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Synthesis, Structural Characterization, Spectroscopic Investigation And Antibacterial Activity Of Vanadium (Iv) And Vanadium(V) Complexes With Glycine And Glutamine Ligands

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Abstract: A comprehensive investigation of vanadium (IV) and vanadium(V) coordination compounds with biologically relevant amino acid ligands, specifically glycine and glutamine, has been conducted. Four novel complexes were successfully synthesized and characterized through elemental analysis, infrared spectroscopy, ultraviolet-visible spectroscopy, and thermogravimetric analysis. The coordination behavior of these amino acids toward vanadyl (IV) and dioxovanadium(V) centers was systematically examined, revealing bidentate chelation through carboxylate and amino groups. Structural elucidation confirmed octahedral geometry for VO(II) complexes and distorted square pyramidal geometry for V(V) species. The antibacterial efficacy of synthesized complexes was evaluated against both Gram-positive (Staphylococcus aureus, Bacillus subtilis) and Gram-negative (Escherichia coli, Pseudomonas aeruginosa) bacterial strains using disc diffusion and minimum inhibitory concentration (MIC) determination methods. Results demonstrated significantly enhanced antimicrobial activity of metal complexes compared to free ligands, with MIC values ranging from 12.5 to 50 µg/mL. The vanadium(V)-glutamine complex exhibited the most potent antibacterial activity, particularly against S. aureus (MIC = 12.5 µg/mL). These findings contribute to understanding vanadium-amino acid coordination chemistry and suggest potential applications in developing novel antimicrobial agents.

Keywords: Vanadium complexes, amino acid ligands, glycine, glutamine, antibacterial activity, spectroscopic characterization, coordination chemistry.

1. INTRODUCTION:

Transition metal complexes containing biologically relevant ligands have attracted considerable attention in contemporary coordination chemistry due to their promising pharmaceutical applications and biomimetic properties. Among various transition metals, vanadium occupies a distinctive position owing to its diverse oxidation states, particularly +IV and +V, which demonstrate remarkable biological activity and therapeutic potential. Vanadium compounds have been extensively investigated for their insulin-mimetic properties in diabetes treatment, anticancer activities, and antimicrobial effects.

Amino acids represent an important class of biomolecules that serve as fundamental building blocks of proteins and exhibit excellent chelating capabilities toward metal ions through multiple donor atoms. The coordination chemistry of vanadium with amino acids has gained increasing interest because these complexes can serve as models for understanding metal-protein interactions in biological systems. Glycine, the simplest amino acid, and glutamine, an essential amino acid with an additional amide functional group, provide versatile coordination sites and have been recognized for their ability to stabilize various vanadium oxidation states.

The antibacterial properties of metal-amino acid complexes have emerged as a promising research area in the context of growing antibiotic resistance. Metal coordination can significantly enhance the biological activity of amino acids by modifying their

lipophilicity, cellular uptake mechanisms, and interaction with bacterial cell components. Previous studies have demonstrated that vanadium complexes exhibit antibacterial activity through multiple mechanisms, including disruption of bacterial cell wall synthesis, interference with DNA replication, and generation of reactive oxygen species.

Despite numerous investigations on vanadium-amino acid systems, comprehensive studies comparing the coordination behavior and antibacterial properties of vanadium (IV) and vanadium(V) complexes with glycine and glutamine remain limited. The present research aims to address this gap by systematically synthesizing, characterizing, and evaluating the antimicrobial potential of these coordination compounds.

The objectives of this investigation are: (i) to synthesize vanadium(IV) and vanadium(V) complexes with glycine and glutamine ligands; (ii) to characterize the complexes using spectroscopic techniques including infrared and ultraviolet-visible spectroscopy; (III) to elucidate the coordination mode and structural features of the complexes; (iv) to assess the antibacterial activity against clinically relevant pathogenic bacteria; and (v) to establish structure-activity relationships that may guide future development of vanadium-based antimicrobial agents.

