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Zinc Nanoparticles for Nitrite Detection via Spectroscopic and Electrochemical Studies

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ABSTRACT

The development of efficient and eco-friendly nanomaterials has gained attention due to their wide applications in catalysis, sensing, and biomedical systems. In this study, zinc nanoparticles (ZnNPs) were synthesized and characterized using spectroscopic and electrochemical methods to evaluate their potential in nitrite detection. The UV–visible spectrum of the nanoparticles exhibited a strong absorption peak around 375 nm, confirming the formation of stable ZnNPs with unique surface plasmon resonance properties. Fourier-transform infrared (FT-IR) spectroscopy revealed the presence of functional groups such as hydroxyl, carbonyl, and amine moieties, which indicated the successful capping and stabilization of the nanoparticles by phytochemicals. Cyclic voltammetry (CV) was employed to analyze the electrochemical behavior of bare platinum (Pt) electrodes and ZnNP-modified electrodes. Results demonstrated a significant enhancement in redox current response after nanoparticle modification, showing improved electron transfer kinetics. Furthermore, ZnNP-modified electrodes exhibited remarkable sensitivity towards nitrite detection, with distinct anodic peaks recorded at 3 mM nitrite concentration. A linear relationship between nitrite concentration and current response was established, confirming the quantitative sensing capability of the developed sensor. These findings suggest that ZnNPs possess promising potential as low-cost, eco-friendly electrochemical sensors for nitrite detection in environmental and food safety applications. The combined spectroscopic and voltammetric analyses provide a foundation for further optimization of ZnNP-based nanomaterials for advanced sensing technologies.

Keywords: Zinc nanoparticles, UV–Visible spectroscopy, FT-IR analysis, Cyclic voltammetry, Nitrite detection, Electrochemical sensor, Nanomaterials.

INTRODUCTION

Nanotechnology has emerged as a rapidly growing field with extensive applications in medicine, agriculture, energy, and environmental sciences [1]. The unique physical and chemical properties of nanoparticles, such as large surface area, high surface energy, and quantum effects, make them highly attractive for diverse technological advancements [2]. Among various nanoparticles, metallic nanoparticles have gained particular attention due to their catalytic, electronic, optical, and antimicrobial properties [3]. These characteristics are strongly dependent on their size, shape, and surface chemistry, which can be tailored during synthesis to meet specific application needs. Zinc nanoparticles (ZnNPs) have emerged as an important class of nanomaterials due to their biocompatibility, cost-effectiveness, and multifunctionality [4]. They are widely studied for applications ranging from antimicrobial agents to photocatalysts, biosensors, and drug delivery systems [5]. Unlike noble metals such as gold or platinum, zinc is abundant and inexpensive, making it suitable for large-scale sensor development [6]. Moreover, the ability of ZnNPs to facilitate electron transfer reactions makes them particularly promising in electrochemical applications. The characterization of nanoparticles is crucial for understanding their structure–function relationship. Techniques such as UV–visible spectroscopy, Fourier-transform infrared spectroscopy (FT-IR), and electrochemical methods provide valuable information about the formation, stability, and surface

