules may be improving the redox properties and electron-donation ability of the complex by acting similarly to hydroxyl groups [55]. The presence of the nickel ion, play a role in improving the lower IC₅₀ value. As expected, ascorbic acid (used as a standard reference) determined the strongest antioxidant activity, with the lowest IC₅₀ value ($\approx 184.78 \mu\text{M}$). Overall, these findings suggest that the coordination of water molecules in compound **C3** enhances antioxidant activity by improving the stabilization of reactive radical species. The results obtained are presented in Figure III.53.

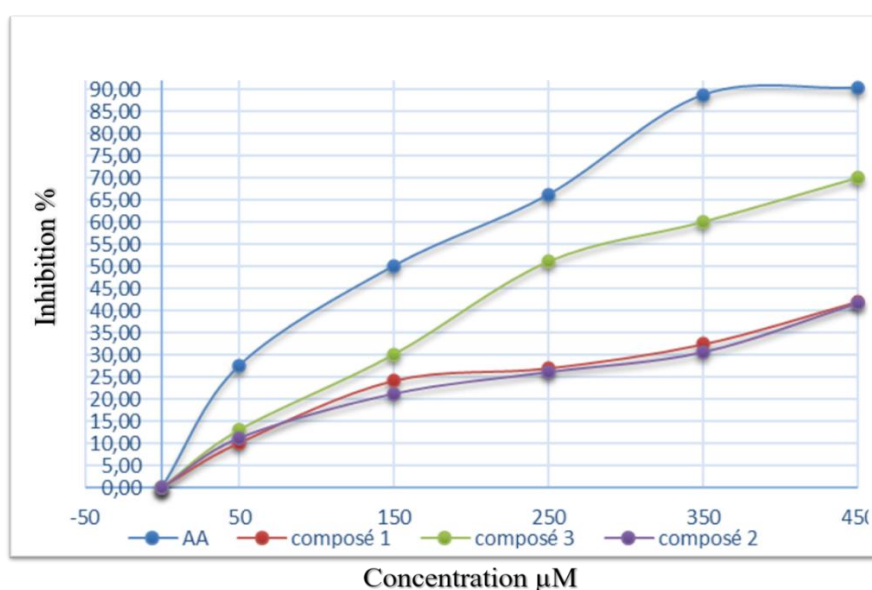


Figure III.53. Antioxidant activity of different concentrations of synthesized compounds (**C1-C3**) and ascorbic acid in DPPH scavenging assay.

III.7. Molecular Docking

The biological activities of the synthesized compounds (**C1-C3**) were assessed through a molecular docking study. The docking analysis of our complexes were performed using Molegro Virtual Docker MVD 2019. 7. 0 software removing all water molecules against the active site of proteins of *Klebsiella pneumonia* (PDB ID: 6RD3) as the ligand 1,10-phenontroline showed high anti-bacterial activity in vitro [56, 57]. The structure of the protein database and three-dimensional structure for all compounds were done by ChemDraw 3D. The parameters that were calculated during the docking were the energy values involved, such as the MolDock Score, Hbond and Rerank Score as

well as the RMSD value. The parameter that is generally used to calculate the drug-receptor binding strength was the Rerank Score. Three-dimensional structure of a DNA gyrase/topoisomerase II enzyme (6RD3), usually found in bacteria. This enzyme is critical in regulating DNA supercoiling, bacterial replication, and DNA repair and transcription. It is a major therapeutic target because its inhibition ultimately deters bacteria from replicating their DNA, stopping their growth. For this reason, it is often utilized in docking studies to evaluate compounds with antibacterial potential. Molecular Docking studies (Figure III.54) conducted against the 6RD3 enzyme determined ciprofloxacin exhibited the greatest binding affinity (Rerank = -85.19; (C3) complex (-78.45) (C2) (-72.08; while (C1) displayed the least binding affinity (-60.56) (Table III.12). Complex (C3) is indicated to be the most active of the four prepared complex, but is still less active than ciprofloxacin. The order of bindings of metabolic activity was found to be downstream ciprofloxacin > complex (C3) > complex (C2) > complex (C1) with bindings interacting at the active site but did not show much. Complex (C2) as well did not produce a high score, despite many dense layers of hydrogen and steric interactions, it did possess poor binding stability. The (C3) complex exhibited binding affinity and targeted residue at (-78.45) number of the layers still showed many interactions with active site with Tyr35 even of the same selection that exhibited coordinates that ciprofloxacin interacts with in between. These findings indicate that the (C3) complex was the most effective out of the synthesized complexes, although it was still less effective than the reference drug. It is worth mentioning that the results obtained from in silico studies matched well with the in vitro antibacterial studies where (C3) was also determined to have higher antibacterial activity compared to (C1) and (C2).

Table III.12. Interactions and Rerank scores of synthesized complexes (C1-C3) and ciprofloxacin with the 6RD3 enzyme.

Ligand	Enzyme	Type of Interaction	Residue	Rerank Score
Complex (C1)	6RD3	- Hydrogen bond - Steric interactions	Met 36, Try 35, Asn 63, Gln 61, Ala 62 Gln 71, Asn 59, Val 60, Thr 34, Asp 18, Gln 33	-60.56
Complex (C2)	6RD3	- Hydrogen bond - Steric interactions	Gln 71, Ser 68 Val 60, Ala 72, Glu 66, Ser 67, Thr 56	-72.08

Complex (C3)	6RD3	- Hydrogen bond - Steric interactions	Gln 71, Gln 61, Ala 72, Asn 59, Try 35 Ala 72, Trp 73, Asp 70, Val 70, Val 60,	-78.45
Ciprofloxacin	6RD3	- Hydrogen bond - Steric interactions	Try 35, Arg 37, Try 311, Lps 16, Ser 124 Try 35, Asp 106, Leu 108, Phe 111	-85.19

