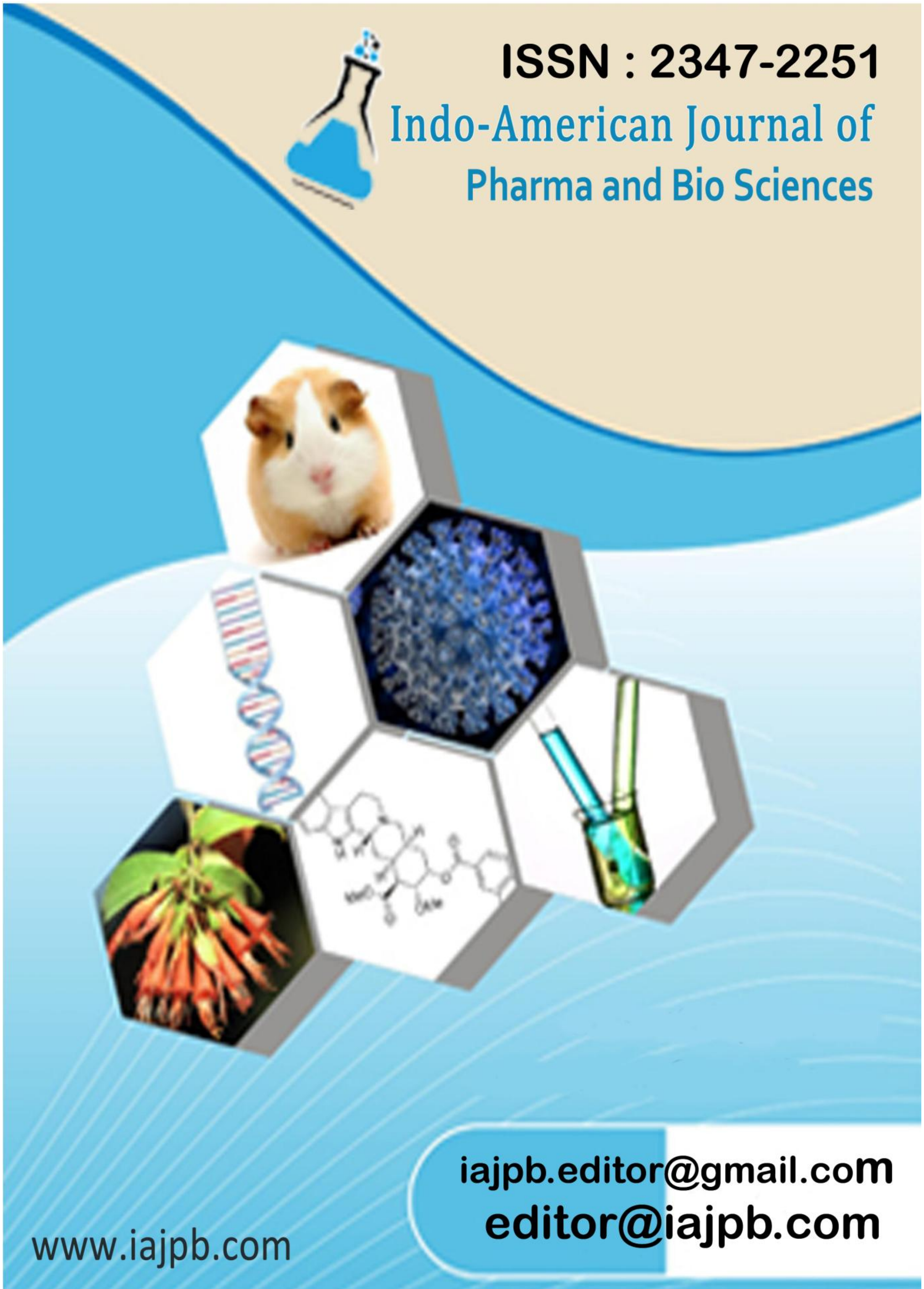
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Recent Advances in the Biological Studies of Iron and Vanadium Schiff Base Complexes: A Comparative Review