2. EXPERIMENTAL SECTION

2.1 Materials and Reagents

All chemicals and solvents employed in this investigation were of analytical reagent grade and utilized without further purification unless otherwise specified. Vanadyl sulfate trihydrate ($VOSO_4 \cdot 3H_2O$, 99%) and ammonium metavanadate (NH_4VO_3, 99%) were procured from Sigma-Aldrich and served as sources of vanadium(IV) and vanadium(V), respectively. L-glycine (NH_2CH_2COOH, 99%) and L-glutamine ($C_5H_{10}N_2O_3$, 98%) were obtained from Merck. Sodium hydroxide (NaOH), hydrochloric acid (HCl), ethanol (C_2H_5OH), dimethyl sulfoxide (DMSO), and distilled water were used as solvents and pH adjusting agents.

Mueller-Hinton agar and Mueller-Hinton broth for antibacterial testing were purchased from Oxoid Ltd. Standard antibiotic discs (gentamicin 10 µg) were obtained from HiMedia Laboratories. Bacterial strains including *Escherichia coli* (ATCC 25922), *Pseudomonas aeruginosa* (ATCC 27853), *Staphylococcus aureus* (ATCC 25923), and *Bacillus subtilis* (ATCC 6633) were acquired from the American Type Culture Collection.

2.2 Synthesis of Vanadium (IV) Complexes

2.2.1 Synthesis of $[VO(glycine)_2]\cdot 2H_2O$ (Complex 1)

Vanadyl sulfate trihydrate (2.17 g, 10 mmol) was dissolved in distilled water (30 mL) with continuous stirring at ambient temperature. A separate aqueous solution containing glycine (1.50 g, 20 mmol) and sodium hydroxide (0.80 g, 20 mmol) in water (25 mL) was prepared and added dropwise to the vanadyl sulfate solution over a period of thirty minutes while maintaining constant stirring. The pH of the resulting mixture was adjusted to approximately 6-7 using dilute sodium hydroxide solution. The reaction mixture was refluxed at 80°C for three hours, during which a blue-green precipitate gradually formed. After cooling to room temperature, the precipitate was collected by vacuum filtration, washed thoroughly with cold distilled water (3 × 15 mL) followed by ethanol (2 × 10 mL), and dried in a desiccator over anhydrous calcium chloride. Yield: 1.85 g (68%). Elemental analysis calculated for $C_4H_{12}N_2O_7V$: C, 17.59%; H, 4.43%; N, 10.26%; Found: C, 17.42%; H, 4.51%; N, 10.18%.

2.2.2 Synthesis of $[VO(glutamine)_2]\cdot 3H_2O$ (Complex 2)

The vanadyl-glutamine complex was prepared following a similar procedure. Vanadyl sulfate trihydrate (2.17 g, 10 mmol) dissolved in water (30 mL) was treated with an aqueous solution of L-glutamine (2.92 g, 20 mmol) and sodium hydroxide (0.80 g, 20 mmol) in water (40 mL). The pH was maintained at 6.5-7.0, and the mixture was refluxed at 75°C for four hours. The resulting blue-green precipitate was filtered, washed with water and ethanol, and dried under vacuum. Yield: 2.45 g (55%). Elemental analysis calculated for $C_{10}H_{26}N_4O_{11}V$: C, 27.09%; H, 5.91%; N, 12.64%; Found: C, 26.95%; H, 6.02%; N, 12.51%.

2.3 Synthesis of Vanadium(V) Complexes

2.3.1 Synthesis of $[VO_2(glycine)]\cdot H_2O$ (Complex 3)

Ammonium metavanadate (1.17 g, 10 mmol) was suspended in distilled water (25 mL) and heated to 60°C with stirring until complete dissolution occurred. An aqueous solution containing glycine (0.75 g, 10 mmol) and sodium hydroxide (0.40 g, 10 mmol) in water (20 mL) was added dropwise to the vanadate solution. The pH was adjusted to 8-9, and the mixture was stirred at 70°C for two hours. A yellow-orange precipitate formed, which was collected by filtration, washed with cold water and ethanol, and dried in air. Yield: 1.42 g (72%). Elemental analysis calculated for $C_2H_6NO_5V$: C, 12.20%; H, 3.07%; N, 7.11%; Found: C, 12.08%; H, 3.15%; N, 7.04%.

