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Research Article

Synthesis, characterization and Bioactivity Evaluation of Heteroleptic Zinc(II) Complexes: Antioxidant and α-Amylase Inhibition Studies

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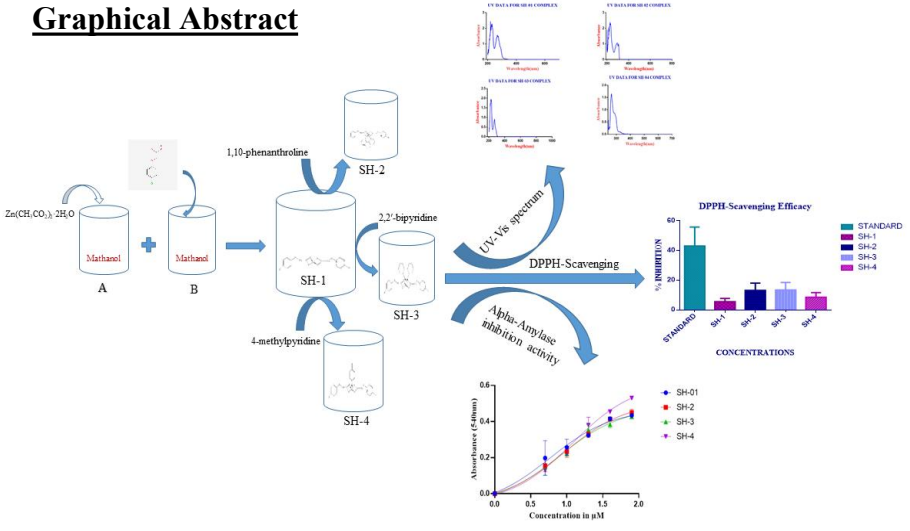
Abstract

A series of four zinc(II) complexes (SH-1 to SH-4) were successfully prepared through the reaction of zinc acetate dihydrate with 4-chlorophenoxyacetic acid (SH-1) in methanol and further reaction with additional ligands (1,10-phenanthroline, 2,2'-bipyridine, and 4-methylpyridine, respectively). The complexes were obtained in satisfactory yields (66-78%) and thoroughly characterized using elemental analysis and atomic absorption spectroscopy, which verified their proposed structure. FT-IR spectral analysis confirmed bidentate chelation of the carboxylate moiety to the zinc center, demonstrating metal-ligand interaction. UV-Visible spectroscopy showed characteristic absorption bands in the 200-300 nm range, corresponding to ligand-centered π→π* electronic transitions. Biological assessments revealed concentration-dependent antioxidant activity against DPPH radicals and inhibitory effects on α-amylase enzyme, with the 2,2'-bipyridine-containing complex (SH-3) show high performance in both biological assays compared to other complexes. The IC_{50} value of SH-3 is 5.867 ± 0.066 for biological activity. SH-4 shows a higher yield of 78%.

Keywords: Zinc(II) complexes, synthesis, structural characterization, antioxidant activity, enzyme inhibition study

Graphical Abstract



1. Introduction

Zinc (Zn), a group IIB element of the first transition series, exhibits distinctive chemical properties characterized by its exclusive +II oxidation state. With an electronic configuration of $[Ar]4s^23d^{10}$, Zn^{2+} is redox-inactive yet demonstrates unique chemical behavior among transition metals due to its specific charge density characteristics. This particular electronic structure and oxidation state confer zinc complexes with notable stability and coordination properties that differ from other transition metal compounds [1]. Zinc demonstrates characteristic Lewis acid behavior, displaying strong binding

affinity toward diverse Lewis base ligands. This metal center commonly adopts stable tetrahedral or octahedral coordination geometries in its complexes, reflecting its versatile coordination chemistry [2]. The human body contains approximately 3 mg of zinc, making it the second most prevalent bio-essential trace metal found in the body [3]. Zinc plays a crucial role in fundamental biological processes and is a vital element in nearly all enzyme categories [4]. "Zinc acts as an effective enzyme inhibitor for multiple enzymes [5]. Moreover, Zinc regulates important physiological functions like cellular recovery from oxidative stress [6-8]. A lack of zinc in the central nervous system can lead to various pathologic issues [9]. Zinc deficiency might lead to the growth of tumors during all stages of tumor development [7] . Figure 1 illustrates several health complications associated with zinc deficiency in humans.

Zinc(II) carboxylate complexes exhibit unique structural diversity and distinctive chemical properties that set them apart from other metal carboxylates. A key feature of these compounds is the versatile coordination behavior of the carboxylate ligand, which can bind to the zinc center in multiple configurations: as a monodentate ligand, in a bridging bidentate mode, or as a chelating bidentate ligand. This remarkable coordination flexibility contributes significantly to the complexes' varied architectures and functional applications in coordination chemistry[10-12].
During this process, the carboxylate ligand may alter its coordination behavior [9]. The carboxylate shift method produces zinc carboxylate complexes with a variety of geometries, including octahedral, tetrahedral, square pyramidal and trigonal-bipyramidal, in one, two, and three dimensions [13,14]. The bidentate chelators like 1,10-phenanthroline (phen) or 2,2'-bipyridine (bipy) locks part of the zinc coordination sphere. This creates a highly stable, neutral complex unit [Zn(carboxylate) $_2$(N-donor)$_2$] or similar. This chelate effect significantly enhances thermal and solution stability compared to complexes with only monodentate ligands coordinated with Zinc, and plays key performance in biological applications.