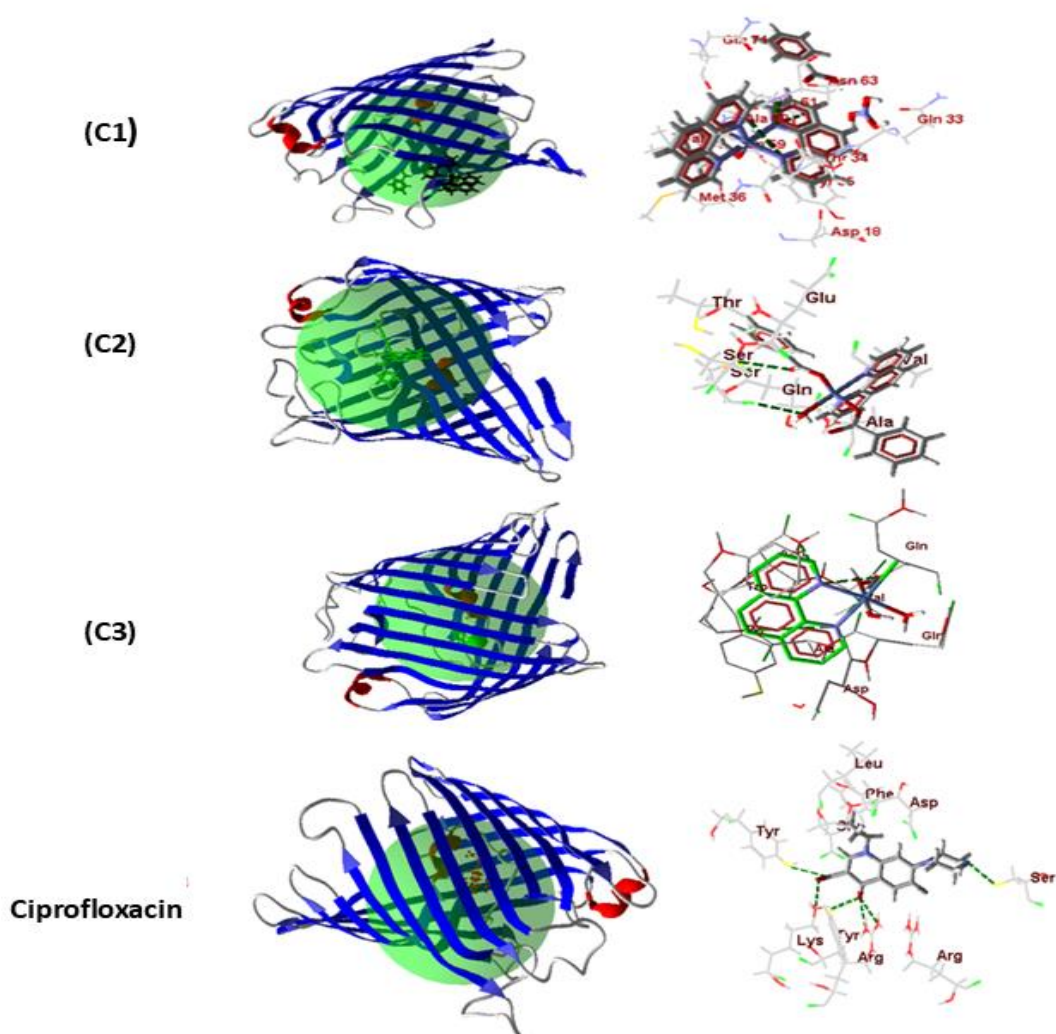


Figure III.54. 2D and 3D plots of the interaction of complexes (C1-C3) with the active site of the DNA gyrase/topoisomerase II enzyme (6RD3).

III.8. Conclusion

In this chapter, we produced and analyzed three new complexes (**C1-C3**) by employing spectroscopic (UV and IR) methods, crystallographic methods for their structure and molecular organization, and Hirshfeld surface analysis allowing us to understand intermolecular interactions in the crystal lattice by highlighting steric contacts and weak bonds while stabilizing the structures.

Additionally, DFT/B3LYP calculations at different basis sets to model molecules calculations provided detailed information related to the optimized geometry of the all complexes, molecular orbitals, and electronic parameters helped reinforce the relative stability of the compounds with respect to electron density on the reactive sites. We then performed molecular docking studies toward the 6RD3 enzyme, indicating the complexes with different binding affinities, indicating that (**C3**) as the potentially most active of the three while still being less active to ciprofloxacin (reference drug). From the analysis of ligand-enzyme interactions, the active site residues involved were identified, mainly Tyr35 and Gln71, which stabilizes the binding mode at the active site. The results of the studies were aligned with our experiments, and were strengthened in conclusion that (**C3**) may be a useful compound for enzyme inhibition.

References

- [1] Bencini, A., Lippolis, V. (2010). 1, 10-Phenanthroline: A versatile building block for the construction of ligands for various purposes. *Coordination Chemistry Reviews*, 254(17-18), 2096-2180.
- [2] Jennifer, S. J., Muthiah, P. T. (2014). Mixed-ligand complexes of Ca (II), Ba (II), Mn (II) and Pd (II) with 1, 10-phenanthroline and 5-chloro thiophene 2-carboxylic acid ligands: Role of hybrid carboxylate–water clusters and ligands of crystallisation in building up of supramolecular architectures. *Inorganica Chimica Acta*, 414, 170-180.
- [3] Lakshminarayanan, S., Jeyasingh, V., Murugesan, K., Selvapalam, N., Dass, G. (2021). Molecular electrostatic potential (MEP) surface analysis of chemo sensors: An extra supporting hand for strength, selectivity & non-traditional interactions. *Journal of Photochemistry and Photobiology*, 6, 100022.
- [4] Jacobsen, H. (2008). Localized-orbital locator (LOL) profiles of chemical bonding. *Canadian Journal of Chemistry*, 86(7), 695-702.
- [5] Luo, J., Gu, G. N., & Wang, X. W. (2020). Crystal structure of (2-carboxy-4-(3-carboxy-5-carboxylatophenoxy) benzoato- κ^2 O, O') bis (1, 10-phenantroline- κ^2 N, N') cobalt (II), C₄₀H₂₄N₄O₉Co. *Zeitschrift für Kristallographie-New Crystal Structures*, 235(6), 1543-1545.
- [6] Ghouari, N., Benali-Cherif, R., Takouachet, R., Falek, W., Missaoui, D., Rahmouni, A., & Benali-Cherif, N. (2023). Crystal engineering of a new pharmaceutical polymorph of gallic acid monohydrate: a structural comparative study and chemical computational quantum investigations. *CrystEngComm*, 25(45), 6279-6290.
- [7] Dutta, D., Sharma, P., Gomila, R. M., Frontera, A., Barcelo-Oliver, M., Verma, A. K., Bhattacharyya, M. K. (2022). Solvent-driven structural topologies in phenanthroline-based co-crystals of Zn (II) involving fascinating infinite chair-like {[(bzH)₄ Cl₂] 2-} _n assemblies and unconventional layered infinite {bz-H₂ O-Cl} _n anion-water clusters: antiproliferative evaluation and theoretical studies. *New Journal of Chemistry*, 46(12), 5638-5652.
- [8] Derardja, A. A., Golea, L., Benali-Cherif, R., Luneau, D., Boutobba, Z., Boumedjane, Y., Harkat, H. (2022). Synthesis, crystal structure, DFT calculations, Hirshfeld surface analysis and molecular docking studies of a new manganese complex. *Inorganic Chemistry Communications*, 146, 110198.
- [9] Hidaoui, S., Hamdi, N., Akouibaa, M., Benali-Cherif, R., Vaclav, E., Dusek, M., El Bali, B. (2022). Synthesis, crystal structure and catalytic activity of the new hybrid phosphate (C₄H₁₂N₂)[Co(H₂O)₆](HPO₄)₂. *Journal of Molecular Structure*, 1265, 133296.