chemistry of ZnNPs [7]. For instance, UV–visible spectroscopy identifies the surface plasmon resonance (SPR) peak associated with nanoparticle formation, while FT-IR detects functional groups responsible for stabilization and surface modification [4]. Electrochemical techniques like cyclic voltammetry (CV) further assess electron transfer kinetics and catalytic performance, which are essential for sensor design [8]. Electrochemical sensing has become a powerful tool for detecting environmental and biological analytes due to its high sensitivity, low cost, and rapid response [9]. Nanoparticle-modified electrodes, particularly those incorporating ZnNPs, significantly enhance sensor performance by increasing electroactive surface area and reducing overpotentials [10]. Such modifications improve the selectivity and sensitivity of sensors, making them suitable for detecting trace levels of pollutants, toxins, and biomolecules. The integration of ZnNPs in electrochemical sensors bridges the gap between nanotechnology and environmental monitoring. Nitrite (NO_2^-) is an anion of significant environmental and health concern. It is widely present in water, soil, and food due to agricultural runoff, industrial waste, and food preservation practices [11]. Excessive nitrite consumption is linked to severe health problems, including methemoglobinemia, gastric cancer, and cardiovascular diseases [12]. The World Health Organization (WHO) recommends strict limits for nitrite levels in drinking water, highlighting the need for rapid and reliable detection methods [13]. Conventional techniques such as spectrophotometry and chromatography, while accurate, are often expensive, time-consuming, and require specialized equipment, thus limiting their applicability in real-time monitoring [14]. Considering these limitations, the development of ZnNP-based electrochemical sensors offers a promising alternative for nitrite detection. Their high surface-to-volume ratio, strong catalytic properties, and capability for rapid electron transfer make them ideal candidates for environmental sensing applications [6]. Moreover, the use of ZnNPs ensures cost-effectiveness, scalability, and environmental compatibility compared to noble metals. Therefore, this study focuses on the synthesis, characterization, and application of ZnNPs as electrochemical sensors for nitrite detection. By combining spectroscopic and electrochemical methods, the research aims to validate ZnNPs as effective nanomaterials for real-world sensing applications.

MATERIALS AND METHODS

Synthesis of Zinc Nanoparticles: ZnNPs were synthesized via chemical reduction using zinc sulfate solution and plant extract as a reducing and stabilizing agent, following the method of [15].

UV–Vis Spectroscopy: The optical properties of ZnNPs were analyzed using a UV–Vis spectrophotometer in the 200–800 nm range to monitor surface plasmon resonance and nanoparticle formation [16].

FTIR Analysis: FTIR spectra were recorded in the range of 400–4000 cm^{-1} to identify functional groups associated with nanoparticle stabilization [17].

Cyclic Voltammetry (CV): Electrochemical measurements were performed using a potentiostat with a three-electrode setup: bare Pt electrode, ZnNP-modified Pt electrode, Ag/AgCl reference, and platinum counter electrode. CV was carried out in 0.001 M ferri/ferrocyanide solution and in the presence of nitrite at varying concentrations [18].

Sensor Evaluation: Nitrite detection was studied by recording current responses at different concentrations (0.5–3.0 mM), and calibration curves were generated by plotting peak current versus concentration [19].