1.1 Antioxidant

These compounds exhibit antioxidant properties through multiple mechanisms of action against oxidative processes [15, 16]. Living organisms possess an intrinsic antioxidant defense system comprising enzymes such as superoxide dismutase, glutathione peroxidase, and catalase, which work collectively to counteract oxidative stress by neutralizing harmful reactive oxygen species [17]. To prevent free radical-induced oxidation and prolong shelf life, processed food industry routinely employs BHA and BHT as synthetic antioxidant additives in various products) [18, 19]. Key natural antioxidants comprise compounds such as coumarins, carotenoids, flavonoids, tocopherols and others.[20]

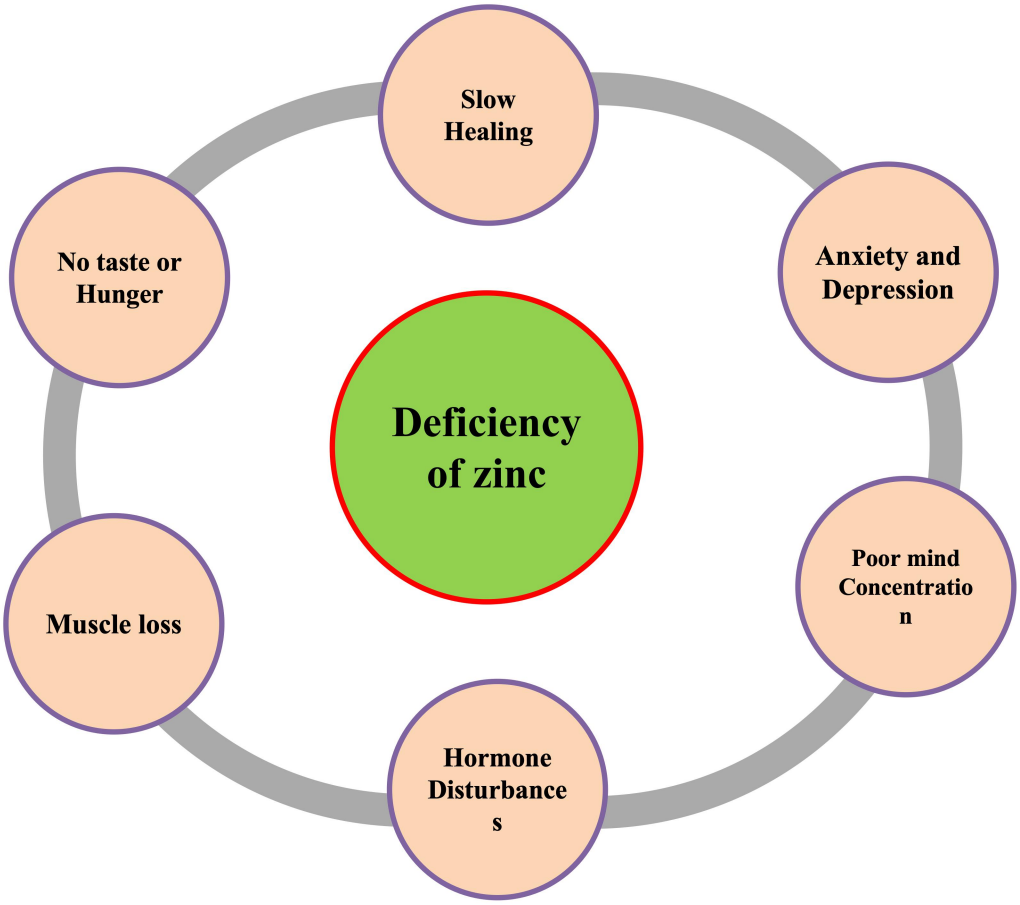


Figure 1. Health disorders resulting from zinc deficiency in humans.