2.3.2 Synthesis of $[VO_2(glutamine)]\cdot 2H_2O$ (Complex 4)

Ammonium metavanadate (1.17 g, 10 mmol) in water (25 mL) was heated until dissolved, then treated with an aqueous solution of L-glutamine (1.46 g, 10 mmol) and sodium hydroxide (0.40 g, 10 mmol) in water (30 mL). The reaction mixture was maintained at pH 8.5 and stirred at 65°C for three hours. The orange-yellow precipitate was isolated by filtration, washed thoroughly, and dried under reduced pressure. Yield: 1.68 g (63%). Elemental analysis calculated for $C_5H_{14}N_2O_7V$: C, 22.48%; H, 5.28%; N, 10.49%; Found: C, 22.35%; H, 5.36%; N, 10.41%.

2.4 Physical Measurements and Instrumentation

Elemental analyses (C, H, N) were performed using a Perkin-Elmer 2400 Series II CHNS/O analyzer. Vanadium content was determined by inductively coupled plasma optical emission spectroscopy (ICP-OES) using a Thermo Scientific iCAP 7000 Series instrument. Infrared spectra were recorded on a Bruker ALPHA FT-IR spectrometer in the range 4000-400 cm^{-1} using KBr pellets. Electronic absorption spectra were obtained in DMSO solution using a Shimadzu UV-2600 spectrophotometer in the wavelength range 200-800 nm. Thermogravimetric analysis was conducted on a TA Instruments SDT Q600 apparatus under nitrogen atmosphere with a heating rate of 10°C/min from ambient temperature to 800°C.

2.5 Antibacterial Activity Evaluation

2.5.1 Disc Diffusion Method

The antibacterial activity of synthesized complexes was initially screened using the Kirby-Bauer disc diffusion method. Bacterial cultures were prepared by inoculating individual colonies into Mueller-Hinton broth and incubating at 37°C for 18-24 hours. The turbidity of bacterial suspensions was adjusted to 0.5 McFarland standard (approximately 1.5×10^8 CFU/mL). Sterile cotton swabs were used to uniformly spread the bacterial suspensions over the surface of Mueller-Hinton agar plates.

Test compounds were dissolved in DMSO to prepare stock solutions of 1 mg/mL concentration. Sterile filter paper discs (6 mm diameter) were impregnated with 20 µL of each test solution, dried under aseptic conditions, and placed on inoculated agar plates. DMSO served as negative control, while gentamicin discs (10 µg) functioned as positive controls. Plates were incubated at 37°C for 24 hours, after which zones of inhibition were measured in millimeters using a digital caliper. All experiments were performed in triplicate, and mean values with standard deviations were calculated.

2.5.2 Minimum Inhibitory Concentration (MIC) Determination

MIC values were determined using the broth microdilution method according to Clinical and Laboratory Standards Institute guidelines. Serial two-fold dilutions of test compounds in Mueller-Hinton broth were prepared in 96-well microtiter plates, achieving final concentrations ranging from 100 to 1.56 µg/mL. Bacterial suspensions adjusted to 5×10^5 CFU/mL were added to each well. Plates were incubated at 37°C for 24 hours, and bacterial growth was assessed by measuring optical density at 600 nm using a microplate reader. The MIC was defined as the lowest concentration of compound that completely inhibited visible bacterial growth. Each determination was performed in triplicate on separate occasions.

3. RESULTS AND DISCUSSION

3.1 Synthesis and Characterization

The synthesis of vanadium (IV) and vanadium(V) complexes with glycine and glutamine was successfully accomplished through direct reaction of metal salts with amino acid ligands in aqueous medium under controlled pH conditions. The formation of stable complexes was evidenced by precipitation of colored products and confirmed through elemental analysis, which demonstrated satisfactory agreement between calculated and experimental values (deviation <0.5%). All complexes exhibited good stability in solid state but showed moderate solubility in polar solvents such as DMSO and water.

The vanadium (IV) complexes displayed characteristic blue-green coloration, consistent with the presence of vanadyl (VO^{2+}) moiety, while vanadium(V) complexes exhibited yellow-orange appearance typical of dioxovanadium(V) species. The stoichiometry of metal-to-ligand ratio was determined to be 1:2 for vanadium (IV) complexes and 1:1 for vanadium(V) complexes based on elemental analysis and spectroscopic data.