- [10] Novikov, A. S. (2021). IsoStar program suite for studies of noncovalent interactions in crystals of chemical compounds. *Crystals*, 11(2), 162.
- [11] Lv, L. L., Xia, W. M., Cheng, Y. Z., Zhang, L. P., Wang, X. D. (2019). Synthesis, structure, DNA binding and anticancer activity of a new tetranuclear Pb (II) complex constructed by 8-hydroxyquinolate and 4-nitrobenzoate ligands. *Main Group Metal Chemistry*, 42(1), 60-66.
- [12] Kar, P., Biswas, R., Ida, Y., Ishida, T., Ghosh, A. (2011). A unique example of structural diversity tuned by apparently innocent o-, m-, and p-nitro substituents of benzoate in their complexes of mn (II) with 4, 4'-bipyridine: 1d ladder, 2d sheet, and 3d framework. *Crystal growth & design*, 11(12), 5305-5315.
- [13] Đaković, M., Vinković, M., Roca, S., Popović, Z., Vicković, I., Vikić-Topić, D., Kusić, Z. (2012). Structural study of picolinamide complexes of Ni (II), Zn (II), Cd (II), and Hg (II) nitrates in solid state and solution. *Journal of coordination chemistry*, 65(6), 1017-1032.
- [14] Ouf, A. E. F., Ali, M. S., Saad, E. M., Mostafa, S. I. (2010). pH-metric and spectroscopic properties of new 4-hydroxysalicylidene-2-aminopyrimidine Schiff-base transition metal complexes. *Journal of Molecular Structure*, 973(1-3), 69-75.
- [15] Singh, C., Mukhopadhyay, S., Das, S. K. (2018). Polyoxometalate-supported bis (2, 2'-bipyridine) mono (aqua) nickel (II) coordination complex: an efficient electrocatalyst for water oxidation. *Inorganic chemistry*, 57(11), 6479-6490.
- [16] Bhattacharyya, M. K., Dutta, D., Nashre-ul-Islam, S. M., Frontera, A., Sharma, P., Verma, A. K., Das, A. (2020). Energetically Significant antiparallel π -stacking contacts in Co (II), Ni (II) and Cu (II) coordination compounds of pyridine-2, 6-dicarboxylates: Antiproliferative evaluation and theoretical studies. *Inorganica Chimica Acta*, 501, 119233.
- [17] Obaleye, J. A., Lawal, M., Jadeja, R. N., Gupta, V. K., Nnabuike, G. G., Bamigboye, M. O., Bhagariya, P. (2021). Crystal structure, spectroscopic, DFT calculations and antimicrobial study of the Cu (II) complex bearing second-generation quinolone ofloxacin and 2, 2'-bipyridine. *Inorganica Chimica Acta*, 519, 120264.
- [18] Báez-Castro, A., Baldenebro-López, J., Cruz-Enríquez, A., Höpfl, H., Glossman-Mitnik, D., Valentín, M. S., Campos-Gaxiola, J. J. (2014). Synthesis, structure, characterization and photophysical properties of copper (i) complexes containing polypyridyl ligands. *RSC Advances*, 4(80), 42624-42631.
- [19] Chattaraj, P. K., Maiti, B. (2002). Chemical reactivity dynamics and quantum chaos in highly excited hydrogen atoms in an external field: A quantum potential approach. *International Journal of Molecular Sciences*, 3(4), 338-359.

- [20] Chandrakumar, K. R. S., Pal, S. (2002). The concept of density functional theory based descriptors and its relation with the reactivity of molecular systems: A semi-quantitative study. *International Journal of Molecular Sciences*, 3(4), 324-337.
- [21] Parr, R. G., Szentpály, L. V., Liu, S. (1999). Electrophilicity index. *Journal of the American Chemical Society*, 121(9), 1922-1924.
- [22] Tsirelson, V. G., Stash, A. (2002). Analyzing experimental electron density with the localized-orbital locator. *Structural Science*, 58(5), 780-785.
- [23] Sevvanthi, S., Muthu, S., Raja, M., Aayisha, S., Janani, S. P. E. S. (2020). PES, molecular structure, spectroscopic (FT-IR, FT-Raman), electronic (UV-Vis, HOMO-LUMO), quantum chemical and biological (docking) studies on a potent membrane permeable inhibitor: dibenzoxepine derivative. *Heliyon*, 6(8).
- [24] Ganesan, T. S., Elangovan, N., Vanmathi, V., Sowrirajan, S., Chandrasekar, S., Murthy, K. S., Thomas, R. (2022). Spectroscopic, Computational (DFT), Quantum mechanical studies and protein-ligand interaction of Schiff base 6, 6-((1, 2-phenylenebis (azaneylylidene)) bis (methaneylylidene)) bis (2-methoxyphenol) from o-phenylenediamine and 3-methoxysalicylaldehyde. *Journal of the Indian Chemical Society*, 99(10), 100713.
- [25] Liu, J. Z., Zhang, Z., Shi, Z. W., Gao, P. (2011). Aquabis (benzoato- κ O)(1, 10-phenanthroline- κ 2N, N') zinc (II). *Structure Reports*, 67(1), m30-m30.
- [26] Dong, X. Y., Xu, X., Yang, L. (2009). Aquabis (benzoato- κ O)(5, 5'-dimethyl-2, 2'-bipyridine- κ 2N, N') copper (II). *Structure Reports*, 65(11), m1290-m1290.
- [27] Sabeg, Y., Benali-Cherif, R., Falek, W., Takouachet, R., Golea, L., Aygün, M., Benali-Cherif, N. (2025). Comprehensive study of a novel cobalt (II) complex: Synthesis, X-ray crystal structure, Hirshfeld surface analysis, computational quantum investigations, and molecular docking insights. *Polyhedron*, 271, 117445.
- [28] Saha, U., Dutta, D., Nath, H., Franconetti, A., Frontera, A., Bhattacharyya, M. K. (2019). Supramolecular association in Cu (II) coordination complexes involving energetically significant NO $\cdots$ NO π -hole interaction and cooperative π -stacked ternary assembly: Experimental and theoretical studies. *Inorganica Chimica Acta*, 488, 159-169.
- [29] Bhattacharyya, M. K., Saha, U., Dutta, D., Das, A., Verma, A. K., & Frontera, A. (2019). Solvent-driven structural topology involving energetically significant intra-and intermolecular chelate ring contacts and anticancer activities of Cu (II) phenanthroline complexes involving benzoates: experimental and theoretical studies. *RSC advances*, 9(29), 16339-16356.