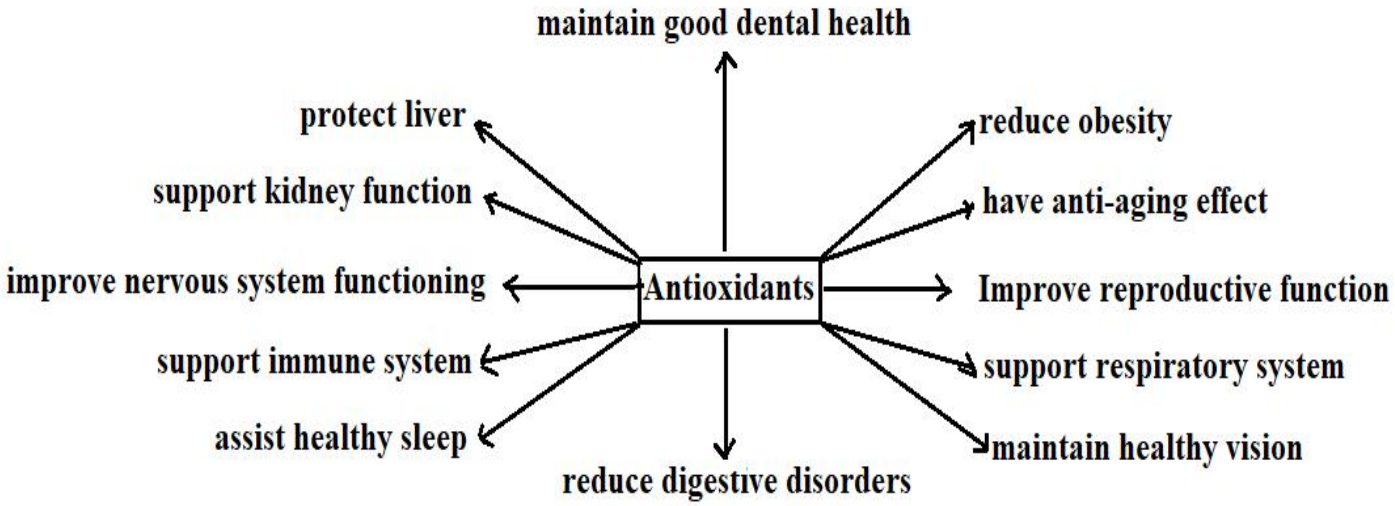


Figure 2. Highlights some of the important beneficial aspects of the antioxidants

1.2 Enzymatic activity

Enzymes bind to their specific substrates in a highly selective manner, enabling these substrates to undergo biochemical transformations at dramatically accelerated rates [21]. Enzyme activity is critically dependent on optimal temperature and pH conditions, with maximal catalytic efficiency occurring at 37°C (normal human body temperature). Activity declines at lower temperatures and is irreversibly lost above 40°C due to thermal denaturation. While enzymes serve as precise biocatalysts in industrial processes, their application faces limitations including narrow reaction specificity, instability in organic solvents, and thermal ability. These challenges have made protein engineering a vibrant research field, focusing on developing novel enzymes with enhanced properties through both natural optimization strategies and in vitro directed evolution approaches [21].

Enzyme inhibition occurs when there is a decline in enzyme-mediated reactions, enzyme synthesis, or catalytic activity. Different classes of enzyme inhibitors can slow down these reaction rates [30].

2. Materials and Methods

2.1. Chemicals reagents

All chemicals and reagents used in this study were of analytical grade and were purchased from Sigma-Aldrich. The antioxidant standard was vitamin C (ascorbic acid). The ligands employed included 4-chlorophenoxyacetic acid, 4-methylpyridine, 2,2′-bipyridine, and 1,10-phenanthroline. The solvents used were methanol, ethanol, and dimethyl sulfoxide (DMSO). Biochemical reagents included α-amylase enzyme, starch, and dinitrosalicylic acid. The free radical species used in the antioxidant assay was DPPH (2,2-diphenyl-1-picrylhydrazyl).

2.2. Instrumentation

The synthesized complexes were characterized using the following techniques: melting points were determined with a Stuart SMP10 apparatus (UK); FT-IR spectra were recorded using an infrared spectrophotometer; and UV–Vis spectral analyses were carried out on a PerkinElmer UV–Vis spectrophotometer.

2.3. Synthesis of complexes

SH-1. The synthesis was carried out by first dissolving stoichiometric amounts of zinc acetate dihydrate (0.293 g, 1.0 mM) and 4-chlorophenoxyacetic acid (0.5 g, 2.0 mmol) separately in methanol in ratio of 1:2 followed by dropwise addition of the zinc acetate solution to the 4-chlorophenoxyacetic acid solution under constant stirring; the resulting mixture was then heated at 70°C with continuous stirring for 4-5 hours, after completing materials the reaction it was allowed to cool to room temperature and confirmed with TLC which give different spots with the starting materials, after that filtered it to remove methanol and kept it to dry, and left for crystallization under ambient conditions.

SH-2. Complex SH-2 was synthesized following the same initial procedure as SH-1, with the additional step of dropwise addition of 1,10-phenanthroline (0.18 g, 1.0 mmol) (nitrogen donor ligand) into the reaction mixture. The solution was then refluxed for four additional hours before being cooled to room temperature. The product confirmed by TLC and then transferred to a crystallization vessel and allowed to crystallize under ambient conditions, maintaining a 1:2:1 molar ratio of zinc acetate dihydrate, 4-chlorophenoxyacetic acid, and nitrogen donor ligand throughout the synthesis.

SH-3. The synthesis of complex SH-3 followed the same initial protocol as SH-1, with the subsequent addition of 2,2′-bipyridine (0.15 g, 1.0 mmol) (nitrogen donor ligand) via dropwise addition into the reaction mixture. Following a 4-hour reflux period, the solution was cooled to room temperature and transferred to a crystallization vessel for slow evaporation. The reaction maintained strict stoichiometric 1:2:1 molar ratio of zinc acetate dihydrate: 4-

chlorophenoxyacetic acid: 2,2′-bipyridine throughout the synthetic process.

SH-4. The synthesis of complex SH-4 followed the same initial procedure as SH-1. Subsequently, 4-methylpyridine (0.09 g, 1.0 mmol) (nitrogen donor ligand) was added dropwise to the reaction mixture, followed by a 4-hour reflux period. After completion, the solution was cooled to room temperature and transferred to a crystallization vessel.

Table 1. Enzymes and their industrial applications.