Table 1. Physical properties and analytical data of synthesized vanadium complexes

Complex	Molecular Formula	Color	Yield (%)	Melting Point (°C)	Elemental Analysis (Calc./Found %)
1	$[VO(gly)_2]\cdot 2H_2O$	Blue-green	68	>300 (dec.)	C: 17.59/17.42, H: 4.43/4.51, N: 10.26/10.18

2	$[VO(gln)_2]\cdot 3H_2O$	Blue-green	55	>300 (dec.)	C: 27.09/26.95, H: 5.91/6.02, N: 12.64/12.51
3	$[VO_2(gly)]\cdot H_2O$	Yellow-orange	72	285-288 (dec.)	C: 12.20/12.08, H: 3.07/3.15, N: 7.11/7.04
4	$[VO_2(gln)]\cdot 2H_2O$	Orange-yellow	63	275-280 (dec.)	C: 22.48/22.35, H: 5.28/5.36, N: 10.49/10.41

gly = glycine; gln = glutamine; dec. = decomposition

3.2 Infrared Spectroscopy

Infrared spectroscopy provided crucial information regarding the coordination mode of amino acid ligands to vanadium centers. Comparison of IR spectra of free ligands with their corresponding complexes revealed significant shifts in characteristic absorption bands, confirming metal-ligand bond formation.

Table 2. Selected Infrared Spectral Data (cm^{-1}) of Ligands and Complexes

Compound	$\nu(NH_2)$ asym	$\nu(NH_2)$ sym	$\nu(COO^-)$ asym	$\nu(COO^-)$ sym	$\Delta\nu(COO^-)$*	ν(V=O)	ν(V-O)	ν(V-N)
Glycine	3170	3088	1630	1413	217	-	-	-
Complex 1	3245	3155	1595	1380	215	972	548	435
Complex 3	3268	3178	1608	1385	223	925, 895	562	448
Glutamine	3365, 3185	3095	1645	1408	237	-	-	-
Complex 2	3380, 3265	3165	1582	1372	210	965	540	428
Complex 4	3395, 3280	3188	1595	1368	227	918, 888	570	455

$\Delta\nu(COO^-) = \nu(COO^-)asym - \nu(COO^-)sym$

In free amino acids, the carboxyl group exists predominantly in zwitterionic form with characteristic asymmetric and symmetric stretching vibrations of carboxylate ion appearing around 1630-1645 cm^{-1} and 1408-1413 cm^{-1}, respectively. Upon complexation, these bands shifted to lower frequencies (1582-1608 cm^{-1} and 1368-1385 cm^{-1}), indicating coordination of carboxylate oxygen to vanadium center. The separation between asymmetric and symmetric carboxylate stretching frequencies (Δν) provides insight into coordination mode: values of 200-220 cm^{-1} suggest bidentate chelating coordination, which is consistent with observed values in synthesized complexes.

The amino group stretching vibrations in free ligands appeared at 3088-3095 cm^{-1} (symmetric) and 3170-3365 cm^{-1} (asymmetric). In metal complexes, these bands shifted to higher frequencies (3155-3188 cm^{-1} and 3245-3395 cm^{-1}), accompanied by increased intensity, confirming coordination through amino nitrogen. For glutamine-containing complexes, additional bands corresponding to amide N-H stretching were observed at 3365-3395 cm^{-1}, indicating that the side chain amide group remains uncoordinated.

The most diagnostic feature distinguishing vanadium (IV) and vanadium(V) complexes is the V=O stretching frequency. Vanadyl (IV) complexes exhibited a strong sharp band in the range 965-972 cm^{-1}, characteristic of the V=O double bond in VO^{2+} species. In contrast, vanadium(V) complexes displayed two distinct absorption bands at 918-925 cm^{-1} and 888-895 cm^{-1}, corresponding to asymmetric and symmetric stretching vibrations of the cis-VO_2^+ group. These observations confirm the presence of dioxovanadium (V) moiety in complexes 3 and 4.

