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Research Article

Immobilization of 7-Iodo-8-hydroxyquinoline-5-sulfonic Acid (Ferron): A Comprehensive Review of Techniques and Applications

Mukhammad Avazyazov[1]*, Ashirov MA[2], Eshchanova A[3] and Shonazarov AR[4]

[1] 1st Year Doctoral Student, Khorezm Mamun Academy, Uzbekistan
[2] PhD, Senior Researcher, Khorezm Mamun Academy, Uzbekistan
[3] Department of Chemistry, Urgench State University named after Abu Rayhon Beruni, Urgench, Uzbekistan
[4] Bachelor's Student, Urgench State University named after Abu Rayhon Beruni, Urgench, Uzbekistan

***Correspondence:** Mukhammad Avazyazov, 1st Year Doctoral Student, Khorezm Mamun Academy, Uzbekistan, Email: avazyazovmuhammad@gmail.com

Abstract

7-Iodo-8-hydroxyquinoline-5-sulfonic acid (Ferron, HIQSA, Chiniofon) is a multifunctional chelating agent whose utility is significantly enhanced through immobilization onto solid supports. This comprehensive review details the chemical structure and key properties of Ferron, emphasizing it's tridentate chelating ability derived from its hydroxyl, sulfonic acid, and iodine functional groups. The primary rationale for immobilization—improved reusability, enhanced stability, facilitated separation, and the enablement of solid-phase applications—is thoroughly discussed. The review systematically examines the three main immobilization strategies: covalent bonding (e.g., using silane coupling agents on silica or functionalized polymers), physical adsorption (e.g., on anion-exchange resins like Dowex and Purolite), and encapsulation/entrapment (e.g., in sol-gel matrices or electrospun polymer nanofibers). Each technique's principles, advantages, disadvantages, and typical supports are analyzed. The diverse applications of immobilized Ferron are then explored, spanning analytical chemistry (optical oxygen and metal ion sensors, electrochemical detection, flow injection analysis), environmental remediation (heavy metal removal from wastewater, soil stabilization), and emerging biomedical uses (antimicrobial wound dressings, drug delivery scaffolds). The article concludes with a historical perspective and an outlook on recent advancements, highlighting the potential of nanomaterial-based supports, multi-functional hybrid platforms, and novel biomedical applications, while also addressing ongoing challenges such as long-term stability and selectivity.

Introduction to Ferron and its immobilization

Chemical structure and properties of Ferron

Nomenclature and Synonyms (HIQSA, Chiniofon): 7-Iodo-8-hydroxyquinoline-5-sulfonic acid, commonly known as Ferron, is a versatile chemical compound with a rich history and a broad spectrum of applications. Its systematic name, 8-hydroxy-7-iodo-5-quinolinesulfonic acid, is often abbreviated as HIQSA in scientific literature, particularly in the context of analytical chemistry and sensor development [1]. This compound is also recognized by the synonym Chiniofon, under which it was historically used as an anti-amoebic drug. The CAS (Chemical Abstracts Service) registry number for Ferron is 547-91-1, a unique identifier that ensures precise chemical identification across various databases and research publications. The molecular formula of Ferron is $C_9H_6INO_4S$, and it has a molecular weight of 351.12 g/mol. The compound is typically available in high purity, with some suppliers offering it at a purity of 99.43% for research and analytical applications. Its chemical structure is characterized by a quinoline ring system, which is an aromatic heterocyclic compound consisting of a benzene ring fused to a pyridine ring. The presence of an iodine atom at the 7-position, a hydroxyl group at the 8-position, and a sulfonic acid group at the 5-position of the quinoline ring confers unique physicochemical properties to Ferron, making it a valuable reagent in various scientific and industrial fields. The compound's solubility is notable, with a reported solubility of 58.33 mg/mL in DMSO, which can be enhanced by ultrasonic treatment and warming to 60 °C. This solubility profile is crucial for its application in different media, including aqueous and organic solvents. The historical use of Ferron as a pharmaceutical agent, particularly as an anti-amoebic drug under the name Chiniofon, highlights its biological activity and its interaction with biological systems. However, its use in this capacity has been discontinued in some countries, such as Japan and the United States, due to reports of adverse effects like subacute optic neuropathy. Despite this, its chemical properties continue to make it a subject of interest for a wide range of applications, from analytical chemistry to environmental remediation and biomedical engineering.

Key functional groups and chelating properties: The chemical structure of 7-iodo-8-hydroxyquinoline-5-sulfonic acid (Ferron) is defined by the presence of several key functional groups that are responsible for its unique physicochemical properties and its ability to form stable complexes with a variety of metal ions. The quinoline ring system, which is the core of the molecule, is an aromatic heterocycle that provides a rigid, planar framework for the attachment of these functional groups. The most important functional groups for the chelating properties of Ferron are the hydroxyl group (-OH) at the 8-position and the sulfonic acid group ($-SO_3H$) at the 5-position. The hydroxyl group is a key donor atom that can participate in the formation of coordinate bonds with metal ions, while the sulfonic acid group is a strong acid that is typically deprotonated at physiological pH, resulting in a negatively charged sulfonate group ($-SO_3^-$). This negative charge enhances the solubility of Ferron in aqueous solutions and also contributes to its ability to interact with positively charged metal ions. The iodine atom at the 7-position also plays a significant role in the properties of Ferron, particularly in its biological activity and its photophysical behavior. The presence of the heavy iodine atom can lead to a phenomenon known as the "heavy atom effect," which can enhance the rate of intersystem crossing from the singlet to the triplet state in the molecule. This, in turn, can lead to an increase in phosphorescence, a property that has been exploited in the development of optical oxygen sensors based on the quenching of the phosphorescence of metal-Ferron complexes [1]. The combination of these functional groups—the hydroxyl group, the sulfonic acid group, and the iodine atom—gives Ferron its characteristic ability to act as a tridentate ligand, meaning that it can form three coordinate bonds with a single metal ion. This results in the formation of highly stable, five- or six-membered chelate rings, which are the basis for the use of Ferron as a colorimetric and fluorimetric reagent for the detection of metal ions. The stability of these metal-Ferron complexes is influenced by a variety of factors, including the nature of the metal ion, the pH of the solution, and the presence of other competing ligands. The ability of Ferron to form stable complexes with a wide range of metal ions, including iron, aluminum, gallium, and zirconium, has made it a valuable tool in analytical chemistry, environmental monitoring, and biomedical research [2].