Enzyme(s)	Industrial Applications
Cellulases	Biofuel industry: Breaks cellulose into glucose for ethanol fermentation [22].
Proteases, Amylases, Lipases	Detergents: Removes protein, starch, and oil stains from tableware [23]
Amylase, Glucanases, Proteases	Brewing: Degrades polysaccharides and proteins in malt [24].
Beta-Glucanases	Improves beer quality and filtration efficiency [25].
Amyloglucosidase , Pullulanases	Produces low-calorie beer and controls fermentation [25].
Acetolactate Decarboxylase (ALDC)	Enhances fermentation yield by reducing diacetyl production [25].
Papain	Food processing: Tenderizes meat [26].
Lipases	Manufacture of Camembert and blue cheeses [27].
Proteases	Ophthalmology: Cleans proteins from contact lenses to prevent infections [29].
Amylases	Starch industry: Converts starch to glucose and other syrups [30].

The reaction employed stoichiometric ratios of 1:2:1 (zinc acetate dihydrate: 4-chlorophenoxyacetic acid: nitrogen donor ligand) to ensure proper complex formation. The product was then allowed to crystallize under ambient conditions.

2.4. The DPPH-scavenging efficacy of complexes

The antioxidant potential of zinc (II) complexes was evaluated through DPPH radical scavenging assay following a modified Shanab et al. protocol. The experimental procedure involved:

Reaction Setup

Test solutions of the complexes (SH-1 to SH-4) at concentrations ranging from 8 to 64 µM, as well as the standard (ascorbic acid), were mixed with 1 mL of ethanolic DPPH solution (255 µM).

Incubation Conditions

The reaction was carried out in the dark at room temperature for 40 minutes.

Analysis

Absorbance measurements at 517 nm (UV-Vis spectrophotometer)
Triplicate determinations for statistical reliability.
The DPPH radical-scavenging activity can be calculated using the following formula:

$$Inhibition\ power = \frac{A_{Con} - A_{Sam}}{A_{Con}} \times 100$$

Where:
A_{con}= Absorbance of the control
A_{sam}= Absorbance of the test sample

2.5. Alpha-Amylase Inhibition Assay

The alpha-amylase inhibitory activity of the synthesized complexes was assessed using a standardized protocol. The assay was performed in 96-well plates with the following reaction mixture:
50-µL phosphate buffer (100 mM, pH 6.8)
10-µL alpha-amylase solution (2 µ/mL)

20-µL test compound (varying concentrations)
After pre-incubation at 37°C for 20 minutes, 20 µL of 1% starch solution (in phosphate buffer) was added as substrate and incubated for an additional 30 minutes at 37°C. The reaction was terminated by adding 100 µL DNS reagent, followed by heating at for 10 minutes. Absorbance was measured at 540 nm, with acarbose serving as the reference inhibitor at multiple concentrations.
%age Inhibition (%) = (1 − As/Ac) × 100

Where:
As = Abs of sample
Ac = Abs of control

2.6. Statistics of the data

All experimental measurements were performed in triplicate to ensure reproducibility. Statistical analysis was conducted using GraphPad Prism (version 6), employing two key methodologies:
1: Column statistics and linear regression for calculating IC_{50} values with standard error of the mean (SEM)
2: One-way ANOVA to assess significant differences between groups and evaluate variance
The triplicate measurements provided a robust dataset for reliable statistical interpretation of the results.

Table 2. Details of Synthesized complexes SH-1 to SH-4.