- [30] Takouachet, R., Benali-Cherif, R., Bendeif, E. E., Jelsch, C., Cherif, F. Y., Rahmouni, A., Benali-Cherif, N. (2021). The supramolecular behavior and molecular recognition of adeninium cations on anionic hydrogen selenite/diselenite frameworks: A structural and theoretical analysis. *Journal of Molecular Structure*, 1229, 129836.
- [31] Macrae, C. F., Sovago, I., Cottrell, S. J., Galek, P. T., McCabe, P., Pidcock, E., Wood, P. A. (2020). Mercury 4.0: From visualization to analysis, design and prediction. *Applied Crystallography*, 53(1), 226-235.
- [32] Novikov, A. S. (2021). IsoStar program suite for studies of noncovalent interactions in crystals of chemical compounds. *Crystals*, 11(2), 162.
- [33] Turner, M. J., McKinnon, J. J., Jayatilaka, D., & Spackman, M. A. (2011). Visualisation and characterisation of voids in crystalline materials. *CrystEngComm*, 13(6), 1804-1813.
- [34] Akyüz, S. (1998). The FT-IR spectra of transition metal 3-aminopyridine tetracyanonickelate complexes. *Journal of Molecular Structure*, 449, 23–27.
- [35] Shirvan, S. A.; Khazali, F.; Dezfuli, S. H.; Borsalani, A. (2017). Distorted square-based pyramidal and trigonal bipyramidal geometries in a mercury (II) coordination compound containing 2-(aminomethyl)pyridine ligand. *Molecular Crystals and Liquid Crystals*, 656, 105–112.
- [36] Silvi, B., Savin, A. (1994). Classification of chemical bonds based on topological analysis of electron localization functions. *Nature*, 371(6499), 683-686.
- [37] Savin, A., Nesper, R., Wengert, S., Fässler, T. F. (1997). ELF: The electron localization function. *Angewandte Chemie International Edition in English*, 36(17), 1808-1832.
- [38] Schmider, H. L., & Becke, A. D. (2000). Chemical content of the kinetic energy density. *Journal of Molecular Structure: THEOCHEM*, 527(1-3), 51-61.
- [39] Ponnuchamy, V., Sandak, A., & Sandak, J. (2020). Multiscale modelling investigation of wood modification with acetic anhydride. *Physical Chemistry Chemical Physics*, 22(48), 28448-28458.
- [40] Quiñone, D., Veiga, N., Torres, J., Castiglioni, J., Bazzicalupi, C., Bianchi, A., Kremer, C. (2016). Synthesis, solid-state characterization and solution studies of new phytate compounds with Cu (II) and 1, 10-phenanthroline: Progress in the structural elucidation of phytate coordinating ability. *Dalton Transactions*, 45(30), 12156-12166
- [41] Golovnev, N. N., Molokeev, M. S., Sterkhova, I. V., Lesnikov, M. K. (2018). Two novel mixed-ligand Ni (II) and Co (II) complexes with 1, 10-phenanthroline: Synthesis, structural characterization, and thermal stability. *Chemical Physics Letters*, 708, 11-16.

- [42] Şimşek, M., Tamer, Ö., Dege, N., Avcı, D., Atalay, Y. (2025). Investigation on the effect of complex formation on prominent high static/dynamic first and second hyperpolarizability of Co (II) complex including 4-chloro-Pyridine-2-Carboxylic acid. *Materials Science in Semiconductor Processing*, 188, 109179.
- [43] Kansız, S., Kaştaş, G., Gümüş, M. K., Dege, N., Aydın, R. (2025). Synthesis, Structural Characterization, and Supramolecular Assembly of a One-Dimensional Cobalt (II) Coordination Polymer with Succinato and Isonicotinamide Ligands. *Journal of Structural Chemistry*, 66(4), 722-732.
- [44] Harding, P., Harding, D. J. (2024). Driving molecular self-assembly with π - π interactions. *Trends in Chemistry*.
- [45] Xue, T., Yang, Q. S., Li, L., Chang, X. Y., Ding, Y. S., Zheng, Z. (2025). Supramolecular assemblies of tetravalent terbium complex units: syntheses, structure, and materials properties. *Chemical Science*, 16(16), 6805-6811.
- [46] Spackman, P. R., Turner, M. J., McKinnon, J. J., Wolff, S. K., Grimwood, D. J., Jayatilaka, D., Spackman, M. A. (2021). CrystalExplorer: a program for Hirshfeld surface analysis, visualization and quantitative analysis of molecular crystals. *Applied Crystallography*, 54(3), 1006-1011.
- [47] Spackman, M. A., & Jayatilaka, D. (2009). Hirshfeld surface analysis. *CrystEngComm*, 11(1), 19-32.
- [48] McKinnon, J. J., Jayatilaka, D., Spackman, M. A. (2007). Towards quantitative analysis of intermolecular interactions with Hirshfeld surfaces. *Chemical Communications*, (37), 3814-3816.
- [49] Santos, J. C. D., Neto, J. G., Moreira, A. B., da Silva, L. M., Ayala, A. P., Lage, M. R., Dos Santos, A. O. (2025). Exploring the Potential of a New Nickel (II): Phenanthroline Complex with L-isoleucine as an Antitumor Agent: Design, Crystal Structure, Spectroscopic Characterization, and Theoretical Insights. *Molecules*, 30(13), 2873.
- [50] Abdallah, H. A., El-wahaab, A. (2025). Structure investigation and antimicrobial activities of some new cefradine with 1, 10-phenanthroline metal complexes. *Bulletin of Faculty of Science, Zagazig University*, 2025(2), 242-257.
- [51] Prashanthi, Y., Kiranmai, K., Ira, K, S. K., Chityala, V. K., Shivaraj. (2012). Spectroscopic Characterization and Biological Activity of Mixed Ligand Complexes of Ni (II) with 1, 10-Phenanthroline and Heterocyclic Schiff Bases. *Bioinorganic chemistry and applications*, 2012(1), 948534.

- [52] Alramadhan, S. A., Hammud, H. H., Ali, B. F., Ghabbour, H. A., Sarfaraz, S., Ayub, K. (2023). Structures, characterization and DFT studies of four novel nickel phenanthroline complexes. *Crystals*, 13(5), 738.
- [53] Caspar, Y., from Grenoble Alps, C. H. U. (2019). The resistances of gram-negative bacilli. DU Anti-Infectious Therapeutics.
- [54] Bendaas, R., Messaadia, L., Bekkar, Y., Bourougaa, L., Messaoudi, A. (2025). Comprehensive in vitro and molecular docking analysis of antioxidant and antimicrobial properties of salvia officinalis L. extracts and essential oils. *Journal of Molecular Structure*, 1331, 141621.
- [55] Dehghan, G., Khoshkam, Z. (2012). Tin (II)–quercetin complex: Synthesis, spectral characterisation and antioxidant activity. *Food Chemistry*, 131(2), 422-426.
- [56] Rêgo, A. T., Johnson, J. G., Geibel, S., Enguita, F. J., Clegg, S., Waksman, G. (2012). Crystal structure of the MrkD1P receptor binding domain of *Klebsiella pneumoniae* and identification of the human collagen V binding interface. *Molecular microbiology*, 86(4), 882-893.
- [57] Galdino, A. C. M., Viganor, L., Pereira, M. M., Devereux, M., McCann, M., Branquinho, M. H., Dos Santos, A. L. S. (2022). Copper (II) and silver (I)-1, 10-phenanthroline-5, 6-dione complexes interact with double-stranded DNA: Further evidence of their apparent multi-modal activity towards *Pseudomonas aeruginosa*. *JBIC Journal of Biological Inorganic Chemistry*, 27(1), 201-213.

Conclusion General

Conclusion General

This dissertation deals with coordination compounds in metal–organic chemistry involving heterocyclic compounds, carboxylic acids, and transition metals. In this work, the concepts of coordination chemistry and supramolecular organization are discussed, and the main roles of non-covalent interactions are highlighted. The study focuses on the synthesis and characterization of novel metal–organic complexes based on 1,10-phenanthroline and benzoic acid as organic ligands with biological properties.