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Abstract

Schiff base metal complexes have gained considerable attention in recent years because of their diverse biological activities and potential pharmaceutical applications. Among transition metal complexes, iron and vanadium Schiff base complexes are widely investigated due to their remarkable antimicrobial, antioxidant, anticancer, and catalytic properties. The coordination of Schiff base ligands with iron and vanadium enhances the stability, bioavailability, and biological effectiveness of these compounds. Iron Schiff base complexes are recognized for their low toxicity, redox behavior, and significant antibacterial and antifungal activities, whereas vanadium Schiff base complexes exhibit excellent insulin-mimetic, antimicrobial, and anticancer properties. Recent studies have demonstrated that these complexes interact effectively with microbial cell membranes, enzymes, and DNA, leading to inhibition of microbial growth and cellular damage. Comparative investigations reveal that vanadium complexes generally show stronger antimicrobial and cytotoxic activities, while iron complexes possess better antioxidant potential and biocompatibility. The present review summarizes recent advances in the synthesis, biological properties, and antimicrobial applications of iron and vanadium Schiff base complexes, with emphasis on their mechanisms of action, therapeutic potential, and future prospects in medicinal chemistry and drug development.

Keywords: Schiff base complexes, Iron complexes, Vanadium complexes, antimicrobial activity, biological applications.

1. Introduction

Schiff base complexes have become an important area of research in coordination chemistry, medicinal chemistry, and bioinorganic science because of their remarkable structural diversity and wide range of biological applications. Schiff bases are organic compounds containing an azomethine functional group (–C=N–), usually formed through the condensation reaction between primary amines and aldehydes or ketones. Since the discovery of Schiff bases by Hugo Schiff in 1864, these compounds have attracted continuous scientific attention due to their easy synthesis, strong coordination ability, and versatile chemical behavior. The presence of donor atoms such as nitrogen, oxygen, and sulfur allows Schiff base ligands to form stable complexes with transition metal ions, resulting in compounds with enhanced physicochemical and biological properties.

Transition metal Schiff base complexes have been extensively investigated because metal coordination often increases the biological activity of organic ligands. Chelation reduces the polarity of the metal ion and enhances the lipophilic character of the complex, thereby improving its permeability through biological membranes. As a result, Schiff base metal complexes exhibit significant antimicrobial, antioxidant, anticancer, antiviral, anti-inflammatory, and catalytic activities. Among various transition metals, iron and vanadium have gained considerable importance because of their biological relevance, variable oxidation states, redox properties, and therapeutic potential.

Iron is one of the most essential transition metals in living organisms and plays a critical role in oxygen transport, electron transfer reactions, enzymatic catalysis, and DNA synthesis. Iron-containing biomolecules such as hemoglobin, cytochromes, and iron-sulfur proteins are vital for maintaining normal physiological functions. Iron Schiff base complexes possess excellent redox behavior

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Vol. 24, Issue 2, May 2026

and can participate in electron transfer reactions, making them highly useful in medicinal and biological applications. These complexes are known for their antimicrobial, antioxidant, enzyme-mimetic, and anticancer activities. Furthermore, iron complexes generally exhibit lower toxicity and better biocompatibility compared to many other transition metal complexes, making them attractive candidates for pharmaceutical research.

Vanadium is another biologically important transition metal that has attracted growing scientific interest because of its multiple oxidation states and unique biochemical behavior. Vanadium compounds are widely recognized for their insulin-mimetic, antimicrobial, antioxidant, and anticancer properties. Vanadium Schiff base complexes exhibit strong interactions with biological macromolecules such as proteins, enzymes, and nucleic acids. These complexes can inhibit microbial growth through mechanisms involving oxidative stress generation, enzyme inhibition, and interference with DNA replication. The coordination of vanadium with Schiff base ligands improves the stability, solubility, and biological efficiency of the complexes. Recent studies have shown that vanadium Schiff base complexes possess excellent activity against several Gram-positive and Gram-negative bacterial strains as well as fungal pathogens.