(A) Zinc(II)-bis-(4-chlorophenoxy acetate) (SH-1)				(B) Zinc(II)-bis-(4-chlorophenoxy acetate)-N,N-(1,10-phenanthroline) (SH-2)			
Molecular Formula	**Molecular**	**Yield**	**M.P**	**Molecular Formula**	**Molecular**	**Yield**	**M.P**
$C_{16}H_{10}Cl_2O_6Zn$	434.56	75%	228°C	$C_{28}H_{18}Cl_2O_6Zn$	614.76	66%	142°C
Elemental Composition: Corbon: 44.29% Observed (44.22% theoretical) Hydrogen: 2.37% Observed (2.32% theoretical) FT-IR Spectral Features: 1560 $cm^{-1:}$ Strong Asymmetric COO- stretch ($\tilde{\nu}_{as}$) 1467 $cm^{-1:}$ Strong symmetric COO- stretch ($\tilde{\nu}_{as}$) $\Delta\tilde{\nu}$ = 93 cm^{-1} (Indicative of chelating bidentate coordination) 451 cm^{-1}: Zn-O vibrational mode Zinc Content (AAS): Measured: 15.02% Calculated: 15.05%				Elemental Analysis (Observed vs Calculated) Corbon: 54.59% (54.70%) Hydrogen: 2.87% (2.95%) Nitrogen: 4.48% (4.56%) FT-IR Spectral signatures: 1593 $cm^{-1:}$ Strong COO- stretch ($\tilde{\nu}_{as}$) 1488 $cm^{-1:}$ Strong COO- stretch ($\tilde{\nu}_{s}$) $\Delta\tilde{\nu}$ = 105 cm^{-1} (Chelating bidentate coordination) 724 cm^{-1}: Aromatic ring vibration 455 cm^{-1}: Zn-O vibrational mode 505 cm^{-1}: Zn-N stretching Zinc Content (AAS): Measured: 10.55% Calculated: 10.64%			
(C) Zinc(II)-bis-(4-chlorophenoxy acetate)-N,N-(2,2 bipyridine) (SH-3)				(D) Zinc(II)-bis-(4-chlorophenoxy acetate)-N-4-methylpyridine (SH-4)			
Molecular Formula	**Molecular**	**Yield**	**M.P**	**Molecular Formula**	**Molecular**	**Yield**	**M.P**
$C_{26}H_{18}Cl_2N_2O_6Zn$	590.75	73%	184°C	$C_{22}H_{17}Cl_2NO_6Zn$	527.68	78%	85°C
Elemental Analysis (Observed vs Calculated): Corbon: 52.80% (52.86%) Hydrogen: 3.11% (3.07%) Nitrogen: 4.71% (4.74%) FT-IR Spectral signatures: 1595 $cm^{-1:}$ Strong COO- stretch ($\tilde{\nu}_{as}$) 1454 $cm^{-1:}$ Strong COO- stretch ($\tilde{\nu}_{s}$) $\Delta\tilde{\nu}$ = 141 cm^{-1} (Chelating bidentate coordination) 771 cm^{-1}: Aromatic ring wagging vibration 461 cm^{-1}: Zn-O vibrational mode 506 cm^{-1}: Zn-N stretching Zinc Content (AAS): Measured: 11.01% Calculated: 11.07%				Elemental Analysis (Observed vs Calculated): Corbon: 50.01% (50.07%) Hydrogen: 3.31% (3.25%) Nitrogen: 2.61% (2.65%) FT-IR Spectral signatures: 1556 $cm^{-1:}$ Strong COO- stretch ($\tilde{\nu}_{as}$) 1423 $cm^{-1:}$ Strong COO- stretch ($\tilde{\nu}_{s}$) $\Delta\tilde{\nu}$ = 133 cm^{-1} (Chelating bidentate coordination) 723 cm^{-1}: Aromatic ring wagging vibration 490 cm^{-1}: Zn-O vibrational mode 503 cm^{-1}: Zn-N stretching Zinc Content (AAS): Measured: 12.36% Calculated: 12.40%			

Note: (A) Zinc(II)-bis-(4-chlorophenoxy acetate) (SH-1); (B) Zinc(II)-bis-(4-chlorophenoxy acetate)-N,N-(1,10-phenanthroline) (SH-2); (C) Zinc(II)-bis-(4-chlorophenoxy acetate)-N,N-(2,2′-bipyridine) (SH-3); and (D) Zinc(II)-bis-(4-chlorophenoxy acetate)-N-(4-methylpyridine) (SH-4), showing molecular formula, molecular weight, yield, melting point, elemental analysis, FT-IR spectral features, and zinc content (AAS).

3. Results and discussions

3.1. FT-IR Results

The FT-IR spectra (4000–400 cm^{-1}) provided crucial insights into the formation and structural features of the zinc(II) carboxylate complexes. This analytical technique confirmed the deprotonation and coordination of the carboxylate ligand, as evidenced by the disappearance of the broad O–H stretching band (3200–2500 cm^{-1}) characteristic of free carboxylic acid. The observed spectral changes verify the conversion of –COOH to carboxylate (COO-) upon complexation with zinc(II). Additionally, the FT-IR data helped elucidate the binding mode of the carboxylate ligand to the metal center.

The carboxylate ligand's coordination was further verified by Zn-O bond vibrations appearing as weak-medium bands at 490-451 cm^{-1}. Key IR features in metal carboxylates include the asymmetric (ν_a) and symmetric (ν) COO- stretches, with their separation ($\Delta\nu$) indicating binding mode. The coordination mode of carboxylate ligands can be determined by their $\Delta\nu$ values:

$\Delta\nu > 250$ cm^{-1} → Monodentate, $150 < \Delta\nu < 250$ cm^{-1} → Bridging bidentate, $\Delta\nu < 150$ cm^{-1} → Chelating bidentate.

The $\Delta\nu$ values of the synthesized complexes (SH-1: 93 cm^{-1}, SH-2: 105 cm^{-1}, SH-3: 141 cm^{-1}, SH-4: 133 cm^{-1}) all fall below 150 cm^{-1}, indicating a chelating bidentate coordination

mode for the carboxylate ligands. For the nitrogen-containing complexes (SH-2, SH-3, SH-4), FT-IR analysis revealed Characteristic Zn-N stretching vibrations at 503-506 cm-¹ and strong ring wagging modes at 723-771 cm-¹. These spectral features collectively confirm the successful incorporation of ligands in complexes SH-2, SH-3, SH-4.

Table 3. Physicochemical properties of the synthesized complexes.

Complex	Molecular Formula	Molar Mass (g/mol)	Yield (%)	Melting Point (°C)	Solubility Profile
SH-1	$C_{16}H_{10}Cl_2O_6Zn$	434.56	75	228	Methanol, ethanol, acetone, DMSO
SH-2	$C_{28}H_{18}Cl_2N_2O_6Zn$	614.76	66	142	Methanol, ethanol, chloroform, DMSO
SH-3	$C_{26}H_{18}Cl_2N_2O_6Zn$	590.75	73	184	Methanol, ethanol, chloroform, DMSO
SH-4	$C_{26}H_{17}Cl_2NO_6Zn$	527.68	78	85	Methanol, et

Table 4. Comparative infrared spectral data (cm^{-1}) of the ligand acid and metal complexes.