In this present study, we successfully synthesized three novel metal complexes with different geometries: (benzoate)-bis(1,10-phenanthroline)-cobalt (II) nitrate benzoic acid (**C1**), Aqua-bis(benzoato- κ O)(1,10-phenanthroline- κ^2 N, N') cobalt (II) (**C2**), and triaqua (1,10-phenanthroline- κ^2 N,N')chloro-nickel(II) chloride (**C3**). The molecular structure and crystallographic data of these crystal structures were characterized using single-crystal X-ray diffraction analysis. The coordination of the ligand to a center metal ion of compounds was confirmed through spectral studies (FT-IR and UV-Vis). Furthermore, the intermolecular interactions in the crystal lattice were identified by the hirshfeld surface method, which increases the stability and supramolecular architectures of metal-organic compounds. Thereafter, we optimized the molecular geometry and studied the electronic and energetic properties of laboratory compounds by DFT/B3LYP calculations at different basis sets (like PBE0/LANL2DZ, 3-21G, and 6-311+G (d, p)), which provided accurate and reliable results. On the other hand, we synthesized the other three known complexes: [Mn (Phen)₂(Cl)₂] (**C4**), [Cu(Phen)₂(NCS)₂] (**C5**), and [Ni(Phen)(bz) (H₂O)₃]. bzH (**C6**) with different crystal data details compared to the literature.

Additionally, antimicrobial studies were conducted against *E. coli*, *S. aureus*, and *P. aeruginosa* using the disk diffusion and agar dilution techniques. The results demonstrated a moderate antibacterial activity of the metal complexes compared to the ligand and standard antibiotics. The radical scavenging activity of the free ligand and its metal complexes was evaluated using the DPPH test. Compound (**C3**) possesses the highest activity (IC₅₀ $\approx$ 301.49 μ M) has significantly greater free radical scavenging ability compared to compounds (**C1**) and (**C2**). Both (**C1**) and (**C2**) complexes showed

good free radical scavenging activity, with half-maximal inhibitory concentration (IC_{50}) values of approximately 420.86 and 411.59 μ M, respectively, whereas ascorbic acid (used as a positive control) exhibited a lower IC_{50} value of approximately 184.78 μ M. Overall, there is a consensus from these finding that the coordination of water molecules included in compound (C3) promotes antioxidant activity by improving stabilization of reactive radical species.

Molecular docking performed on the active site of *Klebsiella pneumoniae* DNA gyrase/topoisomerase II (PBD ID: 6RD3) were examined using Docking parameters MolDock Score, H-bond interactions, Rerank Score and RMSD. The Rerank Score indicates the strength of the binding between drug and receptor and the highest degree of binding affinity for the synthesized complexes was (C3) with -78.45 , while (C2) (-72.08) and (C1) (-60.56) had lower levels of binding affinity. The reference drug ciprofloxacin had the greatest degree of binding affinity with a Rerank Score of -85.19 . While there was a great deal of hydrogen and sterically based interactions for (C2), there were low levels of binding stability. However, (C3) has demonstrated significant binding to the active-site key-residues (Tyr35), and therefore can be viewed as the most effective of the synthesized complexes, similar to the reference drug. In silico data support in vitro data.

Overall, from this study provide an excellent basis to advance the development of novel metal-organic compounds for use in various application areas. In particular, the antibacterial and antioxidant properties of these complexes metals (C1-C3) demonstrate a high level of promise within the field of therapeutic medicinal chemistry as potential new types of antimicrobial or antioxidant therapeutic agents to help alleviate the negative effects of oxidative stress. Additionally, because of the structural flexibility and tunable properties of these compounds, they could be explored for new materials to be used in drug development, biomedical research, and materials science, indicating that they may have utility beyond the areas of their chemical characterization alone.

Appendix

Table 1. Bond Lengths for complex **C1**.

Atom	Atom	Length (Å)	Atom	Atom	Length (Å)
Co1	O1	2.1680(17)	C8	C9	1.400(4)
Co1	O1 ¹	2.1679(17)	C9	C10	1.423(4)
Co1	N1 ¹	2.096(2)	C9	C17	1.399(3)
Co1	N1	2.096(2)	C10	C11	1.338(4)
Co1	N2	2.113(2)	C11	C12	1.425(3)
Co1	N2 ¹	2.113(2)	C12	C13	1.403(4)
O1	C1	1.252(2)	C12	C16	1.399(3)
O1	C1 ¹	1.252(2)	C13	C14	1.353(4)
N1	C6	1.325(3)	C14	C15	1.383(4)
N1	C17	1.355(3)	C16	C17	1.430(3)
N2	C15	1.327(3)	O2	C18	1.197(4)
N2	C16	1.354(3)	O3	C18	1.302(4)
C1	C1 ¹	0.000(7)	C18	C19	1.481(4)
C1	C2	1.493(5)	C19	C20	1.364(4)
C2	C3 ¹	1.388(4)	C19	C24	1.367(4)
C2	C3	1.388(4)	C20	C21	1.367(5)
C3	C4	1.313(8)	C21	C22	1.336(6)
C4	C5	1.154(8)	C22	C23	1.353(6)
C5	C5 ¹	1.284(9)	C23	C24	1.378(5)
C6	C7	1.400(4)	O4	N3	1.201(5)
C7	C8	1.348(4)	O5	N3	1.204(3)

Table 2. Bond Angles for complex **C1**.

Atom	Atom	Atom	Angle (°)	Atom	Atom	Atom	Angle (°)
O1 ¹	Co1	O1	60.15(9)	C5	C4	C3	98.0(8)
N1 ¹	Co1	O1 ¹	154.20(7)	C4	C5	C5 ¹	152.0(5)
N1 ¹	Co1	O1	97.25(7)	N1	C6	C7	122.7(3)
N1	Co1	O1	154.20(7)	C8	C7	C6	119.4(3)
N1	Co1	O1 ¹	97.25(7)	C7	C8	C9	120.1(3)
N1 ¹	Co1	N1	107.25(11)	C8	C9	C10	124.4(2)
N1 ¹	Co1	N2	100.49(8)	C17	C9	C8	116.9(3)
N1	Co1	N2 ¹	100.50(8)	C17	C9	C10	118.7(2)
N1 ¹	Co1	N2 ¹	78.54(8)	C11	C10	C9	121.8(3)
N1	Co1	N2	78.54(8)	C10	C11	C12	121.1(3)
N2	Co1	O1	89.34(7)	C13	C12	C11	124.1(3)
N2 ¹	Co1	O1	92.04(7)	C16	C12	C11	118.6(2)
N2	Co1	O1 ¹	92.04(7)	C16	C12	C13	117.3(2)
N2 ¹	Co1	O1 ¹	89.34(7)	C14	C13	C12	119.6(3)
N2	Co1	N2 ¹	178.40(11)	C13	C14	C15	119.4(3)
C1	O1	Co1	89.73(17)	N2	C15	C14	123.5(2)
C1 ¹	O1	Co1	89.73(17)	N2	C16	C12	122.8(2)
C1 ¹	O1	C1	0.0(3)	N2	C16	C17	117.0(2)
C6	N1	Co1	128.72(19)	C12	C16	C17	120.2(2)
C6	N1	C17	117.6(2)	N1	C17	C9	123.2(2)
C17	N1	Co1	113.36(15)	N1	C17	C16	117.2(2)
C15	N2	Co1	129.06(17)	C9	C17	C16	119.5(2)
C15	N2	C16	117.4(2)	O2	C18	O3	123.5(4)
C16	N2	Co1	112.88(15)	O2	C18	C19	123.2(4)
O1	C1	O1 ¹	120.4(3)	O3	C18	C19	113.3(3)