The increasing emergence of multidrug-resistant microorganisms has become a major global health concern. Conventional antibiotics are gradually losing effectiveness because of microbial resistance mechanisms such as mutation, biofilm formation, and enzyme-mediated drug degradation. Consequently, there is an urgent need for the development of novel antimicrobial agents with improved efficacy and lower resistance potential. Transition metal Schiff base complexes have emerged as promising alternatives due to their ability to target multiple biological pathways simultaneously. The antimicrobial activity of these complexes is mainly attributed to chelation theory, according to which metal coordination enhances membrane penetration and interaction with microbial biomolecules.

Recent advances in bioinorganic chemistry and nanotechnology have further expanded the biomedical applications of iron and vanadium Schiff base complexes. Researchers have developed nano-sized formulations, polymer-supported complexes, and hybrid materials to improve targeted drug delivery, therapeutic efficiency, and biological selectivity. Structural modification of Schiff base ligands through the introduction of electron-donating or electron-withdrawing substituents has also been explored to optimize biological performance. Comparative investigations indicate that vanadium Schiff base complexes generally exhibit stronger antimicrobial and cytotoxic properties, whereas iron complexes provide superior antioxidant activity and lower toxicity.

Despite considerable progress in this field, several challenges remain unresolved, including toxicity control, poor water solubility, limited clinical studies, and instability under physiological conditions. Therefore, detailed comparative studies are essential to understand the biological mechanisms and therapeutic potential of these complexes. The present review aims to discuss recent advances in the biological and antimicrobial applications of iron and vanadium Schiff base complexes, with emphasis on their synthesis, structural characteristics, biological mechanisms, comparative efficiency, and future prospects in medicinal and pharmaceutical research.

2. Methodology

2.1 Literature Collection and Data Sources

The present comparative review was carried out through a detailed survey of published scientific literature related to iron and vanadium Schiff base complexes and their biological applications. Research articles, review papers, and conference proceedings published between 2015 and 2026 were collected from reputed scientific databases, including ScienceDirect, SpringerLink, Wiley Online Library, PubMed, and Google Scholar.

2.2 Classification of Schiff Base Complexes

The collected literature was categorized into two major groups:

2.2.1 Iron Schiff Base Complexes

Studies involving Fe(II) and Fe(III) Schiff base complexes with biological and

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Vol. 24, Issue 2, May 2026

antimicrobial applications were grouped under this category.

2.2.2 Vanadium Schiff Base Complexes

Studies involving V(IV) and V(V) Schiff base complexes with pharmacological and antimicrobial activities were classified separately for comparative evaluation.

2.3 Structural Characterization Techniques

The reviewed studies commonly employed various spectroscopic and analytical techniques for characterization of Schiff base complexes. These techniques include:

- Fourier Transform Infrared Spectroscopy (FT-IR)
- UV–Visible Spectroscopy
- Nuclear Magnetic Resonance (NMR)
- Mass Spectrometry
- X-ray Diffraction (XRD)
- Thermogravimetric Analysis (TGA)
- Magnetic Susceptibility Measurements
- Elemental Analysis

These methods were used to determine ligand coordination, oxidation states, geometry, thermal stability, and structural properties of the synthesized complexes

2.4 Biological Evaluation

The biological activity of Schiff base complexes was analyzed from experimental reports involving antibacterial, antifungal, antioxidant, anti-cancer and anti-diabetics studies.

Antibacterial Studies

The antimicrobial activity was evaluated using:

- Agar well diffusion method
- Disc diffusion method
- Minimum inhibitory concentration (MIC) method
- Broth dilution technique

The tested bacterial strains commonly included:

- *Staphylococcus aureus*
- *Bacillus subtilis*
- *Escherichia coli*

ISSN 2347-2251 www.iajpb.com
Vol. 24, Issue 2, May 2026

- *Pseudomonas aeruginosa*

Antifungal Studies

Antifungal activity was evaluated against:

- *Candida albicans*
- *Aspergillus niger*

Antioxidant and Cytotoxic Studies

Several studies examined:

- Free radical scavenging activity
- DNA binding interactions
- Enzyme inhibition
- Cytotoxic effects against cancer cell lines

2.5 Data Interpretation

The collected experimental data from different studies were analyzed and interpreted comparatively. Antimicrobial activity was evaluated using inhibition zone diameter and MIC values, while antioxidant and cytotoxic studies were compared using reported percentage inhibition and IC50 values.