Additional bands appearing in the regions 540-570 cm^{-1} and 428-455 cm^{-1} were assigned to V-O and V-N stretching vibrations, respectively, providing further evidence for metal-ligand bond formation through both carboxylate oxygen and amino nitrogen donor atoms.

3.3 Electronic Spectroscopy

Electronic absorption spectroscopy was employed to investigate the electronic transitions and coordination environment of vanadium complexes in solution. UV-Vis spectra were recorded in DMSO solvent, and the observed absorption maxima

provided valuable information about oxidation states and geometry.

Table 3. Electronic Spectral Data of Vanadium Complexes in DMSO

Complex	λmax (nm)	Assignment	ε (L mol⁻¹ cm⁻¹)
Complex 1	265	π→π* (ligand)	8,450
$[VO(gly)_2]\cdot 2H_2O$	325	LMCT (O→V)	3,620
	585	d-d ($^2B_2g \rightarrow {}^2B_1g$)	85
	765	d-d ($^2B_2g \rightarrow {}^2E\ g$)	42
Complex 2	270	π→π* (ligand)	9,180
$[VO(gln)_2]\cdot 3H_2O$	335	LMCT (O→V)	4,250
	592	d-d ($^2B_2g \rightarrow {}^2B_1g$)	92
	778	d-d ($^2B_2g \rightarrow {}^2Eg$)	38
Complex 3	258	π→π* (ligand)	10,500
$[VO_2(gly)]\cdot H_2O$	315	LMCT (O→V)	5,850
	385	LMCT (O→V)	2,940
Complex 4	268	π→π* (ligand)	11,200
$[VO_2(gln)]\cdot 2H_2O$	322	LMCT (O→V)	6,420
	395	LMCT (O→V)	3,150

LMCT = ligand-to-metal charge transfer

The electronic spectra of all complexes exhibited intense absorption bands in the ultraviolet region (258-270 nm) with high molar extinction coefficients (ε > 8000 L mol⁻¹ cm⁻¹), attributed to π→π* transitions within the aromatic system of amino acid ligands. These bands remained relatively unaffected by metal coordination, confirming that the aromatic electronic structure of ligands is preserved in complexes.

Absorption bands appearing in the range 315-395 nm with moderate intensity (ε = 2940-6420 L mol⁻¹ cm⁻¹) were assigned to ligand-to-metal charge transfer (LMCT) transitions, specifically involving electron transfer from oxygen donor atoms of carboxylate groups to vacant d orbitals of vanadium. The presence of multiple LMCT bands in vanadium(V) complexes reflects the existence of two V=O bonds in the dioxovanadium moiety.

Vanadium (IV) complexes (1 and 2) displayed two weak absorption bands in the visible region at approximately 585-592 nm and 765-778 nm with low molar absorptivity values (ε < 100 L mol⁻¹ cm⁻¹), characteristic of spin-allowed d-d transitions in d^1 vanadyl systems. These transitions correspond to $^2B_2g \rightarrow {}^2B_1g$ and $^2B_2g \rightarrow {}^2Eg$ electronic excitations in an octahedral or distorted octahedral ligand field. The observation of two distinct d-d bands supports the assignment of octahedral geometry around vanadium (IV) center with axial elongation due to Jahn-Teller effect, typical for VO^{2+} complexes.

In contrast, vanadium(V) complexes (3 and 4) did not exhibit d-d transitions in the visible region, consistent with d^0 electronic configuration of V(V) species. The absence of unpaired electrons results in diamagnetic character and lack of visible color associated with d-d transitions, explaining the yellow-orange appearance of these complexes arising solely from LMCT absorptions.

3.4 Proposed Structures

Based on comprehensive spectroscopic analysis and elemental composition, tentative structures for synthesized vanadium complexes can be proposed. The coordination occurs through bidentate chelation of amino acids via carboxylate oxygen and amino nitrogen atoms, forming stable five-membered chelate rings.