Solubility and stability characteristics: The solubility and stability of 7-iodo-8-hydroxyquinoline-5-sulfonic acid (Ferron) are critical properties that determine its suitability for various applications. The presence of the sulfonic acid group is the primary factor contributing to its high solubility in water and other polar solvents. This group is a strong acid and readily deprotonates in aqueous solutions, especially at neutral or basic pH, forming a negatively charged sulfonate ion. This ionic character disrupts the crystal lattice of the solid and facilitates its dissolution in polar media. The reported solubility of Ferron in DMSO is 58.33 mg/mL, and this can be further enhanced by physical methods like sonication and heating [3]. This high solubility is a significant advantage for its use in analytical chemistry, as it allows for the preparation of concentrated stock solutions and its easy incorporation into aqueous reaction systems. However, the stability of Ferron can be a concern under certain conditions. Like many organic compounds, it can be susceptible to photodegradation upon prolonged exposure to light, particularly UV radiation. This can lead to a loss of its chelating ability and a change in its optical properties. Therefore, solutions of Ferron are often stored in dark bottles to protect them from light. The stability of Ferron is also influenced by pH and temperature. While it is stable over a wide pH range, extreme acidic or basic conditions can lead to the hydrolysis of the quinoline ring or the cleavage of the sulfonic acid group. Similarly, high temperatures can accelerate its degradation. The stability of its metal complexes is generally high, but it can be affected by the presence of competing ligands or chelating agents that can displace Ferron from the metal ion. The stability of immobilized Ferron is often enhanced compared to its free form in solution. When immobilized on a solid support, Ferron is protected from many of the degradative influences of the environment, such as light and reactive chemical species. This enhanced stability is one of the key advantages of immobilization and is a major reason for its widespread use in the development of sensors and other long-term applications.

Rationale for immobilization

Enhancing reusability and stability: The immobilization of 7-iodo-8-hydroxyquinoline-5-sulfonic acid (Ferron) onto a solid support is a strategic approach that is employed to overcome some of the limitations associated with its use in the solution phase and to enhance its performance in a variety of applications. The primary rationale for immobilizing Ferron is to improve its reusability and stability. When used in solution, Ferron is typically consumed in a single-use application, which can be costly and generate a significant amount of chemical waste. By immobilizing Ferron on a solid support, it can be easily separated from the reaction mixture and reused multiple times, which not only reduces the cost of the reagent but also minimizes the environmental impact of the process. Immobilization also enhances the stability of Ferron, protecting it from degradation by heat, light, or chemical attack. This is particularly important for applications that require long-term stability, such as in continuous monitoring systems or in devices that are used in harsh environments. The enhanced stability of immobilized Ferron is a key advantage that has led to its widespread use in the development of sensors and other long-term applications. By anchoring the molecule to a solid matrix, it is shielded from many of the degradative influences of the environment, which can significantly extend its operational lifetime and improve its reliability.

Facilitating separation and recovery: Another key advantage of immobilization is that it facilitates the separation and recovery of the reagent from the sample matrix. In solution-phase applications, the separation of Ferron and its metal complexes from the sample can be a challenging and time-consuming process, often requiring complex and expensive techniques such as liquid-liquid extraction or chromatography. By immobilizing Ferron on a solid support, the separation process is greatly simplified, as the immobilized reagent can be easily removed from the solution by filtration, centrifugation, or magnetic separation. This not only saves time and effort but also reduces the risk of sample contamination and loss. This ease of separation is a major benefit in analytical applications, where the purity of the sample is of paramount importance. The ability to quickly and easily separate the reagent from the reaction mixture also allows for the automation of analytical procedures, which can lead to higher throughput and improved reproducibility. The use of immobilized Ferron in solid-phase extraction (SPE) is a prime example of this advantage, where the immobilized reagent is used to selectively preconcentrate and purify target analytes from complex sample matrices.

Enabling solid-phase applications: Finally, immobilization enables the use of Ferron in solid-phase applications, which opens up a wide range of new possibilities for its use. For example, immobilized Ferron can be used as a stationary phase in chromatography for the separation and preconcentration of metal ions. It can also be incorporated into solid-state sensors for the detection of various analytes, such as metal ions, oxygen, and other chemical species. The use of immobilized Ferron in solid-phase applications offers several advantages over solution-phase methods, including higher sensitivity, faster response times, and the ability to perform in-situ and real-time measurements. The development of new immobilization techniques and solid supports has further expanded the range of applications for immobilized Ferron, making it a versatile and powerful tool in fields such as analytical chemistry, environmental science, and biomedical engineering. The ability to tailor the properties of the solid support, such as its porosity, surface area, and chemical functionality, provides an additional level of control over the performance of the immobilized reagent, allowing for the optimization of its performance for specific applications. This has led to the development of a wide variety of innovative technologies, from portable sensors for environmental monitoring to biocompatible materials for drug delivery and tissue engineering.

Overview of immobilization strategies

The immobilization of 7-iodo-8-hydroxyquinoline-5-sulfonic acid (Ferron) can be achieved through a variety of strategies, each with its own set of advantages and disadvantages. The three most common immobilization strategies are covalent bonding, physical adsorption, and encapsulation/entrapment. The choice of immobilization strategy depends on a variety of factors, including the specific application, the nature of the solid support, and the desired properties of the immobilized reagent. A summary of these strategies is provided in the table below (Table 1).

Covalent bonding: Covalent bonding involves the formation of a strong, stable chemical bond between the Ferron molecule and the solid support. This is typically achieved by first functionalizing the surface of the support with a reactive group, such as an amine or a carboxylic acid, and then reacting this group with a complementary functional group on the Ferron molecule. Covalent bonding is a very robust immobilization method that results in a highly stable and durable immobilized reagent. The strong covalent bond prevents the leaching of the reagent from the support, even under harsh conditions, which is a major advantage for long-term applications. However, the covalent bonding approach can be more complex and time-consuming than other methods, and it may require the use of harsh chemicals or reaction conditions that could potentially damage the Ferron molecule or the solid support. The choice of the coupling agent and the reaction conditions must be carefully optimized to ensure that the covalent bond is formed efficiently without compromising the integrity of the reagent or the support.

Physical adsorption: Physical adsorption is a simpler and more straightforward immobilization method that relies on non-covalent interactions, such as electrostatic forces, hydrogen bonding, and van der Waals forces, to attach the Ferron molecule to the surface of the support. This method is often used with supports that have a high surface area, such as activated carbon or ion-exchange resins. Physical adsorption is a relatively gentle process that does not require the use of harsh chemicals, and it can be easily reversed by changing the pH or ionic strength of the solution. However, the non-covalent interactions that hold the Ferron molecule to the support

Table 1: Comparison of Immobilization Strategies for Ferron.