The results were interpreted based on:

- Metal ion oxidation state
- Ligand structure
- Chelation behavior
- Electron-donating and withdrawing substituents
- Geometry and stability of complexes

The final comparative analysis was used to identify the most promising Schiff base systems for future antimicrobial and biomedical applications.

3. Results and Discussion

The comparative biological and antimicrobial performance of iron and vanadium Schiff base complexes was analyzed based on recently reported experimental studies. Parameters such as antibacterial activity, antifungal activity, antioxidant efficiency, cytotoxicity, and biological stability were considered for evaluation. The results indicate that both iron and vanadium Schiff base complexes possess significant biological activity; however, their effectiveness strongly depends on ligand structure, oxidation state, coordination geometry, and substituent groups attached to the Schiff base framework.

ISSN 2347-2251 www.iajpb.com

Indo-American Journal of Pharma and Bio Sciences

Vol. 24, Issue 2, May 2026

3.1 Antibacterial Activity of Schiff Base Complexes

Recent studies demonstrate that both iron and vanadium Schiff base complexes exhibit considerable antibacterial activity against Gram-positive and Gram-negative bacterial strains. The antimicrobial mechanism is mainly associated with enhanced lipophilicity after chelation, which facilitates penetration through bacterial cell membranes and disrupts essential cellular processes such as DNA replication, protein synthesis, and enzyme activity.

Vanadium Schiff base complexes generally show stronger antibacterial activity compared to iron complexes because of their higher redox activity and stronger interaction with microbial biomolecules. However, iron complexes demonstrate better biocompatibility and reduced toxicity, making them suitable for biomedical applications.

Table 1. Comparative Antibacterial Activity of Iron and Vanadium Schiff Base Complexes

Microorganism	Iron Schiff Base Complexes	Vanadium Schiff Base Complexes
Staphylococcus aureus	Moderate inhibition	Strong inhibition
Bacillus subtilis	Moderate activity	High activity
Escherichia coli	Good activity	Excellent activity
Pseudomonas aeruginosa	Moderate activity	Strong activity

Graph:1 – Comparative antibacterial activity of Iron and Vanadium Schiff Base Complexes against different bacterial strains

ISSN 2347-2251 www.iajpb.com
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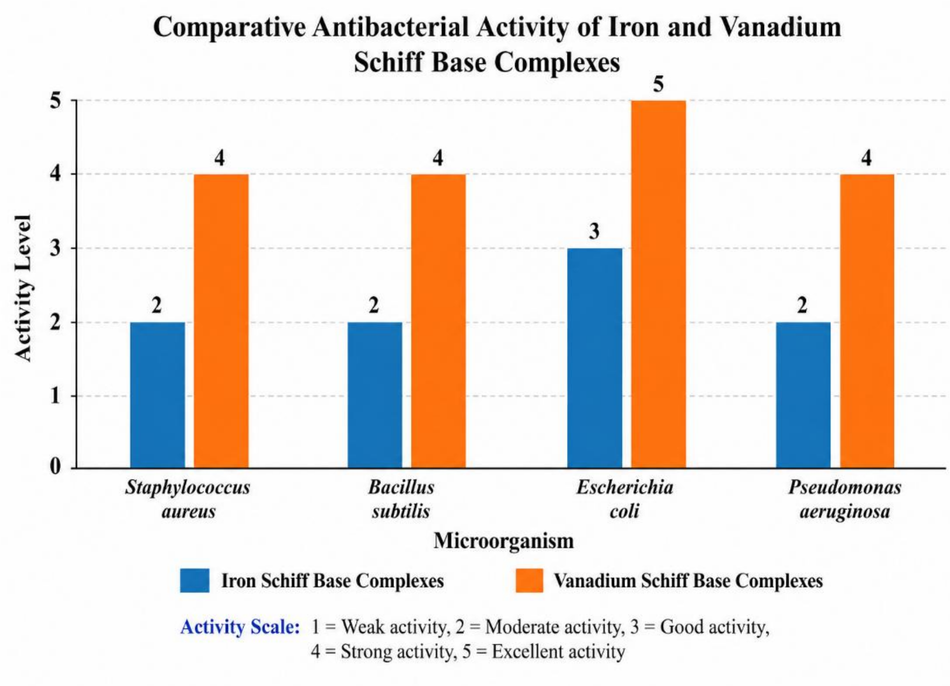
Vol. 24, Issue 2, May 2026