Atom	Atom	Atom	Angle (°)	Atom	Atom	Atom	Angle (°)
O1 ¹	C1	C2	119.81(16)	C20	C19	C18	118.5(3)
O1	C1	C2	119.80(16)	C20	C19	C24	118.8(3)
C1 ¹	C1	O1	0(10)	C24	C19	C18	122.7(3)
C1 ¹	C1	O1 ¹	0(10)	C19	C20	C21	120.6(4)
C1 ¹	C1	C2	0(10)	C22	C21	C20	120.7(4)
C1	C2	C1 ¹	0.000(1)	C21	C22	C23	119.8(4)
C3	C2	C1 ¹	119.2(2)	C22	C23	C24	120.6(4)
C3 ¹	C2	C1 ¹	119.2(2)	C19	C24	C23	119.6(4)
C3 ¹	C2	C1	119.2(2)	O4	N3	O5	118.7(2)
C3	C2	C1	119.2(2)	O4	N3	O5 ²	118.7(2)
C3	C2	C3 ¹	121.6(5)	O5	N3	O5 ²	122.5(4)
C4	C3	C2	139.2(6)				

Code symmetry: ¹1/2-X, +Y,1-Z; ²3/2-X, +Y,2-Z

Table 3. Torsion Angles for complex **C1**.

A	B	C	D	Angle (°)	A	B	C	D	Angle (°)
Co1	O1	C1	O1 ¹	-0.002(2)	C8	C9	C17	C16	179.3(2)
Co1	O1	C1	C1 ¹	0.00(14)	C9	C10	C11	C12	0.8(4)
Co1	O1	C1	C2	180.000(1)	C10	C9	C17	N1	178.2(2)
Co1	N1	C6	C7	173.8(2)	C10	C9	C17	C16	-1.1(3)
Co1	N1	C17	C9	-173.42(18)	C10	C11	C12	C13	179.6(3)
Co1	N1	C17	C16	5.9(3)	C10	C11	C12	C16	-0.4(4)
Co1	N2	C15	C14	-169.0(2)	C11	C12	C13	C14	-178.4(3)
Co1	N2	C16	C12	171.03(18)	C11	C12	C16	N2	179.4(2)
Co1	N2	C16	C17	-8.8(2)	C11	C12	C16	C17	-0.8(3)
O1 ¹	C1	C2	C1 ¹	0(100)	C12	C13	C14	C15	-1.1(4)

A	B	C	D	Angle (°)	A	B	C	D	Angle (°)
O1	C1	C2	C1 ¹	0(75)	C12	C16	C17	N1	-177.8(2)
O1 ¹	C1	C2	C3	16.2(2)	C12	C16	C17	C9	1.6(3)
O1	C1	C2	C3	-163.8(2)	C13	C12	C16	N2	-0.6(4)
O1	C1	C2	C3 ¹	16.2(2)	C13	C12	C16	C17	179.2(2)
O1 ¹	C1	C2	C3 ¹	-163.8(2)	C13	C14	C15	N2	-0.4(4)
N1	C6	C7	C8	-1.2(5)	C15	N2	C16	C12	-0.8(3)
N2	C16	C17	N1	2.0(3)	C15	N2	C16	C17	179.4(2)
N2	C16	C17	C9	-178.7(2)	C16	N2	C15	C14	1.3(4)
C1 ¹	O1	C1	O1 ¹	0(65)	C16	C12	C13	C14	1.5(4)
C1 ¹	O1	C1	C2	0(100)	C17	N1	C6	C7	0.2(4)
C1 ¹	C1	C2	C3 ¹	0(6)	C17	C9	C10	C11	-0.1(4)
C1 ¹	C1	C2	C3	0(100)	O2	C18	C19	C20	-6.8(5)
C1 ¹	C2	C3	C4	178.4(7)	O2	C18	C19	C24	173.9(3)
C1	C2	C3	C4	178.4(7)	O3	C18	C19	C20	171.9(3)
C2	C3	C4	C5	2.3(11)	O3	C18	C19	C24	-7.4(5)
C3 ¹	C2	C3	C4	-1.6(7)	C18	C19	C20	C21	-179.5(3)
C3	C4	C5	C5 ¹	-1.8(19)	C18	C19	C24	C23	-179.6(3)
C6	N1	C17	C9	1.2(3)	C19	C20	C21	C22	-0.5(7)
C6	N1	C17	C16	-179.5(2)	C20	C19	C24	C23	1.1(5)
C6	C7	C8	C9	0.8(4)	C20	C21	C22	C23	0.3(7)
C7	C8	C9	C10	-179.2(3)	C21	C22	C23	C24	0.7(7)
C7	C8	C9	C17	0.4(4)	C22	C23	C24	C19	-1.4(7)
C8	C9	C10	C11	179.5(3)	C24	C19	C20	C21	-0.1(5)
C8	C9	C17	N1	-1.5(4)					

Code symmetry: ¹/2-X, +Y, 1-Z

Table 4. Bond Lengths for complex **C2**.

Atom	Atom	Length (Å)	Atom	Atom	Length (Å)
Co	O1W	2.1010(15)	C11	C12	1.373(4)
Co	O1	2.0368(14)	C12	C13	1.374(4)
Co	O3	1.9956(16)	C13	C14	1.386(3)
Co	N1	2.0979(15)	C15	N1	1.325(3)
Co	N2	2.1609(17)	C15	C16	1.400(3)
O1	C1	1.267(2)	N1	C26	1.360(2)
O2	C1	1.251(2)	N2	C24	1.326(3)
C1	C2	1.506(3)	N2	C25	1.360(2)
C2	C3	1.381(3)	C16	C17	1.358(3)
C2	C7	1.391(3)	C17	C18	1.402(3)
C3	C4	1.387(3)	C18	C19	1.427(3)
C4	C5	1.371(4)	C18	C26	1.403(3)
C5	C6	1.373(4)	C19	C20	1.353(3)
C6	C7	1.385(3)	C20	C21	1.429(3)
O3	C8	1.265(3)	C21	C22	1.403(3)
O4	C8	1.241(3)	C21	C25	1.406(3)
C8	C9	1.498(3)	C22	C23	1.361(4)
C9	C10	1.388(3)	C23	C24	1.403(3)
C9	C14	1.383(3)	C25	C26	1.433(3)
C10	C11	1.376(3)			

Table 5. Bond Angles for complex **C2**.