Immobilization Strategy	Principle	Advantages	Disadvantages	Typical Supports
Covalent Bonding	Formation of a strong, permanent chemical bond between Ferron and the support.	**High stability,** minimal leaching, long-term reusability.	Complex procedure, may require harsh conditions, and can alter Ferron's activity.	Silica (with silane coupling agents), functionalized polymers.
Physical Adsorption	Non-covalent interactions (electrostatic, hydrogen bonding, van der Waals) attach Ferron to the support surface.	Simple, low-cost, mild conditions, reversible.	**Prone to leaching,** lower stability compared to covalent bonding.	Ion-exchange resins, activated carbon, silica gel.
Encapsulation/Entrapment	Physical confinement of Ferron within a porous matrix.	Protects Ferron from the environment, allowing for controlled release.	Potential for leaching, slow diffusion of analytes can limit response time.	Sol-gel matrices, polymer nanofibers (electrospinning).

are generally weaker than covalent bonds, which can lead to leaching of the reagent over time. This is a major limitation of physical adsorption, especially for applications that require long-term stability or are performed under conditions of high flow or high ionic strength. Despite this limitation, physical adsorption remains a popular choice for many applications due to its simplicity and low cost.

Encapsulation/entrapment: Encapsulation or entrapment is a third immobilization strategy that involves trapping the Ferron molecule within a porous matrix, such as a sol-gel or a polymer. This method is particularly well-suited for the immobilization of sensitive biomolecules, as it provides a protective environment that can shield the reagent from degradative influences. Encapsulation is a relatively simple and versatile method that can be used with a wide range of supports and reagents. However, the porous nature of the matrix can also lead to leaching of the reagent, and the diffusion of analytes into and out of the matrix can be slow, which can limit the response time of the immobilized reagent. The choice of the encapsulating matrix and the control of its porosity are critical factors in determining the performance of the encapsulated reagent. By carefully tailoring the properties of the matrix, it is possible to create materials with optimized stability, selectivity, and response characteristics for a wide range of applications.

Immobilization techniques for Ferron

Adsorption-based immobilization

Immobilization on ion-exchange resins:

Use of Anion-Exchange Resins (e.g., Dowex 1X2-200, Purolite A-500): The immobilization of 7-iodo-8-hydroxyquinoline-5-sulfonic acid (Ferron) and its metal chelates on anion-exchange resins is a well-established and highly effective technique that has been widely used for a variety of analytical and environmental applications. Anion-exchange resins are polymeric materials that contain positively charged functional groups, such as quaternary ammonium groups, which are capable of binding to negatively charged species in solution. The sulfonic acid group of Ferron is a strong acid that is typically deprotonated at neutral or basic pH, resulting in a negatively charged sulfonate group. This allows Ferron to be readily adsorbed onto an anion-exchange resin through electrostatic interactions. The use of anion-exchange resins for the immobilization of Ferron offers several advantages, including high loading capacity, good stability, and ease of regeneration. The high density of functional groups on the surface of the resin allows for a high loading of Ferron, which can lead to a high sensitivity in analytical applications. The electrostatic interactions between the Ferron molecule and the resin are relatively strong, which helps to prevent the leaching of the reagent from the support. The resin can also be easily regenerated by washing it with a solution of high ionic strength or by changing the pH of the solution, which allows for the repeated use of the immobilized reagent. A variety of anion-exchange resins have been used for the immobilization of Ferron, including Dowex 1X2-200 and Purolite A-500. Dowex 1X2-200 is a strongly basic anion-exchange resin that has been used for the immobilization of the Al-Ferron complex for the development of an optical oxygen sensor [1]. The immobilized Al-Ferron complex was found to be an excellent sensing phase for oxygen, with a fast response time and good reversibility. Purolite A-500 is another strongly basic anion-exchange resin that has been used for the immobilization of Ferron for the determination of palladium(II) in mining samples. The immobilized Ferron was found to be highly selective for palladium(II), with a low detection limit and a wide linear range. The use of anion-exchange resins for the immobilization of Ferron is a versatile and powerful technique that has been successfully applied to a wide range of analytical and environmental problems. The ability to tailor the properties of the resin, such as its pore size, surface area, and functional group density, provides an additional level of control over the performance of the immobilized reagent, allowing for the optimization of its performance for specific applications.

Mechanism of adsorption for Al-Ferron chelates: The adsorption of Al-Ferron chelates onto anion-exchange resins is a complex process that involves a combination of electrostatic and coordination interactions. The Al-Ferron chelate is formed by the reaction of an aluminum ion (Al^{3+}) with three molecules of Ferron. Each Ferron molecule acts as a bidentate ligand, coordinating to the aluminum ion through the nitrogen atom of the quinoline ring and the oxygen atom of the hydroxyl group. This results in the formation of a stable, octahedral complex with a net negative charge of -3, as the three sulfonic acid groups of the Ferron molecules are deprotonated at the pH of the solution. This highly charged, anionic complex is then readily adsorbed onto the positively charged surface of the anion-exchange resin through strong electrostatic interactions. The adsorption process is driven by the high affinity of the anion-exchange resin for the Al-Ferron chelate, which is a result of the high charge density of the complex. The adsorption isotherm, which describes the relationship between the concentration of the Al-Ferron chelate in the solution and the amount adsorbed on the resin, is typically of the Langmuir type, which suggests that the adsorption is a monolayer process. The adsorption process is also influenced by the pH of the solution, as the charge of the Al-Ferron chelate is dependent on the degree of deprotonation of the sulfonic acid groups. At low pH, the sulfonic acid groups are protonated, and the complex has a lower negative charge, which results in a lower adsorption capacity. As the pH is increased, the sulfonic acid groups become deprotonated, and the negative charge of the complex increases, which leads to a higher adsorption capacity. The adsorption process is also affected by the ionic strength of the solution, as high concentrations of other anions can compete with the Al-Ferron chelate for the binding sites on the resin. The mechanism of adsorption of Al-Ferron chelates on anion-exchange resins has been studied in detail, and it is now well understood. This understanding has allowed for the optimization of the immobilization process and the development of highly efficient and selective analytical methods based on this principle.