The comparative data indicate that vanadium complexes exhibit larger inhibition zones and lower minimum inhibitory concentration (MIC) values against bacterial pathogens. This enhanced activity may be attributed to the multiple oxidation states of vanadium, which facilitate electron transfer reactions and oxidative stress generation within microbial cells. Iron complexes also exhibit effective antibacterial behavior but generally show lower activity than vanadium complexes. Nevertheless, their reduced cytotoxicity and greater biological compatibility make them promising candidates for therapeutic applications.

3.2 Antifungal Activity

Iron and vanadium Schiff base complexes also demonstrate significant antifungal properties against fungal pathogens such as *Candida albicans* and *Aspergillus niger*. Chelation between the metal ion and Schiff base ligand increases membrane permeability and interferes with fungal enzyme systems, resulting in inhibition of fungal growth.

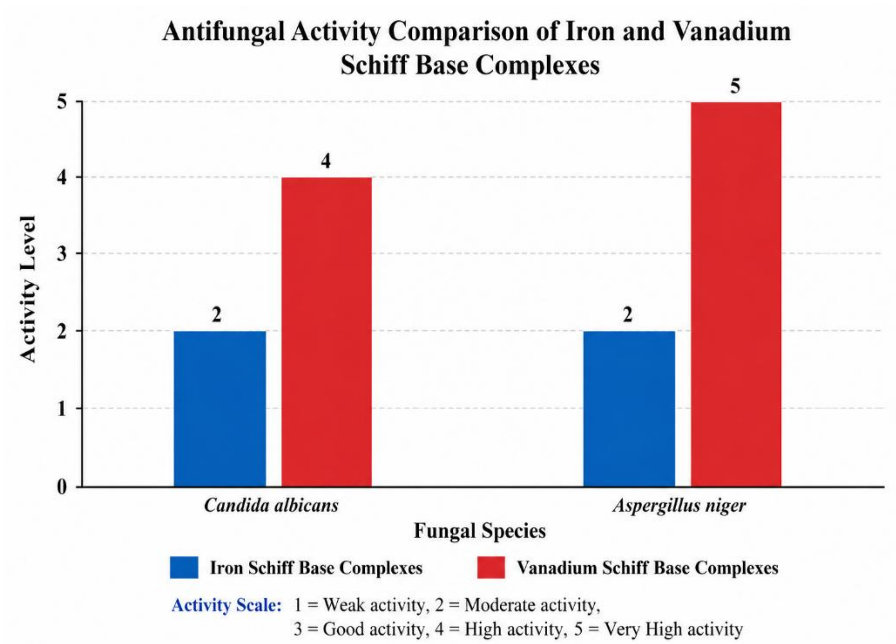
ISSN 2347-2251 www.iajpb.com

Vol. 24, Issue 2, May 2026

Table 2. Antifungal Activity of Schiff Base Complexes

Fungal Species	Iron Complexes	Vanadium Complexes
Candida albicans	Moderate	High
Aspergillus niger	Moderate	Very High

Graph 2 – Antifungal activity comparison of Iron and Vanadium Schiff Base Complexes



Vanadium Schiff base complexes show superior antifungal activity due to their stronger oxidative properties and better interaction with fungal cell membranes. Iron complexes also inhibit fungal growth effectively, particularly when ligands contain electron-donating substituents that improve coordination stability and biological interaction.