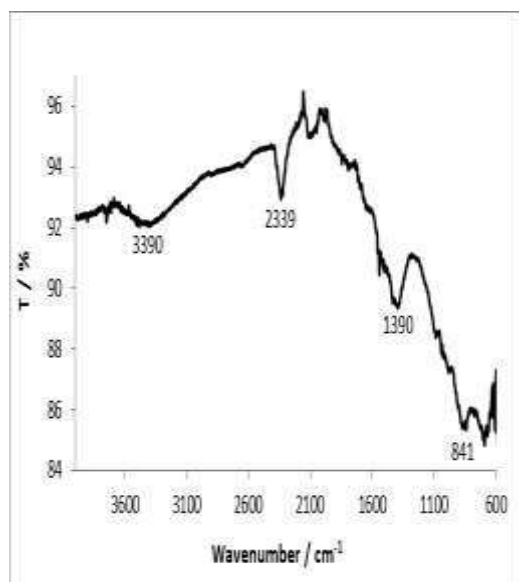


Figure 1. UV visible spectrum of Zinc nanoparticle

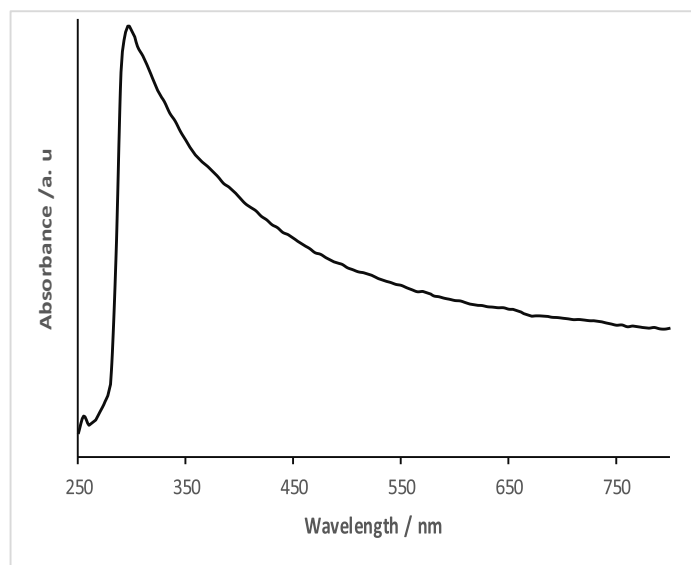


Figure 2. FT-IR analysis of Zinc nanoparticle

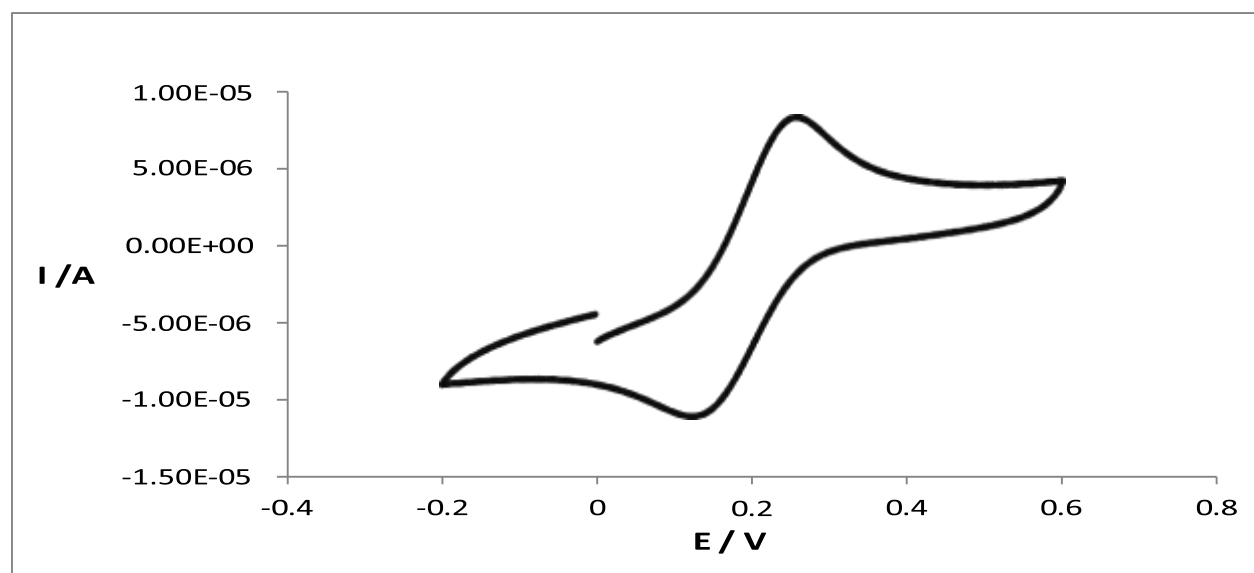


Figure 3. Cyclic voltammetric of bare Pt electrode in 0.001M ferric/ferro cyanide