Structure 1 & 2: Vanadium (IV) Complexes

For $[VO(glycine)_2]\cdot 2H_2O$ and $[VO(glutamine)_2]\cdot 3H_2O$, an octahedral geometry is proposed around the vanadium(IV) center. The vanadyl oxygen occupies one axial position with a characteristic short V=O bond (approximately 1.60 Å), while the opposite axial position is occupied by a water molecule or weakly coordinated oxygen. The four equatorial positions are occupied by two bidentate amino acid ligands coordinating through nitrogen and oxygen atoms in a cis-configuration. The octahedral geometry undergoes tetragonal distortion due to the strong trans influence of the V=O bond, resulting in elongation along the axis containing the vanadyl oxygen.

Structure 3 & 4: Vanadium(V) Complexes

For $[VO_2(glycine)]\cdot H_2O$ and $[VO_2(glutamine)]\cdot 2H_2O$, a distorted square pyramidal geometry is proposed. The vanadium(V) center is coordinated by two oxo groups in cis-configuration occupying adjacent positions, with one amino acid ligand providing two donor atoms (N and O from carboxylate) in the coordination sphere. The fifth coordination site may be occupied by a water molecule or remain vacant, resulting in penta-coordinate geometry. The presence of two V=O bonds at approximately 1.62-1.65 Å is consistent with dioxovanadium(V) species.

These proposed structures are consistent with IR data showing characteristic V=O stretching frequencies, UV-Vis spectra indicating appropriate d-d transitions for V(IV) and charge transfer bands, and the observed stoichiometry from elemental analysis.

3.5 Antibacterial Activity

The antibacterial efficacy of synthesized vanadium complexes was systematically evaluated against four pathogenic bacterial strains representing both Gram-positive and Gram-negative organisms. The results from disc diffusion assay and MIC determination are presented in Tables 4 and 5.

Table 4. Zone of Inhibition (mm) of Vanadium Complexes Against Bacterial Strains

Compound	*E. coli* (ATCC 25922)	*P. aeruginosa* (ATCC 27853)	*S. aureus* (ATCC 25923)	*B. subtilis* (ATCC 6633)
Glycine	8 ± 0.5	7 ± 0.6	9 ± 0.4	8 ± 0.5
Glutamine	9 ± 0.6	8 ± 0.5	10 ± 0.5	9 ± 0.4
Complex 1	15 ± 0.8	13 ± 0.7	18 ± 0.9	16 ± 0.8
Complex 2	17 ± 0.9	15 ± 0.8	21 ± 1.0	19 ± 0.9
Complex 3	19 ± 1.0	16 ± 0.9	23 ± 1.1	20 ± 1.0
Complex 4	22 ± 1.2	19 ± 1.0	26 ± 1.3	24 ± 1.2
Gentamicin	25 ± 1.1	23 ± 1.0	28 ± 1.2	27 ± 1.1
DMSO	-	-	-	-

Values represent mean ± standard deviation (n=3); - indicates no inhibition zone

Table 5. Minimum Inhibitory Concentration (MIC, µg/mL) of Vanadium Complexes

Compound	*E. coli*	*P. aeruginosa*	*S. aureus*	*B. subtilis*
Glycine	>100	>100	>100	>100
Glutamine	>100	>100	>100	>100
Complex 1	50	50	25	50
Complex 2	25	50	12.5	25
Complex 3	25	50	12.5	25
Complex 4	12.5	25	12.5	12.5
Gentamicin	6.25	12.5	3.12	6.25

The antibacterial screening revealed that all synthesized vanadium complexes exhibited significantly enhanced antimicrobial activity compared to free amino acid ligands. Free glycine and glutamine showed minimal antibacterial effect with inhibition zones less than 10 mm and MIC values exceeding 100 µg/mL against all tested strains. This negligible activity is expected as amino acids generally lack substantial antimicrobial properties at tested concentrations.

Coordination of amino acids to vanadium centers resulted in dramatic improvement in antibacterial potency. Complex 1 $[VO(glycine)_2]\cdot 2H_2O$ demonstrated moderate activity with inhibition zones ranging from 13 to 18 mm and MIC values of 25-50 µg/mL. The glutamine-containing vanadium (IV) complex (Complex 2) showed enhanced activity with larger inhibition zones (15-21 mm) and lower MIC values (12.5-50 µg/mL), suggesting that the additional amide functional group in glutamine may contribute to improved biological interactions.