3.3 Antioxidant Activity, Anticancer Activity, Antidiabetic Activity

Iron Schiff base complexes are widely recognized for their antioxidant and enzyme-mimetic activities. Their ability to undergo reversible redox reactions enables scavenging of reactive oxygen species (ROS), thereby protecting biological systems from oxidative damage. Vanadium complexes also exhibit antioxidant behavior but are more widely investigated for insulin-mimetic and anticancer activities.

Table 3. Biological Applications of Iron and Vanadium Schiff Base Complexes

Biological Property	Iron Complexes	Vanadium Complexes
Antioxidant Activity	Excellent	Good
Anticancer Activity	Moderate	High
Antidiabetic Activity	Low	Excellent

Iron complexes exhibit excellent antioxidant activity because of their ability to mimic natural enzymatic systems such as catalase and peroxidase. Vanadium complexes, on the other hand, demonstrate stronger anticancer and insulin-like behavior owing to their ability to interfere with phosphate-dependent biological pathways. The results suggest that iron complexes are more suitable for antioxidant therapies, whereas vanadium complexes possess broader pharmacological potential.

3.4 Effect of Ligand Structure on Biological Activity

The biological activity of Schiff base complexes is strongly influenced by ligand structure and substituent groups. Electron-donating groups such as –OH and $–OCH_3$ generally enhance biological activity by increasing electron density and coordination

ISSN 2347-2251 www.iajpb.com

Vol. 24, Issue 2, May 2026

stability. Ligands containing heterocyclic rings also improve antimicrobial performance because of enhanced interaction with microbial DNA and proteins.

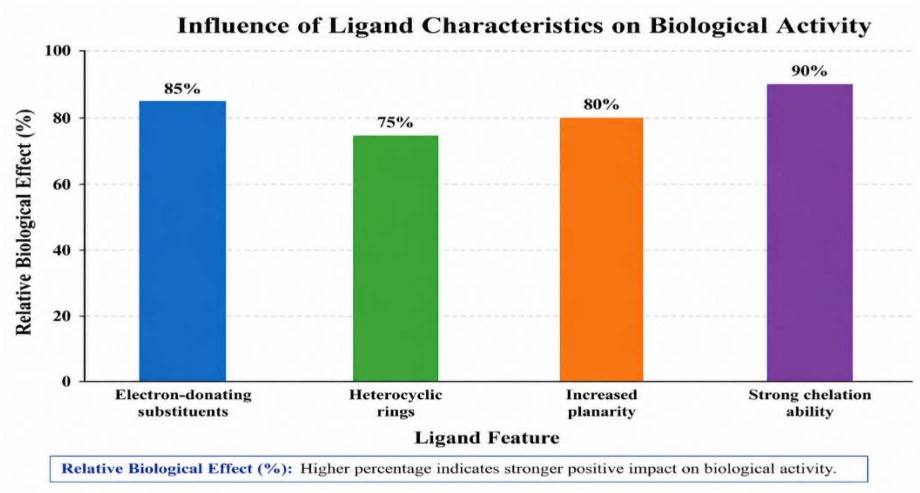
Table 4. Influence of Ligand Characteristics on Biological Activity

Ligand Feature	Biological Effect
Electron-donating substituents	Increased antimicrobial activity
Heterocyclic rings	Improved DNA interaction
Increased planarity	Better membrane penetration
Strong chelation ability	Enhanced stability

Structural modifications in Schiff base ligands significantly influence the biological performance of metal complexes. Enhanced planarity and chelation increase lipophilicity and facilitate penetration through microbial membranes. The presence of donor atoms, such as nitrogen and oxygen, improves coordination stability and biological interactions.