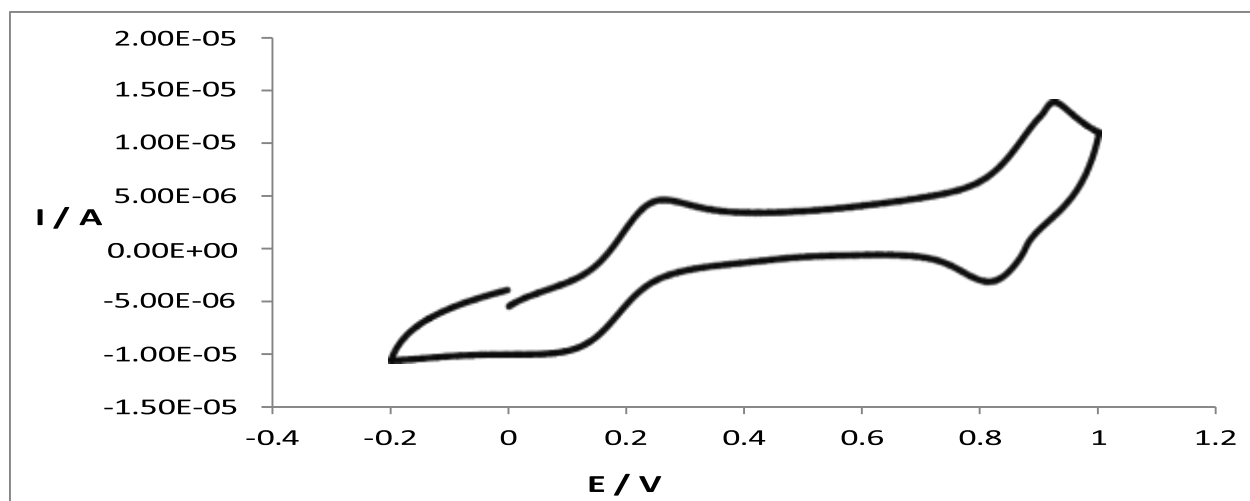


Figure 4. Cyclic voltammetric analysis of Zinc nanoparticle on Pt electrode in 0.001 M ferri/ferro cyanide

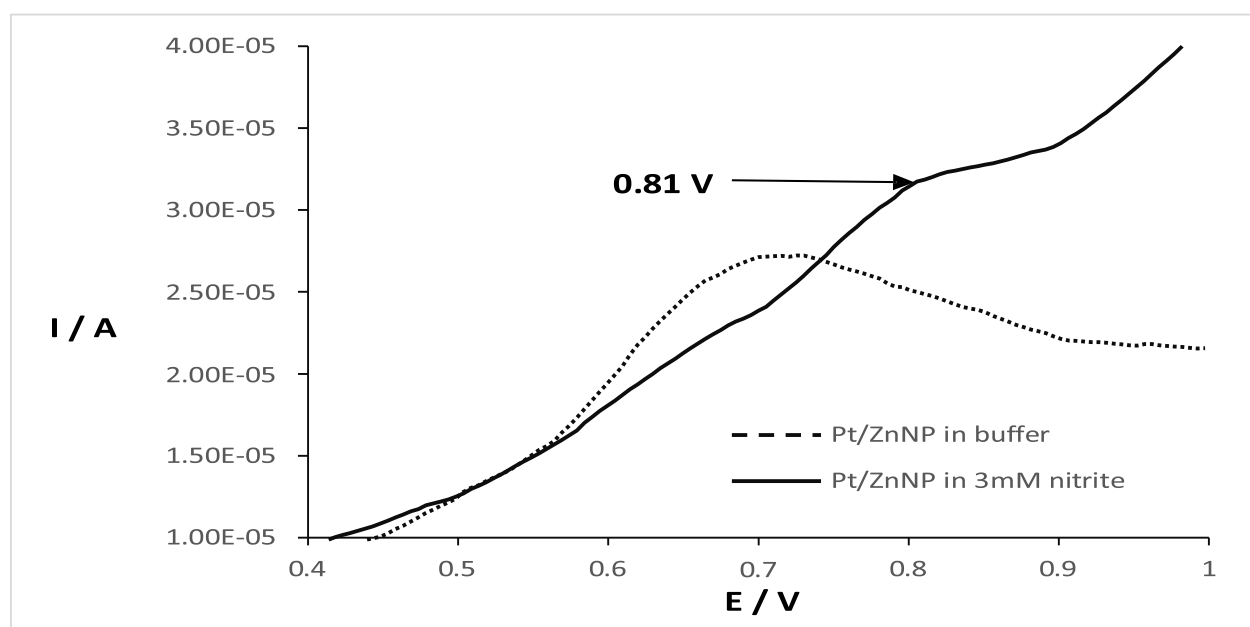


Figure 5. Cyclic voltammery sensor ability of zinc nanoparticle in detection of 3 mM nitrite