Vibration Mode	Ligand Acid	SH-1	SH-2	SH-3	SH-4
ν(OH) stretch	3500-2500	-	-	-	-
ν(C=O) stretch	1703s	-	-	-	-
ν(C-O) stretch	1269s	-	-	-	-
ν_a (COO^-) stretch	-	1560s	1593s	1595s	1556s
ν (COO^-) stretch	-	1467s	1488s	1454s	1423s
Δν (COO^-)	-	93	105	141	133
Aromatic ring wagging	-	-	724	771	723
ν(Zn-N) stretch	-	-	505	506	503
ν(Zn-O) stretch	-	451	455	461	490

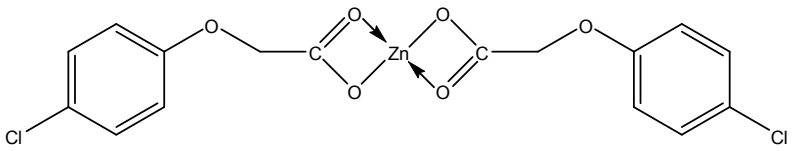


Figure 3. Structure of SH-1.

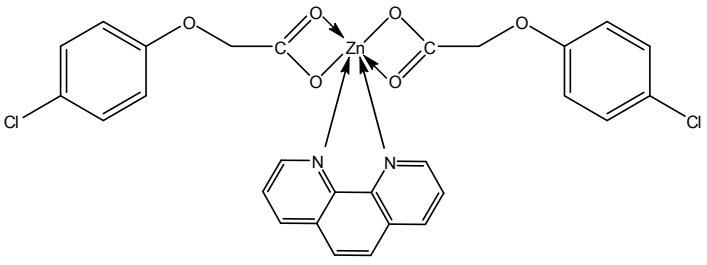


Figure 4. Structure of SH-2.

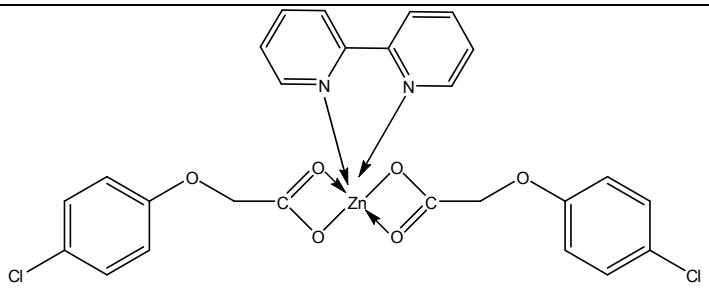


Figure 5. Structure of SH-4.

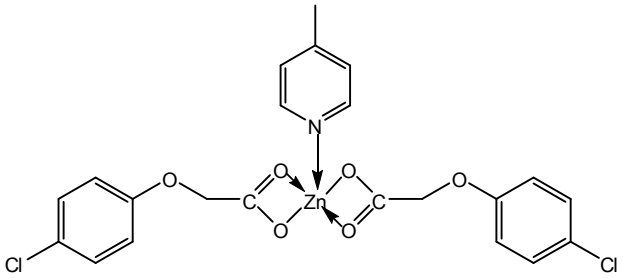


Figure 6. Structure of SH-5.

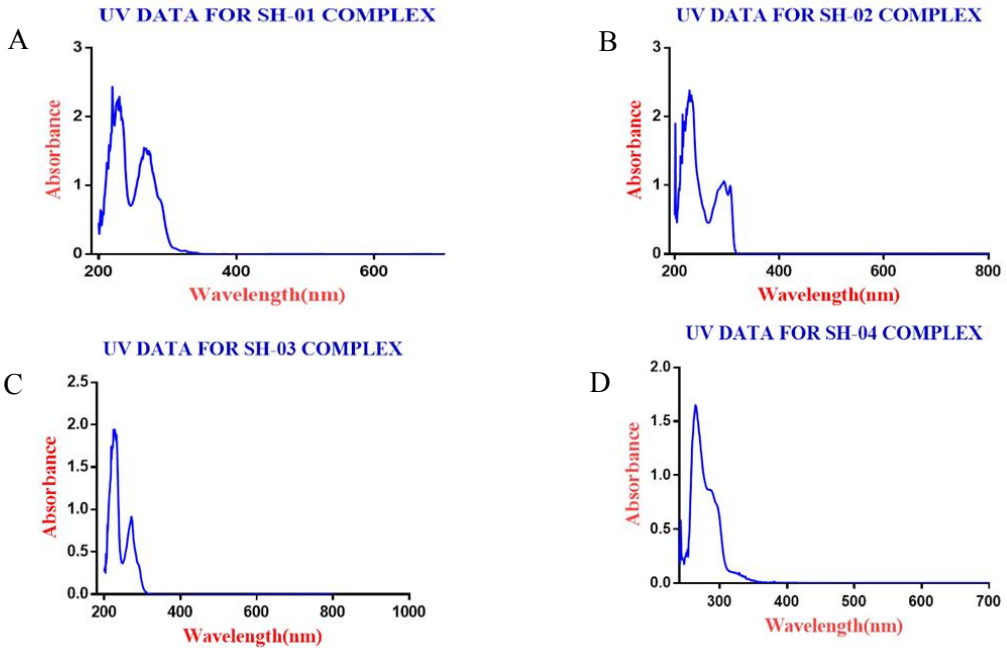


Figure 7. UV-Vis spectra of complexes SH-1 to SH-4. (a) SH-1: Zinc(II)-bis-(4-chlorophenoxy acetate); (b) SH-2: Zinc(II)-bis-(4-chlorophenoxy acetate)-N,N-(1,10-phenanthroline); (c) SH-3: Zinc(II)-bis-(4-chlorophenoxy acetate)-N,N-(2,2′-bipyridine); (d) SH-4: Zinc(II)-bis-(4-chlorophenoxy acetate)-N-(4-methylpyridine).