Figure 5: General structure showing ligand coordination with Iron and Vanadium ions

ISSN 2347-2251 www.iajpb.com
Vol. 24, Issue 2, May 2026



4. Comparative Evaluation of Iron and Vanadium Schiff Base Complexes

The comparative review indicates that both iron and vanadium Schiff base complexes possess remarkable biological and antimicrobial activities. However, vanadium complexes generally exhibit stronger antimicrobial and cytotoxic activities, while iron complexes demonstrate lower toxicity and better biocompatibility.

Table 5. Comparative Summary of Iron and Vanadium Schiff Base Complexes

Property	Iron Complexes	Vanadium Complexes
Antibacterial Activity	Good	Excellent
Antifungal Activity	Moderate	High
Antioxidant Property	Excellent	Good
Cytotoxicity	Low	Moderate
Biocompatibility	High	Moderate
Therapeutic Potential	High	Very High

The overall findings suggest that vanadium Schiff base complexes possess superior antimicrobial and pharmacological activity because of their variable oxidation states and enhanced redox properties. Iron Schiff base complexes, however, provide better biological compatibility and antioxidant efficiency with comparatively lower toxicity. Therefore, both classes of complexes hold great promise for future biomedical and antimicrobial applications, particularly in the development of novel therapeutic agents against drug-resistant microbial strains.

Iron Schiff base complexes were found to possess excellent antioxidant activity, low toxicity, and good biocompatibility. Their ability to participate in redox reactions and mimic natural enzymes makes them suitable for antioxidant and biomedical applications. Vanadium Schiff base complexes, on the other hand, exhibited superior antimicrobial, anticancer, and insulin-mimetic properties because of their multiple oxidation states and strong interaction with biological molecules. Both complexes demonstrated effective antibacterial and antifungal activities against several pathogenic microorganisms including *Staphylococcus aureus*, *Escherichia coli*, *Candida albicans*, and *Aspergillus niger*.

The review also revealed that the biological efficiency of Schiff base complexes strongly depends on ligand structure, coordination geometry, oxidation state, and substituent effects. Structural modifications in Schiff base ligands improve chelation ability, membrane permeability, and interaction with microbial DNA and proteins. Furthermore, advances in nanotechnology and bioinorganic chemistry have expanded the therapeutic applications of these complexes through nano-formulations and targeted drug delivery systems.

The comparative analysis indicated that vanadium Schiff base complexes generally exhibit stronger antimicrobial and cytotoxic effects, whereas iron complexes provide greater biological compatibility and antioxidant protection. Both systems therefore possess significant potential for future pharmaceutical and biomedical applications.

5. Conclusion

Iron and vanadium Schiff base complexes represent an important class of bioactive coordination compounds with promising antimicrobial and therapeutic properties. The incorporation of Schiff base ligands significantly enhances the stability, lipophilicity, and biological activity of the metal complexes. Iron complexes exhibit excellent antioxidant activity, reduced toxicity, and favorable biocompatibility, making them suitable for biomedical and pharmaceutical applications. In contrast, vanadium Schiff base complexes display enhanced antimicrobial, anticancer, and insulin-mimetic properties due to their strong redox behavior and multiple oxidation states.

Comparative evaluation suggests that vanadium complexes are generally more effective against bacterial and fungal pathogens, while iron complexes are more biologically compatible and safer for therapeutic applications. The antimicrobial activity of these complexes is mainly attributed to improved membrane penetration, interaction with microbial DNA and proteins, oxidative stress generation, and enzyme inhibition mechanisms.

Despite the remarkable progress achieved in this field, several challenges remain, including toxicity control, solubility improvement, stability under physiological conditions, and lack of clinical investigations. Future research should focus on developing low-toxicity Schiff base complexes with enhanced selectivity and therapeutic efficiency. Advanced computational studies, nanotechnology-based drug delivery systems, and in vivo biological investigations may further improve the biomedical applicability of these compounds.

Overall, iron and vanadium Schiff base complexes possess enormous potential as next-generation antimicrobial and therapeutic agents for combating multidrug-resistant pathogens and other disease conditions.

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