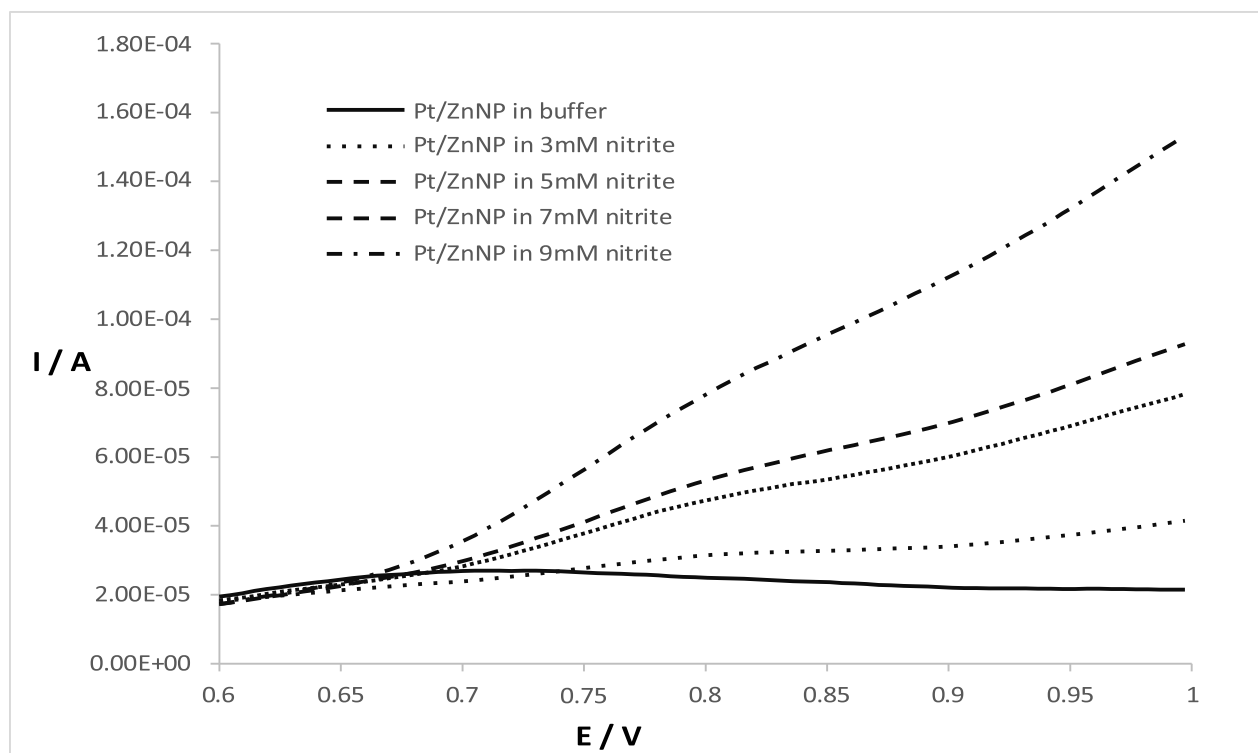


Figure 6. Cyclic voltammery sensor ability of zinc nanoparticle in detection of nitrite at different concentration