3.2. Proposed structures of the complexes

FT-IR show the structures proposed for the synthesized complexes are shown in Figures (3-6)

3.3. UV-Vis spectrum

Further characterization of the synthesized complexes was conducted using UV-Vis spectroscopy to examine their absorption spectra (recorded at 100 µM in ethanol) displayed in Figures 3.5–3.8. All compounds exhibited distinct absorption bands in the 200–300 nm range, which are likely associated with intra-ligand π→π* electronic transitions. A slight red shift (bathochromic shift) was observed in the spectra of SH-2, SH-3, and SH-4, possibly due to the extended π-conjugation in their auxiliary ligands (1,10-phenanthroline and 2,2'-bipyridine). This shift suggests that

the aromatic systems of these co-ligands influence the electronic transitions within the complexes

3.4. DPPH-Scavenging efficacy

The DPPH radical scavenging assay is a widely employed method for evaluating the antioxidant activity of compounds, even at low concentrations, due to its sensitivity in detecting free radical-neutralizing potential. When DPPH (a stable free radical) interacts with an antioxidant capable of donating hydrogen atoms (H^+), its characteristic absorbance at 517 nm diminishes. In this study, the DPPH scavenging activity of synthesized Zn(II) complexes was assessed in ethanol and compared with that of ascorbic acid, a standard reference antioxidant. The results help determine the relative antioxidant efficiency of the complexes.

the percentage inhibition of DPPH radicals at varying concentrations of the synthesized Zn(II) complexes shows at Table 5 and Figure 8, revealing a concentration-dependent antioxidant response. The results indicate that higher concentrations of the complexes lead to increased radical scavenging activity. The IC_{50} values listed in Table 3.3 further quantify this effect, showing that while all complexes exhibit dose-dependent antioxidant behavior, their scavenging efficiency remains lower than that of the standard ascorbic acid (IC_{50} = 102.45 µM). Among the tested complexes, SH-1 displayed the weakest DPPH scavenging ability, highlighting variations in antioxidant potency across the series.

The study revealed notable differences in the DPPH radical scavenging activity of the zinc(II) complexes based on their structural composition. The IC_{50} value for SH-1 (lacking a nitrogen donor ligand) was significantly higher (823.43 µM), indicating weaker antioxidant activity. In contrast, complexes SH-2 to SH-4 exhibited lower IC_{50} values (546.87, 547.34, and 703.45 µM, respectively), suggesting that the presence of nitrogen donor ligands enhances free radical scavenging potential. SH-2 (1,10-phenanthroline) and SH-3 (2,2'-bipyridine) demonstrated comparable and superior activity compared to SH-4, likely due to their extended aromatic ring systems, which may facilitate better electron delocalization and radical stabilization. This structural feature appears to contribute significantly to their higher antioxidant efficiency, reinforcing the role of aromatic nitrogen donors in enhancing the scavenging activity of zinc(II) carboxylate complexes.

3.5. Alpha-Amylase inhibition activity

Table 6 and Figure 9 illustrate the alpha-amylase inhibition activity of the zinc(II) complexes at varying concentrations. The results demonstrate a concentration-dependent enhancement in enzyme inhibition, with higher concentrations of the complexes leading to increased inhibitory effects. Additionally, the lower IC_{50} values presented in Table 6 indicate greater inhibitory potency of the complexes against the alpha-amylase enzyme. The alpha-amylase inhibition efficacy of the synthesized zinc(II) complexes, determined by their IC_{50} values, follows the order: SH-3 > SH-1 > SH-2 > SH-4. Among these, SH-3 exhibits the strongest inhibitory activity with an IC_{50} value of 5.867 ± 0.066, while SH-4 demonstrates the weakest inhibition, showing an IC_{50} value of 12.00 ± 0.082. This trend highlights the varying effectiveness of the complexes in suppressing alpha-amylase activity, with SH-3 being the most potent inhibitor.

Table 5. DPPH Scavenging activity at different concentrations.

Compound	8 µM	16 µM	32 µM	64 µM	128 µM	IC_{50} (µM)
Standard	12.23	20.87	39.09	62.21	81.09	102.45
SH-1	0.9	2.11	5.02	6.31	13.3	823.43
SH-2	2.9	4.02	10.15	20.62	28.22	546.87
SH-3	2.91	4.62	10.19	20.92	28.82	547.34
SH-4	1	3.87	7.76	10.98	19.09	703.45

Table 6. α-Amylase inhibitory activity of synthesized zinc complexes expressed as IC50 values.