Atom	Atom	Atom	Angle (°)	Atom	Atom	Atom	Angle (°)
O1W	Co	N2	175.07(6)	C12	C11	C10	120.2(2)
O1	Co	O1W	92.53(6)	C11	C12	C13	119.8(2)
O1	Co	N1	105.71(6)	C12	C13	C14	120.3(2)
O1	Co	N2	90.30(6)	C9	C14	C13	120.3(2)
O3	Co	O1W	93.52(7)	N1	C15	C16	122.8(2)
O3	Co	O1	99.92(8)	C15	N1	Co	127.29(14)
O3	Co	N1	151.51(8)	C15	N1	C26	117.84(16)
O3	Co	N2	89.97(7)	C26	N1	Co	114.60(12)
N1	Co	O1W	97.53(6)	C24	N2	Co	129.36(14)
N1	Co	N2	77.81(6)	C24	N2	C25	117.81(17)
C1	O1	Co	127.09(13)	C25	N2	Co	112.67(12)
O1	C1	C2	116.63(17)	C17	C16	C15	119.5(2)
O2	C1	O1	125.49(18)	C16	C17	C18	119.67(19)
O2	C1	C2	117.87(17)	C17	C18	C19	123.29(19)
C3	C2	C1	120.54(19)	C17	C18	C26	117.32(18)
C3	C2	C7	118.9(2)	C26	C18	C19	119.39(19)
C7	C2	C1	120.53(19)	C20	C19	C18	120.9(2)
C2	C3	C4	120.1(2)	C19	C20	C21	121.3(2)
C5	C4	C3	120.9(3)	C22	C21	C20	124.0(2)
C4	C5	C6	119.4(2)	C22	C21	C25	117.0(2)
C5	C6	C7	120.5(2)	C25	C21	C20	118.96(19)
C6	C7	C2	120.2(2)	C23	C22	C21	119.6(2)
C8	O3	Co	108.85(14)	C22	C23	C24	119.7(2)
O3	C8	C9	116.58(19)	N2	C24	C23	122.6(2)
O4	C8	O3	122.7(2)	N2	C25	C21	123.24(18)

Atom	Atom	Atom	Angle (°)	Atom	Atom	Atom	Angle (°)
O4	C8	C9	120.7(2)	N2	C25	C26	116.98(16)
C10	C9	C8	120.74(19)	C21	C25	C26	119.77(17)
C14	C9	C8	120.61(19)	N1	C26	C18	122.90(17)
C14	C9	C10	118.66(19)	N1	C26	C25	117.36(16)
C11	C10	C9	120.8(2)	C18	C26	C25	119.73(17)

Table 6. Torsion Angles for complex **C2**.

A	B	C	D	Angle (°)	A	B	C	D	Angle (°)
Co	O1	C1	O2	2.20(18)	C9	C10	C11	C12	-1.0(3)
Co	O1	C1	C2	-176.63(15)	C9	C14	C13	C12	-0.6(3)
Co	O3	C8	O4	-5.68(18)	C10	C11	C12	C13	-0.4(3)
Co	O3	C8	C9	174.45(11)	C11	C12	C13	C14	1.2(3)
Co	N1	C15	C16	-173.6(2)	C15	N1	C26	C18	0.4(2)
Co	N1	C26	C18	174.94(13)	C15	N1	C26	C25	-179.69(19)
Co	N1	C26	C25	-5.17(14)	C15	C16	C17	C18	0.4(3)
Co	N2	C24	C23	173.6(2)	N1	C26	C18	C17	-0.5(2)
Co	N2	C25	C21	-174.49(13)	N1	C26	C18	C19	179.8(2)
Co	N2	C25	C26	6.11(13)	N1	C26	C25	N2	-0.80(19)
O1	C1	C2	C3	0.2(2)	N1	C26	C25	C21	179.77(17)
O1	C1	C2	C7	-178.75(18)	N2	C24	C23	C22	0.4(3)
O2	C1	C2	C3	-178.7(2)	N2	C25	C21	C20	-179.1(2)
O2	C1	C2	C7	2.3(2)	N2	C25	C21	C22	-0.2(2)
C1	C2	C3	C4	-178.2(2)	N2	C25	C26	C18	179.08(17)
C1	C2	C7	C6	177.9(2)	C16	C17	C18	C19	179.7(2)
C2	C3	C4	C5	-0.1(3)	C16	C17	C18	C26	0.1(3)
C2	C7	C6	C5	0.7(3)	C17	C18	C19	C20	-179.1(2)

A	B	C	D	Angle (°)	A	B	C	D	Angle (°)
C3	C4	C5	C6	-0.3(3)	C17	C18	C26	C25	179.60(19)
C4	C5	C6	C7	-0.0(3)	C18	C19	C20	C21	-0.7(3)
O3	C8	C9	C10	-177.2(2)	C18	C26	C25	C21	-0.3(2)
O3	C8	C9	C14	2.9(2)	C19	C20	C21	C22	-178.6(2)
O4	C8	C9	C10	3.0(2)	C19	C20	C21	C25	0.3(3)
O4	C8	C9	C14	-177.0(2)	C20	C21	C22	C23	178.1(3)
C8	C9	C10	C11	-178.3(2)	C20	C21	C25	C26	0.2(2)
C8	C9	C14	C13	179.1(2)	C21	C22	C23	C24	0.7(3)

Table 7. Bond Lengths for complex **C3**.

Atom	Atom	Length (Å)	Atom	Atom	Length (Å)
Ni1	C11	2.425(2)	C2	C3	1.361(12)
Ni1	O1W	2.050(7)	C3	C4	1.399(12)
Ni1	O2W	2.058(5)	C4	C5	1.423(13)
Ni1	O3W	2.059(7)	C4	C12	1.403(10)
Ni1	N1	2.062(6)	C5	C6	1.342(14)
Ni1	N2	2.101(6)	C6	C7	1.446(12)
N1	C1	1.309(9)	C7	C8	1.384(13)
N1	C12	1.384(9)	C7	C11	1.415(11)
N2	C10	1.311(10)	C8	C9	1.362(14)
N2	C11	1.353(9)	C9	C10	1.393(12)
C1	C2	1.407(11)	C11	C12	1.417(11)

Table 8. Bond Angles for complex **C3**.

Atom	Atom	Atom	Angle (°)	Atom	Atom	Atom	Angle (°)
O1W	Ni1	C11	90.74(19)	N1	C1	C2	123.5(7)
O1W	Ni1	O2W	89.3(3)	C3	C2	C1	118.6(8)
O1W	Ni1	O3W	177.8(2)	C2	C3	C4	120.5(8)
O1W	Ni1	N1	90.4(3)	C3	C4	C5	123.8(8)
O1W	Ni1	N2	88.1(3)	C3	C4	C12	117.4(8)
O2W	Ni1	C11	92.24(17)	C12	C4	C5	118.8(8)
O2W	Ni1	O3W	90.0(3)	C6	C5	C4	121.2(8)
O2W	Ni1	N1	173.2(2)	C5	C6	C7	121.5(8)
O2W	Ni1	N2	92.5(2)	C8	C7	C6	124.3(8)
O3W	Ni1	C11	91.36(19)	C8	C7	C11	117.5(8)
O3W	Ni1	N1	90.1(3)	C11	C7	C6	118.2(8)
O3W	Ni1	N2	89.8(3)	C9	C8	C7	119.5(8)
N1	Ni1	C11	94.52(17)	C8	C9	C10	119.9(9)
N1	Ni1	N2	80.7(2)	N2	C10	C9	122.1(8)
N2	Ni1	C11	175.09(18)	N2	C11	C7	121.9(7)
C1	N1	Ni1	129.7(5)	N2	C11	C12	118.6(6)
C1	N1	C12	118.0(6)	C7	C11	C12	119.4(7)
C12	N1	Ni1	112.3(5)	N1	C12	C4	122.0(7)
C10	N2	Ni1	129.7(5)	N1	C12	C11	117.1(6)
C10	N2	C11	119.0(7)	C4	C12	C11	120.9(7)

Table 9. Torsion Angles for complex **C3**.