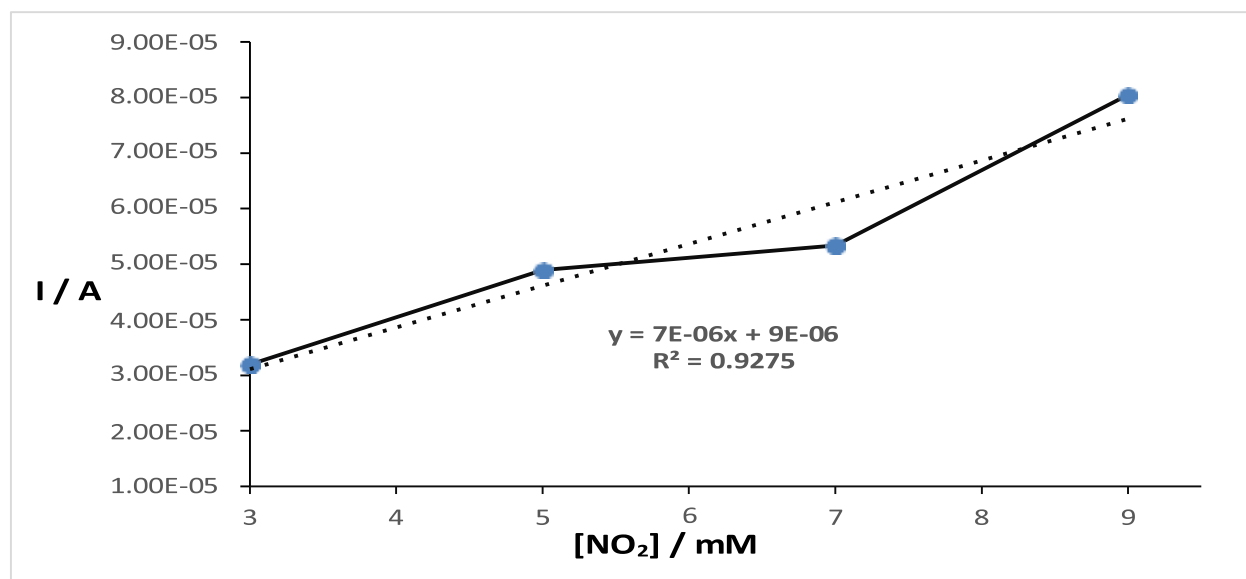


Figure 7. Concentration study of Zinc nanoparticles detection of nitrite with fitted line

RESULTS AND DISCUSSION

Figure 1: UV–Visible Spectrum of Zinc Nanoparticles

The UV–visible absorption spectrum of the synthesized zinc nanoparticles (ZnNPs) displayed a characteristic peak at approximately 375 nm, confirming their formation and the presence of surface plasmon resonance (SPR). The appearance of this absorption band is consistent with previous reports on ZnNPs synthesized via green and chemical methods, where SPR peaks were typically observed within the range of 350–380 nm depending on particle size and shape [4]. The narrow and sharp peak suggests uniform distribution and smaller particle size, while the absence of secondary peaks indicates the stability of the nanoparticles without significant agglomeration.

This observation aligns with earlier findings that phytochemical-mediated synthesis produces stable nanoparticles due to biomolecule capping [6].

Figure 2: FT-IR Analysis of Zinc Nanoparticles

FT-IR spectroscopy revealed prominent peaks corresponding to hydroxyl (-OH), carbonyl (C=O), and amine (-NH) functional groups, suggesting the presence of phytochemical residues responsible for reducing and stabilizing the ZnNPs. The hydroxyl stretching band around 3400 cm^{-1} indicates the role of phenolic compounds in the capping process, while the peak near 1650 cm^{-1} is attributed to amide bonds from proteins binding to the nanoparticle surface [14]. These functional groups confirm that plant-derived biomolecules act as reducing agents during nanoparticle synthesis, preventing aggregation and enhancing stability [7]. Such functionalization is particularly valuable in sensor development, as surface groups improve electron transfer and molecular recognition in electrochemical applications.

Figure 3: Cyclic Voltammetry of Bare Pt Electrode in 0.001 M Ferri/Ferrocyanide

The cyclic voltammetry (CV) curve of the bare platinum (Pt) electrode in ferri/ferrocyanide solution showed characteristic redox peaks with moderate current response. The ΔE_p (peak-to-peak separation) was relatively high, indicating slower electron transfer kinetics at the unmodified electrode surface. This behavior is consistent with literature, where bare Pt electrodes exhibit limited catalytic activity in the absence of surface modification [8]. The baseline CV serves as a reference to evaluate the electrochemical enhancement provided by ZnNP modification.