Compound	IC_{50} ± SEM
SH-1	7.93 ± 0.065
SH-2	9.25 ± 0.069
SH-3	5.867 ± 0.066
SH-4	12.00 ± 0.082

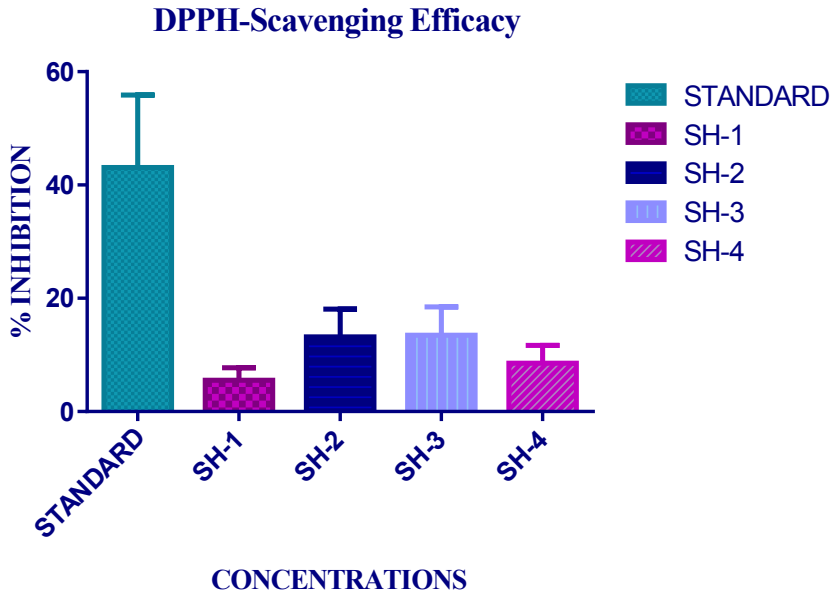


Figure 8. DPPH-Scavenging efficacy of the complexes.

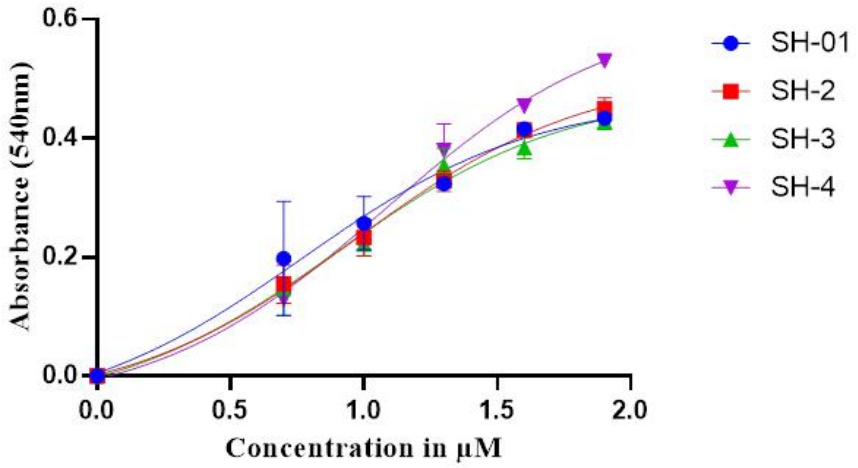


Figure 9. Alpha-amylase inhibition assay of Zinc-complexes.

The outperformance for Bipy could be in luminescence, biological activity, catalytic efficiency and stability. Bipy offers a sweet spot. It provides enough conjugation for strong light absorption and rigidochromism (restriction of motion upon binding), but its slightly less planar and smaller structure reduces detrimental intermolecular π-stacking. This often results in a higher photoluminescence quantum yield (PLQY) for bipy complexes compared to phen analogs, as intermolecular quenching is minimized.

4. Conclusion

A series of zinc(II) complexes (SH1 to SH-4) were prepared by refluxing zinc acetate dihydrate with 4-chlorophenoxyacetic acid (SH-1) in methanol and further reaction with (1,10-phananthroline, 2,2′-bipyridine and 4-methylpyridine) ligands. The reactions proceeded efficiently, yielding crystalline products in moderate to good yields (66–78%). Comprehensive characterization through elemental analysis, AAS, FT-IR, and UV-Vis spectroscopic techniques collectively confirmed both the structural and purity of the synthesized complexes. The complexes displayed concentration-dependent antioxidant activity in DPPH radical scavenging assays, with activity trends reflecting the influence of nitrogenous ligands: SH-3 was most active, followed by SH-2, SH-4, and SH-1. In α-amylase inhibition studies, the complexes exhibited varying potency SH-3 was most active,

followed by SH-1, SH-2, and SH-4 suggesting structure-dependent interactions with the enzyme.

Author contributions

Uzair Khan: Uzair Khan: Conceptualization, Methodology, Supervision, Project administration, Writing–original draft. Zeshan Ahmad: Conceptualization, Supervision, Project administration, Investigation, Data curation, Writing–original draft. Sara Ali: Investigation, Data curation, Writing– original draft. Zama Jan: Writing–review & editing. Murad Khan: Investigation, Resources. Humayun Khan: Investigation, Resources. Sayed Nauman Shah: Investigation, Resources. All authors have read and agreed to the published version of the manuscript.

Ethical approval

Not applicable.

Conflicts of Interest

The authors report no conflicts of interest.

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Data availability statement

The data presented in this study are available on request from the corresponding author.

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