A	B	C	D	Angle (°)	A	B	C	D	Angle (°)
Ni1	N1	C1	C2	-178.9(7)	C5	C4	C12	C11	-1.0(14)
Ni1	N1	C12	C4	178.6(7)	C5	C6	C7	C8	179.4(11)
Ni1	N1	C12	C11	0.4(9)	C5	C6	C7	C11	0.0(16)
Ni1	N2	C10	C9	-178.9(7)	C6	C7	C8	C9	-176.8(11)
Ni1	N2	C11	C7	179.8(6)	C6	C7	C11	N2	178.3(8)
Ni1	N2	C11	C12	-1.1(9)	C6	C7	C11	C12	-0.8(13)
N1	C1	C2	C3	-1.5(15)	C7	C8	C9	C10	-1.7(17)
N2	C11	C12	N1	0.5(11)	C7	C11	C12	N1	179.6(8)
N2	C11	C12	C4	-177.8(8)	C7	C11	C12	C4	1.4(12)
C1	N1	C12	C4	-3.1(13)	C8	C7	C11	N2	-1.3(13)
C1	N1	C12	C11	178.6(8)	C8	C7	C11	C12	179.6(8)
C1	C2	C3	C4	-0.5(16)	C8	C9	C10	N2	-0.9(16)
C2	C3	C4	C5	-179.0(10)	C10	N2	C11	C7	-1.2(12)
C2	C3	C4	C12	0.5(15)	C10	N2	C11	C12	177.9(8)
C3	C4	C5	C6	179.6(11)	C11	N2	C10	C9	2.3(14)
C3	C4	C12	N1	1.3(14)	C11	C7	C8	C9	2.7(15)
C3	C4	C12	C11	179.5(8)	C12	N1	C1	C2	3.2(14)
C4	C5	C6	C7	0.4(18)	C12	C4	C5	C6	0.1(17)
C5	C4	C12	N1	-179.1(9)					

Abstract

In this dissertation, we conducted an in-depth study on metal-organic complexes based on N-heterocyclic and carboxylic acid ligands. We detailed the types of non-covalent bonds and their roles in the stabilization and formation of supramolecular architectures in solid-state materials. In this case, we synthesized three new metal complexes based on 1,10-phenanthroline as an organic ligand with different transition metals. We analyzed and determined the molecular structures of these coordinated compounds by single-crystal X-ray diffraction. We have thus demonstrated these structures using spectroscopic methods such as FT-IR and UV-visible. We next performed a theoretical study to identify intermolecular interactions through Hirshfeld surface, optimize geometries, and discuss electronic, chemical, and physical properties using density functional theory (DFT) and other computational methods, including ELF, LOL, MEP, and RGD. Finally, we demonstrated the antibacterial and antioxidant activity of these compounds, enabling us to deduce their biological importance. Additionally, through molecular docking theory, we predicted and understood the binding modes and interaction mechanisms of these metal complexes with potential biological targets.

Key words: Complex, 1,10-phenanthroline, transition metal, single-crystal, molecular docking, biological activity.

Résumé

Dans cette thèse, nous avons mené une étude approfondie sur les complexes métal-Organiques à base de N-hétérocycliques et d'acide carboxyliques. Nous avons détaillé les différents types des liaisons non covalentes et leur rôle dans la stabilisation et la formation d'architectures supramolécules pour matériaux à l'état solide. Dans ce cas, nous avons synthétisé trois nouveaux complexes métalliques à base de 1,10-phénanthroline comme ligand organique avec différents métaux de transition. Nous avons analysé et déterminé les structures moléculaires de ces composés coordonnés par la diffraction des rayons X sur un monocristal. Nous avons montré ainsi ces structures par les méthodes spectroscopiques telles que FT-IR et UV-visible. Nous avons ensuite effectué une étude théorique pour identifier les interactions intermoléculaires à l'aide de la surface de Hirshfeld, optimiser les géométries et discuter les propriétés électroniques, chimiques et physiques grâce à la théorie de la fonctionnelle de la densité (DFT) et d'autres méthodes computationnelles, y compris ELF, LOL, MEP et RGD. Nous avons enfin montré l'activité antibactérienne et antioxydante de ces composés, ce qui permet d'en déduire l'importance biologique. De plus, grâce à la théorie de l'amarrage moléculaire, nous avons prédit et compris les modes de liaison et les mécanismes d'interaction de ces complexes métalliques avec les candidats cibles biologiques.

Les mots clés : Complexe, 1,10-phenanthroline, métaux de transition, monocristal, amarrage moléculaire, activité biologique.

ملخص

في هذه الأطروحة، أجرينا دراسة متعمقة حول المركبات المعدنية العضوية القائمة على جزيئات N غير المتجانسة الحلقات والأحماض الكربوكسيلية، كما قمنا بتفصيل أنواع الروابط غير التساهمية ودورها في استقرار وتشكيل الهياكل الفوق جزيئية للمواد الصلبة. في هذه الحالة، قمنا بتخليق ثلاث مركبات معدنية جديدة تعتمد على 1,10-فينانثرولين كرابط عضوي مع معادن انتقالية مختلفة. كما قمنا بتحليل وتحديد الهياكل الجزيئية لهذه المركبات المنسقة بواسطة حيود الأشعة السينية أحادي البلورة. بعد ذلك، قمنا بإثبات هذه الهياكل باستخدام طرق طيفية مثل FT-IR و UV-visible. أجرينا دراسة نظرية لتحديد التفاعلات بين الجزيئات بواسطة سطح هير شفيدل، وتحسين الهندسة، ومناقشة الخصائص الإلكترونية والكيميائية والفيزيائية باستخدام نظرية وظيفية الكثافة (DFT) وطرق حسابية أخرى، بما في ذلك تحليلات ELF و LOL و MEP و RGD.

أخيراً، أثبتنا النشاط المضاد للبكتيريا والمضاد للأكسدة لهذه المركبات، مما مكننا من استنتاج أهميتها البيولوجية. بالإضافة إلى ذلك، من خلال نظرية الالتحام الجزيئي، توقعنا وفهمنا أنماط الارتباط وآليات التفاعل لهذه المركبات المعدنية مع الأهداف البيولوجية المحتملة.

الكلمات المفتاحية: مركب، 1,10-فينانثرولين، فلز انتقالي، بلورة أحادية، الالتحام الجزيئي، النشاط البيولوجي.