Factors influencing adsorption efficiency: The efficiency of the adsorption of 7-iodo-8-hydroxyquinoline-5-sulfonic acid (Ferron) and its metal chelates onto anion-exchange resins is influenced by a number of factors, including the pH of the solution, the ionic strength of the solution, the temperature, and the nature of the anion-exchange resin. The pH of the solution is one of the most important factors, as it determines the charge of the Ferron molecule and its metal chelates. At low pH values, the sulfonic acid group of Ferron is protonated, and the molecule has a lower negative charge, which results in a lower adsorption capacity. As the pH is increased, the sulfonic acid group becomes deprotonated, and the negative charge of the molecule increases, which leads to a higher adsorption capacity. The optimal pH for adsorption is typically in the range of 4-6, where the Ferron molecule is fully deprotonated, and the metal chelates are stable. The ionic strength of the solution also has a significant effect on the adsorption efficiency. High concentrations of other anions in the solution can compete with the Ferron molecule and its metal chelates for the binding sites on the resin, which can lead to a decrease in the adsorption capacity. This is a common phenomenon in ion-exchange processes, and it can be minimized by using a low ionic strength buffer or by removing the competing anions from the solution. The temperature of the solution can also affect the adsorption efficiency, as it influences the rate of the adsorption process and the equilibrium constant. In general, the adsorption process is exothermic, which means that the adsorption capacity decreases as the temperature increases. However, the effect of temperature is usually not very significant, and most adsorption experiments are carried out at room temperature. The nature of the anion-exchange resin is another important factor that influences the adsorption efficiency. The capacity of the resin, the type of functional group, and the degree of cross-linking can all affect the adsorption of Ferron and its metal chelates. Resins with a high capacity and a high degree of cross-linking are generally more effective for adsorption, as they have a higher density of binding sites and a more rigid structure. The choice of the anion-exchange resin is therefore a critical step in the optimization of the adsorption process.

Covalent bonding

Immobilization on silica-based supports

Use of silane coupling reagents: Silane coupling reagents are indispensable tools for covalently linking organic molecules to inorganic surfaces, particularly silica. These reagents typically possess a bifunctional structure, with one end capable of reacting with the surface silanol groups of the silica support and the other end bearing a functional group that can react with the molecule to be immobilized. A study on the immobilization of 8-hydroxyquinoline to inorganic carriers describes the use of a new silane coupling reagent to achieve this linkage [4]. The process involves the functionalization of the silica surface with the silane, which introduces a reactive group (e.g., an amino or epoxy group) that can then react with a suitable functional group on the 8-hydroxyquinoline derivative. For Ferron, which has a sulfonic acid group, a silane with an amino group could be used to form a stable amide bond. This method provides a versatile and reliable way to create a strong covalent bond between the ligand and the support, ensuring the long-term stability of the immobilized system. The choice of the silane coupling reagent is critical and depends on the specific functional groups present on both the support and the ligand.

Aminomethylation and derivatization methods: Aminomethylation is another powerful technique for covalently immobilizing 8-hydroxyquinoline derivatives onto solid supports. This method involves the introduction of an aminomethyl group onto the ligand, which can then react with a functionalized support. A study on the immobilization of 8-hydroxyquinoline and 8-hydroxyquinoline-5-sulfonic acid mentions that the immobilization is accomplished through an aminomethylation reaction [5]. This approach allows for the direct attachment of the chelating ligand to the support, creating a stable and robust linkage. The process can be tailored to suit different support materials by selecting appropriate derivatization methods. For example, a support with carboxylic acid groups could be coupled to an aminomethylated Ferron derivative using a carbodiimide coupling agent. This level of control over the immobilization chemistry is a significant advantage of covalent bonding, as it allows for the optimization of the immobilized system's properties for specific applications. The ability to derivatize both the ligand and the support provides a high degree of flexibility in designing immobilized systems with tailored functionalities.

Immobilization on polymer matrices

Covalent attachment to functionalized polymers: Covalent attachment to functionalized polymers is a widely used method for immobilizing chelating agents. This approach involves the reaction of a functional group on the ligand with a complementary functional group on the polymer. For example, a study on the chemical immobilization of 5-amino-8-hydroxyquinoline onto the surface of electrospun fibers from styrene/maleic anhydride copolymers demonstrates this principle [6]. The maleic anhydride groups on the polymer react with the amino group of the 8-hydroxyquinoline derivative to form a stable covalent bond. This method allows for the creation of surfaces with a high density of immobilized ligands, which is beneficial for applications such as solid-phase extraction and catalysis. The choice of the polymer and the functionalization chemistry can be tailored to suit the specific requirements of the application. For Ferron, which has a sulfonic acid group, a polymer with amino or hydroxyl groups could be used to create a stable covalent linkage. This approach provides a high degree of control over the immobilization process and allows for the creation of robust and reusable materials.

Crosslinking with agents like glutaraldehyde: Crosslinking is a powerful technique for immobilizing molecules within a polymer matrix, particularly for creating insoluble and stable materials. Glutaraldehyde is a commonly used crosslinking agent that can react with amino groups on both the polymer and the ligand to form a three-dimensional network. The use of glutaraldehyde vapor to crosslink PVA/Chitosan fibers containing 8-hydroxyquinoline-5-sulfonic acid (SQ) is a prime example of this technique [7]. The crosslinking reaction imparts water insolubility to the fibers, which is essential for their use in aqueous environments, such as in wound dressings or drug delivery systems. The study demonstrated that the crosslinked fibers were stable in an acetate buffer at pH 4.5 for 24 hours, with no significant weight loss, confirming the effectiveness of the crosslinking process [7]. This method is particularly useful for immobilizing water-soluble ligands like Ferron, as it effectively traps them within the polymer matrix, preventing their leaching while maintaining their accessibility for interaction with target molecules. The degree of crosslinking can be controlled to fine-tune the properties of the resulting material, such as its swelling behavior and mechanical strength.

Encapsulation and entrapment

Sol-gel entrapment

Immobilization in silica sol-gel matrices: The immobilization of Ferron and its metal chelates in silica sol-gel matrices has been explored for the development of optical sensors, particularly for humidity sensing. In one study, the Al-Ferron chelate was entrapped in a silica xerogel, and the resulting material was used as an active phase for a phosphorescence-based humidity sensor [8]. The sol-gel process allowed for the creation of a stable, porous matrix that effectively immobilized the chelate while still permitting the diffusion of water molecules. The phosphorescence of the Al-Ferron chelate was found to be quenched by moisture, and this quenching effect was used to quantify the relative humidity in both argon and air gaseous media. The sol-gel-derived sensing phase demonstrated good potential for the analytical quantification of humidity in both continuous and flow-injection systems, with a detection limit of around 0.09% RH in air [8]. This application highlights the suitability of sol-gel entrapment for creating robust and sensitive optical sensors. The ability to control the porosity and surface chemistry of the sol-gel matrix is a key advantage, as it allows for the optimization of the sensor's performance, including its sensitivity, selectivity, and response time.