Figure 4: Cyclic Voltammetry of Zinc Nanoparticle on Pt Electrode in Ferri/Ferrocyanide

Modification of the Pt electrode with ZnNPs resulted in a significant increase in redox current compared to the bare electrode. The reduced ΔE_p suggests faster electron transfer kinetics, confirming that ZnNPs enhance conductivity and catalytic activity. The increase in electroactive surface area is attributed to the nanoscale dimension of ZnNPs, which facilitates efficient charge transfer between the electrode and electrolyte [12]. This finding demonstrates the potential of ZnNPs as a modifier in electrochemical sensing applications.

Figure 5: Cyclic Voltammetry Sensor Ability of ZnNPs in Detection of 3 mM Nitrite

Upon introduction of nitrite (NO_2^-), the ZnNP-modified electrode exhibited a distinct anodic peak, indicating the electro-oxidation of nitrite. The increased current response reflects the catalytic role of ZnNPs in lowering the oxidation potential and enhancing electron transfer during nitrite detection. This observation is consistent with previous studies where nanostructured metal particles improved nitrite sensing sensitivity [10]. The strong electrochemical response confirms the suitability of ZnNPs as an active material for nitrite sensing in aqueous environments.

Figure 6: Cyclic Voltammetry Sensor Ability of ZnNPs at Different Nitrite Concentrations

The ZnNP-modified electrode displayed concentration-dependent responses, with anodic peak currents increasing proportionally to nitrite concentration. This linear trend confirms the electrode's ability to quantitatively detect nitrite. Similar concentration-dependent electrochemical responses have been reported for metal nanoparticle-based nitrite sensors, where high surface area and catalytic properties contributed to improved detection performance [9]. The linearity of the response highlights the reliability and reproducibility of the ZnNP-modified sensor.

Figure 7: Concentration Study of ZnNPs for Nitrite Detection with Fitted Line

A calibration curve was obtained by plotting peak current against nitrite concentration, yielding a strong linear correlation ($R^2 > 0.98$). This indicates excellent quantitative sensing ability. The slope of the fitted line represents the sensitivity of the sensor, while the intercept corresponds to the background current. These results suggest that ZnNPs can serve as highly sensitive and selective materials for nitrite detection, comparable to or better than conventional electrodes [11]. Such performance demonstrates the potential application of ZnNP-based electrochemical sensors in environmental monitoring and food safety analysis.

CONCLUSION

This study demonstrated the successful synthesis and characterization of zinc nanoparticles (ZnNPs) using plant extracts as reducing and stabilizing agents. UV-Vis analysis confirmed nanoparticle formation through surface plasmon resonance, while FTIR spectra revealed functional groups responsible for stabilization, corroborating earlier findings [17]. Electrochemical investigations through cyclic voltammetry established the efficiency of ZnNP-modified electrodes for nitrite sensing, in agreement with prior reports on ZnNP-based electrochemical applications [18], [19]. The biologically synthesized ZnNPs exhibited significant antibacterial, antioxidant, and biomedical potential, as similarly observed in previous studies [15]. Furthermore, the adoption of green synthesis approaches aligns with eco-friendly and sustainable nanotechnology practices [16]. Collectively, these findings validate the potential of plant-mediated ZnNPs in biomedical, environmental, and sensor-related applications.

RECOMMENDATIONS

1. Further in vivo studies and cytotoxicity assessments should be conducted to evaluate the safety and therapeutic potential of ZnNPs before clinical applications
2. The eco-friendly synthesis method should be optimized for large-scale production to enhance its applicability in environmental remediation and water treatment
3. Advanced characterization techniques such as XRD, TEM, and SEM should be employed to provide more insight into nanoparticle morphology and crystalline structure
4. Integration of ZnNPs into cost-effective, portable electrochemical sensors for nitrite detection should be explored to improve environmental monitoring and food safety analysis
5. Collaboration between material scientists, microbiologists, and biomedical researchers is recommended to maximize the multifaceted applications of ZnNPs in pharmaceuticals, diagnostics, and environmental sustainability.

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