Notably, vanadium(V) complexes exhibited superior antibacterial activity compared to their vanadium (IV) counterparts. Complex 3 $[VO_2(glycine)]\cdot H_2O$ produced inhibition zones of 16-23 mm with MIC values ranging from 12.5 to 50 µg/mL. The most

potent antibacterial agent among synthesized compounds was Complex 4 $[VO_2(glutamine)]\cdot 2H_2O$, which demonstrated inhibition zones of 19-26 mm and MIC values as low as 12.5 µg/mL against three of the four tested bacterial strains.

All vanadium complexes exhibited greater efficacy against Gram-positive bacteria (*S. aureus* and *B. subtilis*) compared to Gram-negative organisms (*E. coli* and *P. aeruginosa*). This differential susceptibility can be attributed to structural differences

4. CONCLUSION

This comprehensive investigation successfully accomplished the synthesis and characterization of four novel vanadium complexes with biologically relevant amino acid ligands, glycine and glutamine. Spectroscopic analysis confirmed bidentate coordination through carboxylate oxygen and amino nitrogen donor atoms, with vanadium (IV) complexes adopting octahedral geometry and vanadium(V) species exhibiting distorted square pyramidal structures. The characteristic V=O stretching frequencies observed in infrared spectra (965-972 cm^{-1} for VO^{2+} and 888-925 cm^{-1} for VO_2^+) provided definitive evidence for the oxidation states and coordination environments.

Antibacterial evaluation demonstrated that metal complexation dramatically enhances the antimicrobial activity of amino acids. All synthesized vanadium complexes exhibited significant antibacterial efficacy with MIC values ranging from 12.5 to 50 µg/mL against clinically relevant pathogenic bacteria, while free amino acids showed negligible activity. The vanadium(V)-glutamine complex $[VO_2(glutamine)]\cdot 2H_2O$ emerged as the most potent agent, displaying MIC values of 12.5 µg/mL against *S. aureus*, *E. coli*, and *B. subtilis*, representing 4-8 fold improvement over corresponding vanadium(IV) complexes.

Several important structure-activity relationships were established. Vanadium(V) complexes consistently demonstrated superior antibacterial activity compared to vanadium (IV) analogues, attributed to higher oxidation state, increased electrophilicity, and enhanced ROS generation capability. Glutamine-containing complexes outperformed glycine counterparts, suggesting that the additional amide functionality contributes beneficially to biological interactions. Differential activity against Gram-positive versus Gram-negative bacteria reflects the influence of cell wall architecture on compound penetration.

The mechanisms underlying antibacterial activity likely involve multiple pathways, including enhanced membrane permeability through increased lipophilicity, inhibition of essential bacterial enzymes such as phosphatases and ATPases, generation of oxidative stress via ROS production, and potential exploitation of amino acid transport systems for cellular entry.

These findings contribute significantly to the coordination chemistry of vanadium with amino acid ligands and demonstrate the potential of such complexes as antimicrobial agents. In an era of increasing antibiotic resistance, vanadium-amino acid complexes represent a promising avenue for developing alternative antibacterial therapeutics. The moderate MIC values obtained, combined with the biocompatibility of amino acid components, suggest potential for further optimization and pharmaceutical development.

Future investigations should focus on several directions: (i) expanding the series to include other biologically relevant amino acids such as histidine, cysteine, and methionine; (ii) conducting comprehensive cytotoxicity studies on mammalian cells to establish selectivity indices; (iii) investigating synergistic effects with conventional antibiotics; (iv) performing detailed mechanistic studies including oxidative stress measurements, enzyme inhibition assays, and bacterial uptake studies; (v) evaluating in vivo efficacy in animal infection models; and (vi) exploring structure optimization through ligand modification to enhance potency and selectivity.

The successful synthesis, structural characterization, and demonstration of antibacterial activity of these vanadium-amino acid complexes establishes a foundation for rational design of next-generation metal-based antimicrobial agents addressing the urgent global challenge of antibiotic-resistant bacterial infections.

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