Advantages of sol-gel for optical sensors: Sol-gel entrapment offers several distinct advantages for the development of optical sensors based on immobilized reagents like Ferron. One of the most significant benefits is the optical transparency of the silica matrix, which allows for the direct measurement of absorbance, fluorescence, or phosphorescence without any interference from the support material. This is particularly important for applications that rely on changes in the optical properties of the reagent upon interaction with an analyte. Another key advantage is the ability to control the microenvironment of the immobilized reagent. The polarity, hydrophobicity, and rigidity of the sol-gel matrix can be tailored by incorporating different functional groups or by adjusting the synthesis conditions. This allows for the optimization of the reagent's stability and reactivity, as well as the selectivity of the sensor. Furthermore, the porous nature of the sol-gel matrix facilitates the diffusion of analytes to the immobilized reagent, leading to a rapid response time. The chemical and thermal stability of the silica matrix also ensures the long-term durability of the sensor, making it suitable for use in harsh environments. Finally, the sol-gel process is a low-temperature technique, which allows for the immobilization of thermally sensitive reagents without causing their degradation.

Stability and leaching prevention: One of the primary challenges in the immobilization of reagents is preventing their leaching from the support material, which can lead to a loss of activity and a decrease in the sensor's performance over time. Sol-gel entrapment is a highly effective method for minimizing leaching, as the reagent molecules are physically trapped within the rigid, porous silica matrix. The size of the pores in the sol-gel network can be controlled to be smaller than the size of the reagent molecules, effectively preventing them from diffusing out of the matrix. This physical entrapment provides a much more stable immobilization compared to simple adsorption, where the reagent is only weakly bound to the surface and can be easily desorbed. In the case of the Al-Ferron chelate immobilized in a silica xerogel for humidity sensing, the sol-gel matrix provided a stable environment for the chelate, allowing for reliable and reproducible measurements [8]. The strong interaction between the chelate and the silica network, combined with the physical confinement within the pores, ensures that the active sensing material remains in place, even under continuous flow conditions. This enhanced stability is a key advantage of sol-gel entrapment, making it a preferred method for applications that require long-term, reliable performance.

Electrospinning

Incorporation into polymer nanofibers (e.g., PVA/Chitosan): The incorporation of 8-hydroxyquinoline-5-sulfonic acid (SQ), a close analog of Ferron, into electrospun nanofibers of poly(vinyl alcohol) (PVA) and chitosan (Ch) is a well-documented example of this immobilization technique [7]. In this study, SQ was successfully incorporated into the PVA/Ch fibers by simply adding it to the electrospinning solution. The resulting fibers were continuous, defect-free, and had a cylindrical shape, with an average diameter that increased with the SQ content [7]. The presence of the ionizable sulfo group in SQ was found to allow for ionic interactions with the chitosan molecules in the fibers, which contributed to the stable incorporation of the SQ [7]. The resulting fibrous materials exhibited excellent antibacterial, antifungal, and antitumor activities, demonstrating the potential of this approach for creating advanced wound dressings and drug delivery systems [7]. This method is highly versatile and can be adapted to incorporate a wide range of functional molecules, including Ferron, into various polymer matrices. The ability to control the fiber diameter, porosity, and composition allows for the fine-tuning of the properties of the resulting materials to suit specific applications.

Coaxial electrospinning for core-shell structures: Coaxial electrospinning is an advanced variation of the standard electrospinning technique that allows for the fabrication of core-shell nanofibers. This method uses a spinneret with two concentric capillaries, which allows for the simultaneous extrusion of two different solutions: a core solution and a shell solution. By carefully controlling the flow rates and properties of the two solutions, it is possible to create fibers with a distinct core and shell structure. This technique is particularly useful for the immobilization of reagents, as it allows for the encapsulation of the reagent within the core of the fiber, while the shell can be made from a different material that provides protection or specific surface properties. For example, a sensitive reagent could be encapsulated in a protective polymer shell to prevent its degradation, or a hydrophilic reagent could be encapsulated in a hydrophobic shell to control its release. Coaxial electrospinning offers a high degree of control over the architecture of the fibers, allowing for the design of materials with tailored functionalities for specific applications. While not yet reported for Ferron, this technique holds great promise for creating advanced sensing and drug delivery systems based on immobilized reagents.

Surface modification of electrospun fibers: Surface modification of electrospun fibers is a powerful technique for imparting specific functionalities to the fiber surface without altering the bulk properties of the material. This can be achieved through various methods, including plasma treatment, chemical grafting, and physical adsorption. For example, the chemical immobilization of 5-amino-8-hydroxyquinoline onto the surface of electrospun fibers from styrene/maleic anhydride copolymers is a form of surface modification that creates a functional surface with chelating properties [6]. This approach allows for the creation of materials with a high density of functional groups on the surface, which is beneficial for applications such as biosensing and affinity chromatography. The surface of electrospun fibers can also be modified to improve their biocompatibility, cell adhesion, or protein adsorption properties. For instance, the surface of PVA/Chitosan fibers containing SQ could be further modified with cell-adhesive peptides to enhance their performance in tissue engineering applications. This level of control over the surface chemistry of electrospun fibers provides a powerful tool for designing advanced materials with tailored properties for a wide range of applications.

Applications of immobilized ferron

Analytical chemistry

Optical and luminescent sensing:

Oxygen sensing via phosphorescence quenching: The development of optical sensors for dissolved oxygen based on the phosphorescence quenching of immobilized Al-Ferron chelates is a significant achievement in the field of analytical chemistry. The Al-Ferron chelate, when immobilized on a suitable solid support, exhibits strong room-temperature phosphorescence (RTP) that is highly sensitive to the presence of molecular oxygen. The mechanism of sensing is based on the dynamic quenching of the triplet state of the phosphorescent probe by oxygen molecules that diffuse into the immobilization matrix. The degree of quenching, which can be measured as a decrease in the phosphorescence intensity or a shortening of the phosphorescence lifetime, is directly proportional to the concentration of oxygen. This allows for the quantitative determination of oxygen in a variety of samples, including environmental waters, biological fluids, and industrial process streams. A key advantage of this approach is the use of a ratiometric measurement, where the intensity of the oxygen-sensitive phosphorescence is compared to a stable fluorescence signal from the same chelate, which serves as an internal reference. This self-referencing method compensates for variations in the excitation light intensity and other instrumental factors, leading to a more accurate and reliable measurement. Sol-gel entrapment has been a particularly effective method for immobilizing the Al-Ferron chelate for oxygen sensing, as it provides a rigid and stable matrix that enhances the RTP and prevents leaching of the probe [1]. The resulting sensors have been shown to have high sensitivity, with detection limits in the gas phase as low as 0.0005% (v/v) and for dissolved oxygen of less than 0.01 mg/L [1].

Detection of metal ions (e.g., Fe^{3+}, Al^{3+}, Ga^{3+}): The strong chelating ability of Ferron makes it an excellent reagent for the detection of a wide range of metal ions. When immobilized on a solid support, Ferron can be used to create highly selective and sensitive sensors for metal ions. The principle of these sensors is based on the formation of a stable complex between the immobilized Ferron and the target metal ion, which results in a change in the optical properties of the sensor. This change can be a shift in the absorption or emission spectrum, a change in the intensity of the luminescence, or a change in the lifetime of the luminescence. For example, the Al-Ferron chelate, when immobilized on an anion-exchange resin, exhibits strong room-temperature phosphorescence (RTP) that can be used for the detection of aluminum [9]. The intensity of the RTP is proportional to the concentration of aluminum in the sample, allowing for its quantitative determination. This approach has been extended to the detection of other metal ions, such as gallium (Ga^{3+}), indium (In^{3+}), zirconium (Zr^{4+}), and hafnium (Hf^{4+}), by using the same immobilization strategy [9]. The use of an ion-exchange resin as the support provides a stable and reusable sensing material that is insensitive to moisture and has excellent selectivity. This makes it a promising approach for the development of a new class of metal ion optosensors for a variety of applications, including environmental monitoring and industrial process control.

Use in Flow Injection Analysis (FIA) systems: Flow injection analysis (FIA) is a powerful and widely used technique for the automated analysis of samples. The integration of immobilized reagents into FIA systems offers several advantages, including the simplification of the manifold, the reduction of reagent consumption, and the ability to perform on-line preconcentration and separation. The use of immobilized Ferron in FIA systems has been explored for the determination of metal ions. For example, a solid-phase spectrophotometric method based on the adsorption of the Fe(III)-Ferron complex on an anion-exchange resin has been integrated into an FIA system for the determination of iron [10]. The use of a renewable solid-phase reactor, where the immobilized reagent is packed in a small column, allows for the repeated use of the reagent and simplifies the analytical procedure. The development of such systems requires careful optimization of the flow rates, sample volume, and reaction conditions to ensure high sensitivity and sample throughput. The use of immobilized reagents in FIA systems is a growing area of research, with the potential for the development of portable and automated analytical devices for a wide range of applications.

Electrochemical sensing

Modified electrodes for voltammetric detection: The modification of electrodes with immobilized Ferron is a powerful strategy for the development of highly sensitive and selective voltammetric sensors. By anchoring Ferron onto the surface of a conductive support, such as carbon paste or glassy carbon, the electrode can be tailored to have a specific affinity for the target analyte. The immobilization can be achieved through various methods, including the simple mixing of Ferron with the carbon paste, the covalent attachment of Ferron to a functionalized electrode surface, or the entrapment of Ferron in a polymer film coated on the electrode. The resulting modified electrode can then be used to detect the target analyte by measuring the current that flows in response to a potential sweep. The presence of the immobilized Ferron on the electrode surface can enhance the electron transfer kinetics, lower the overpotential for the redox reaction of the analyte, and increase the preconcentration of the analyte at the electrode surface, all of which contribute to an improved sensitivity and selectivity. For example, a carbon paste electrode modified with a Sb_2O_3-MWCNT-TiO_2 nanohybrid has been used for the voltammetric determination of 8-hydroxy-7-iodo-5-quinoline sulfonic acid (HIQSA) [11]. The nanohybrid provides a large surface area and excellent conductivity, leading to a significant enhancement in the peak current and a lower detection limit. This approach has also been used for the determination of palladium(II) in mining samples, where Ferron was immobilized on a Purolite A-500 anion-exchange resin [12]. The resulting sensor was found to be highly selective and sensitive for palladium(II), demonstrating the potential of this approach for the analysis of complex samples.

Use of nanohybrids (e.g., Sb_2O_3-MWCNT-TiO_2) as

supports: The use of nanohybrid materials as supports for the immobilization of Ferron has emerged as a promising strategy for enhancing the performance of electrochemical sensors. Nanohybrids, which are composite materials composed of two or more nanoscale components, can combine the unique properties of each component to create a synergistic effect. For example, a nanohybrid composed of antimony trioxide (Sb_2O_3), multi-walled carbon nanotubes (MWCNTs), and titanium dioxide (TiO_2) has been used as a support for the immobilization of Ferron for the voltammetric determination of 8-hydroxy-7-iodo-5-quinoline sulfonic acid (HIQSA) [11]. In this nanohybrid, the MWCNTs provide a large surface area and excellent electrical conductivity, which facilitates the electron transfer process and enhances the sensitivity of the sensor. The TiO_2 nanoparticles can improve the stability and biocompatibility of the material, while the Sb_2O_3 can act as a catalyst to further enhance the electrochemical response. The combination of these components in a single nanohybrid material results in a highly efficient and sensitive sensor for the target analyte. The use of such advanced materials as supports for the immobilization of Ferron is a key area of research in the development of next-generation electrochemical sensors with improved performance and a wider range of applications.

Determination of palladium(II) in mining samples: The determination of palladium(II) in complex matrices such as mining samples is a challenging analytical task that requires highly selective and sensitive methods. Immobilized Ferron has been successfully used for this purpose, leveraging its strong chelating ability for palladium ions. In one study, Ferron was immobilized on a Purolite A-500 anion-exchange resin and used as a solid-phase extractant for the preconcentration of palladium(II) from mining samples [12]. The immobilized Ferron was found to be highly selective for palladium(II), even in the presence of other metal ions that are commonly found in mining samples. The adsorbed palladium(II) was then eluted from the resin and determined by a suitable analytical technique, such as atomic absorption spectrometry or voltammetry. The use of immobilized Ferron for the preconcentration of palladium(II) offers several advantages, including high selectivity, low cost, and the ability to reuse the extractant. This approach is effective for the determination of trace levels of palladium(II) in a variety of mining samples, demonstrating its potential as a valuable tool for the analysis of precious metals.

Environmental chemistry

Heavy metal remediation

Removal of toxic metals from wastewater: The removal of toxic metals from industrial wastewater is a critical environmental issue that requires the development of efficient and cost-effective treatment technologies. Immobilized Ferron has shown great promise for this application, due to its high affinity for a wide range of heavy metal ions, such as lead, cadmium, mercury, and chromium. By immobilizing Ferron on a suitable solid support, such as an anion-exchange resin or activated carbon, it is possible to create a highly selective and reusable adsorbent for the removal of these toxic metals from wastewater streams. The process typically involves passing the contaminated water through a column packed with the immobilized Ferron material, where the metal ions are selectively adsorbed onto the surface. The treated water, which is now free of the toxic metals, can then be safely discharged or reused. The immobilized material can be regenerated by treating it with an appropriate eluent, such as a strong acid or a chelating agent, which releases the adsorbed metals and allows for their recovery. This approach offers several advantages over conventional treatment methods, including high efficiency, low cost, and the ability to recover valuable metals. The use of immobilized Ferron for the removal of toxic metals from wastewater is a promising technology that could have a significant impact on the protection of our water resources.

Stabilization of contaminated soils and sediments: The stabilization of heavy metal-contaminated soils and sediments is another important application of immobilized chelating agents. The addition of a chelating agent to a contaminated soil can help to immobilize the heavy metals, reducing their bioavailability and mobility. However, the use of soluble chelating agents can lead to the leaching of the metals into the groundwater, which can cause further contamination. The use of immobilized chelating agents can help to overcome this problem by providing a solid-phase reagent that can be mixed with the contaminated soil. The immobilized reagent can then bind to the heavy metals, forming stable complexes that are less likely to be leached. This approach can be used to reduce the risk of exposure to heavy metals in contaminated sites, making them safer for human health and the environment. The development of such materials requires careful consideration of the soil properties, the type of contamination, and the long-term stability of the immobilized reagent in the soil environment.

Use in composite precipitation technologies: Composite precipitation technologies, which involve the use of a combination of chemical and physical methods for the removal of contaminants, can also benefit from the use of immobilized chelating agents. For example, an immobilized chelating agent can be used in conjunction with a precipitation agent to enhance the removal of heavy metals from wastewater. The chelating agent can be used to selectively bind to the target metal ions, and the resulting complex can then be precipitated out of solution. The use of an immobilized chelating agent can help to improve the selectivity and efficiency of the precipitation process, and it can also simplify the separation of the precipitated solids. This approach can be particularly useful for the treatment of complex industrial wastewaters that contain a mixture of different metal ions. The development of such composite technologies requires a thorough understanding of the chemistry of the chelating agent, the precipitation agent, and the target contaminants.

Water quality monitoring

Determination of dissolved oxygen in natural waters: The determination of dissolved oxygen (DO) in natural waters is a critical parameter for assessing water quality, as it is essential for the survival of aquatic organisms and is an indicator of the level of organic pollution. Traditional methods for measuring DO, such as the Winkler titration or the use of a Clark-type electrode, can be time-consuming, require skilled personnel, and are not suitable for in situ or continuous monitoring. Immobilized Ferron has emerged as a promising alternative for the development of optical sensors for DO, offering a simple, sensitive, and reliable method for its determination. The principle of these sensors is based on the dynamic quenching of the room-temperature phosphorescence (RTP) of the immobilized Al-Ferron chelate by molecular oxygen. The Al-Ferron chelate, when entrapped in a sol-gel matrix or adsorbed on an anion-exchange resin, exhibits strong RTP that is highly sensitive to the presence of oxygen [1]. The degree of quenching is proportional to the concentration of DO, allowing for its quantitative determination. These optical sensors offer several advantages over traditional methods, including high sensitivity, fast response time, immunity to electromagnetic interference, and the ability to be used for remote sensing with fiber optics. The development of such sensors is a significant advancement in the field of environmental monitoring, providing a valuable tool for the real-time assessment of water quality.

Biomedical applications

Antimicrobial and antifungal agents

Incorporation into wound dressings: The incorporation of antimicrobial agents into wound dressings is a common strategy for preventing and treating infections. The use of immobilized 8-hydroxyquinoline derivatives in this context offers several advantages, including sustained release of the active compound, reduced toxicity, and enhanced stability. A study on the incorporation of 8-hydroxyquinoline-5-sulfonic acid (SQ) into electrospun PVA/Chitosan fibers demonstrated the potential of this approach for creating advanced wound dressings [7]. The resulting fibrous materials exhibited excellent antibacterial activity against *Staphylococcus aureus* and antifungal activity against *Candida albicans*, which are common pathogens in wound infections [7]. The SQ-containing mats were also found to suppress the adhesion of *S. aureus* cells to their surface, which is a crucial step in the development of a biofilm and a chronic infection [7]. The ability to control the release of SQ from the fibers is another key advantage, as it allows for the maintenance of a therapeutic concentration of the antimicrobial agent at the wound site over an extended period. This sustained release can help to prevent the development of resistance and promote faster healing.

Drug delivery and tissue engineering

Use in electrospun scaffolds for cell delivery: Electrospun scaffolds are widely used in tissue engineering due to their high surface-to-volume ratio, high porosity, and ability to mimic the extracellular matrix. The incorporation of bioactive molecules, such as 8-hydroxyquinoline derivatives, into these scaffolds can enhance their functionality by promoting cell adhesion, proliferation, and differentiation. A study on the incorporation of 8-hydroxyquinoline-5-sulfonic acid (SQ) into electrospun PVA/Chitosan fibers demonstrated the potential of this approach for creating scaffolds for tissue engineering applications [7]. The resulting fibrous materials were found to be biocompatible and to exhibit good antitumor activity against HeLa cells, which suggests their potential for use in cancer therapy [7]. The ability to control the release of SQ from the fibers is another key advantage, as it allows for the delivery of a therapeutic dose of the drug over an extended period. This sustained release can help to improve the efficacy of the treatment and reduce the frequency of administration. The use of these scaffolds for the delivery of other bioactive molecules, such as growth factors and cytokines, is also a promising area of research.

Potential for controlled release of bioactive molecules: The controlled release of bioactive molecules is a key challenge in drug delivery and tissue engineering. Immobilized 8-hydroxyquinoline derivatives offer a promising solution to this challenge, as they can be incorporated into a variety of matrices that can be designed to have specific release profiles. The release of the active compound can be controlled by a variety of factors, including the type of polymer, the degree of crosslinking, and the pH and temperature of the surrounding environment. A study on the release of 8-hydroxyquinoline-5-sulfonic acid (SQ) from electrospun PVA/Chitosan fibers found that the release occurred through a Fickian diffusion mechanism, with an initial burst release followed by a sustained release [7]. This type of release profile is often desirable for drug delivery applications, as the initial burst can provide a therapeutic dose of the drug quickly, while the sustained release can maintain a therapeutic concentration over an extended period. The ability to control the release of bioactive molecules from these materials provides a powerful tool for designing advanced drug delivery systems and tissue engineering scaffolds with tailored properties for specific applications.

Historical perspective and recent developments

Historical context of Ferron use

Early applications as a colorimetric reagent for iron: The use of Ferron as a colorimetric reagent for the determination of iron dates back to the mid-20th century. The formation of a stable, colored complex between Ferron and Fe(III) in acidic solution provided a simple and sensitive method for the spectrophotometric determination of iron in a variety of samples. The reaction is highly selective, and the intensity of the color is directly proportional to the concentration of iron, allowing for quantitative measurements. The use of Ferron as a colorimetric reagent was a significant improvement over earlier methods, which were often less sensitive and more prone to interference from other metal ions. The development of this method was a major contribution to the field of analytical chemistry and helped to establish Ferron as a valuable reagent for the analysis of iron.

Use as an anti-amoebic drug (Chiniofon): In addition to its use as an analytical reagent, Ferron has also been used as an anti-amoebic drug, under the name Chiniofon. It was introduced in the 1930s and was widely used for the treatment of amoebic dysentery and other intestinal infections caused by amoebae. The mechanism of action of Chiniofon is not fully understood, but it is thought to involve the chelation of metal ions that are essential for the survival of the amoebae. The use of Chiniofon as an anti-amoebic drug was a significant advance in the treatment of these infections, and it remained a first-line treatment for many years. However, with the development of more effective and safer drugs, such as metronidazole, the use of Chiniofon has declined. Nevertheless, it remains an important part of the history of anti-amoebic therapy.

Initial studies on immobilization for sensing (1990s-2000s): The concept of immobilizing Ferron for sensing applications began to emerge in the 1990s and 2000s, driven by the growing interest in the development of solid-phase sensors. The immobilization of Ferron on anion-exchange resins, such as Dowex 2X4, was explored for the preconcentration and determination of Fe(III) [13,14]. This work demonstrated the feasibility of using immobilized Ferron for solid-phase extraction and sensing. The development of room-temperature phosphorescence (RTP) methods for the determination of metal ions, such as gallium, using the Ga(III)-Ferron complex in micellar systems also emerged during this period [15]. These studies laid the groundwork for the development of more advanced sensing systems based on immobilized Ferron, including those that utilize optical fibers and flow injection analysis. The work from this period was crucial in establishing the potential of immobilized Ferron for a wide range of sensing applications.

Recent developments and future outlook (past 5 years)

Advancements in nanomaterial-based immobilization: The use of nanomaterials as supports for the immobilization of Ferron has been a major focus of recent research. Nanomaterials, such as nanoparticles, nanotubes, and nanofibers, offer a high surface-to-volume ratio, which can lead to a high loading capacity for the immobilized reagent. They also offer unique optical, electrical, and catalytic properties that can be exploited to enhance the performance of the sensing system. For example, the use of gold nanoparticles (AuNPs) as a support for the immobilization of a reagent can enhance the sensitivity of an electrochemical sensor due to their high conductivity and catalytic activity. The electrospinning of polymer nanofibers containing an 8-hydroxyquinoline derivative has been demonstrated, and this approach could be readily adapted for the immobilization of Ferron [7]. The use of nanomaterials also allows for the creation of miniaturized and portable sensing devices, which is a major goal of modern analytical chemistry.

Development of multi-functional and hybrid sensing platforms: The development of multi-functional and hybrid sensing platforms, which combine the properties of different materials, has been another area of active research. For example, a hybrid material consisting of a polymer matrix and a nanomaterial, such as a carbon nanotube or a graphene sheet, can offer the mechanical stability of the polymer and the high conductivity of the nanomaterial. The immobilization of Ferron on such a hybrid material could lead to a sensor with enhanced sensitivity and selectivity. The development of multi-functional platforms that can detect multiple analytes simultaneously is also a major goal of current research. This could be achieved by immobilizing different reagents on the same support or by using a single reagent that can respond to multiple analytes. The development of such platforms would have a significant impact on a wide range of applications, including environmental monitoring, medical diagnostics, and food safety.

Exploration of new biomedical applications: The exploration of new biomedical applications of immobilized Ferron has been a growing area of interest in recent years. The antimicrobial properties of 8-hydroxyquinoline derivatives make them attractive candidates for the development of antimicrobial coatings for medical devices and wound dressings. The immobilization of these compounds on a biocompatible polymer matrix could provide a sustained release of the active agent, offering long-term protection against infection. The use of immobilized Ferron for drug delivery applications is also a promising area of research. The ability to complex a drug molecule with Ferron and then immobilize it on a polymer matrix could provide a way to deliver the drug in a controlled manner. The development of such systems could have a significant impact on the treatment of a wide range of diseases, including cancer and infectious diseases.

Challenges and opportunities for future research: Despite the significant progress that has been made in the immobilization of Ferron, there are still several challenges that need to be addressed. One of the main challenges is the long-term stability of the immobilized reagents. The leaching of the reagent from the support material can lead to a loss of activity and a decrease in the performance of the sensor or separation material. The development of more robust immobilization methods, such as covalent bonding, is a key area of future research. Another challenge is the development of sensors with high selectivity for the target analyte. The use of molecularly imprinted polymers (MIPs), which are polymers that are synthesized in the presence of a template molecule, is a promising approach for creating highly selective sensors. The development of portable and low-cost sensing devices is also a major goal of future research. The use of immobilized reagents in combination with microfluidic technology could lead to the development of lab-on-a-chip devices for a wide range of applications. The exploration of new applications in areas such as environmental monitoring, medical diagnostics, and food safety will continue to be a major focus of future research in this field.

Conclusion

The immobilization of 7-iodo-8-hydroxyquinoline-5-sulfonic acid (Ferron) represents a powerful strategy to transform a versatile chelating agent into a robust, reusable, and application-specific tool. By anchoring Ferron to various solid supports through covalent bonding, physical adsorption, or encapsulation, researchers have successfully overcome the limitations of its solution-phase use, unlocking its potential for long-term, solid-phase applications. The choice of immobilization technique is critical and must be tailored to the desired application, balancing factors such as stability, leaching resistance, ease of preparation, and analyte accessibility.

Immobilized Ferron has proven exceptionally valuable in analytical chemistry, serving as the active component in highly sensitive optical sensors for dissolved oxygen and various metal ions (e.g., Al^{3+}, Fe^{3+}, Pd^{2+}), as well as in electrochemical platforms using advanced nanohybrid supports. Its integration into flow injection systems has further automated and streamlined analytical procedures. In the environmental sector, immobilized Ferron offers a promising, cost-effective solution for the remediation of heavy metal pollution in wastewater and contaminated soils. More recently, its incorporation into biocompatible materials like electrospun PVA/chitosan nanofibers has opened exciting new avenues in biomedicine, particularly for developing antimicrobial wound dressings and controlled-release drug delivery scaffolds.

Looking forward, the field is poised for significant advancements. The integration of Ferron with nanomaterials and the development of multi-functional hybrid platforms promise to yield sensors with unprecedented sensitivity, selectivity, and miniaturization. The exploration of molecularly imprinted polymers (MIPs) could further enhance specificity, while combining immobilized systems with microfluidics may lead to portable, low-cost “lab-on-a-chip” devices. Although challenges regarding long-term stability and leaching persist, ongoing research into more robust covalent chemistries and optimized matrix designs is actively addressing these issues. As research continues to bridge chemistry, materials science, and engineering, immobilized Ferron is set to play an increasingly vital role in solving complex problems across analytical, environmental, and biomedical domains.

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