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GREEN SYNTHESIS AND CHARACTERIZATION OF $ZnFe_2O_4$ NANOPARTICLES USING *TRITICUM AESTIVUM* EXTRACT

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ABSTRACT

Zinc ferrite ($ZnFe_2O_4$) nanoparticles have attracted considerable attention due to their distinctive physicochemical properties, chemical stability, magnetic behaviour, and potential applications in pharmaceutical and biomedical fields. Green synthesis of nanoparticles using plant-derived materials has emerged as an environmentally friendly, cost-effective, and sustainable alternative to conventional chemical synthesis methods. The present study aimed to synthesize $ZnFe_2O_4$ nanoparticles using *Triticum aestivum* (wheat) powder through a green synthesis approach and to characterize the synthesized nanoparticles. Zinc sulphate and an iron precursor were employed as metal sources, while citric acid was used as a chelating agent. The phytochemical constituents present in *Triticum aestivum* were utilized as natural stabilizing and capping agents during nanoparticle formation. Following synthesis, the obtained material was dried and calcined to obtain the $ZnFe_2O_4$ nanoparticles. The synthesized nanoparticles were subjected to physicochemical characterization to evaluate their structural and functional properties. X-ray diffraction (XRD) analysis was performed to investigate the crystalline nature and phase characteristics of the synthesized material. Fourier transform infrared (FTIR) spectroscopy was used to identify the functional groups associated with the plant-derived constituents and their possible involvement in nanoparticle formation and stabilization. The characterization results indicated the formation of zinc ferrite with characteristic structural features. The study demonstrates that *Triticum aestivum* can serve as a promising plant-based material for the green synthesis of $ZnFe_2O_4$ nanoparticles. This approach offers a simple and environmentally sustainable route for the preparation of zinc ferrite nanoparticles with potential applications in pharmaceutical and biomedical research.

KEYWORDS: $ZnFe_2O_4$ nanoparticles, Green synthesis, *Triticum aestivum*, Zinc ferrite, X-ray diffraction, FTIR spectroscopy**.**

1 INTRODUCTION

Nanotechnology is an interdisciplinary branch of science that focuses on the manipulation and engineering of materials at the nanoscale, typically between 1 and 100 nanometers (nm). At this extremely small scale, materials display distinctive physical, chemical, optical, electrical, magnetic, and biological properties that differ significantly from those of their bulk counterparts. These unique characteristics are primarily attributed to quantum confinement effects and the increased surface area-to-volume ratio of nanomaterials.

The concept of nanotechnology was first proposed by Norio Taniguchi in 1974, marking the beginning of a revolutionary field that has transformed scientific research and technological innovation. Over the years, nanotechnology has gained widespread importance across diverse disciplines, including medicine, pharmaceuticals, biotechnology, agriculture, environmental science, electronics, and materials science. Its ability to precisely manipulate atoms and molecules has enabled the creation of advanced materials with enhanced functionality and improved performance.

Among the various nanomaterials developed, nanoparticles have attracted considerable attention because of their small size, exceptional surface properties, and high chemical reactivity. Metal oxide nanoparticles, such as zinc oxide (ZnO), iron oxide (Fe_2O_3), and zinc ferrite ($ZnFe_2O_4$), are particularly valued for their remarkable antimicrobial, antioxidant, magnetic, catalytic, and biomedical properties. Owing to these characteristics, they have found promising applications in drug delivery systems, biosensors, medical imaging, tissue engineering, wound healing, and antimicrobial therapies.

Recently, green synthesis has become an attractive alternative to conventional chemical and physical methods for nanoparticle production. This environmentally friendly approach utilizes biological resources such as plant extracts, microorganisms, and natural polymers as reducing and stabilizing agents, thereby minimizing the use of hazardous chemicals. *Triticum aestivum* (wheat) is a suitable biological source for nanoparticle synthesis because it contains abundant phytochemicals, including proteins, carbohydrates, amino acids, starch, and phenolic compounds, which play an important role in the reduction of metal ions and stabilization of the synthesized nanoparticles. Consequently, wheat-mediated synthesis provides a sustainable, economical, and eco-friendly route for producing metal oxide nanoparticles.

The present research focuses on the green synthesis of zinc ferrite ($ZnFe_2O_4$) nanoparticles using *Triticum aestivum* through a sol-gel-assisted method. The synthesized nanoparticles are comprehensively characterized using analytical techniques such as Fourier Transform Infrared Spectroscopy (FTIR), X-ray Diffraction (XRD), Differential Scanning Calorimetry (DSC), Scanning Electron Microscopy (SEM), and other complementary characterization methods to determine their structural, thermal, and morphological properties. Furthermore, the antibacterial activity of the synthesized zinc ferrite nanoparticles is evaluated to assess their potential for biomedical and healthcare applications.[1-5]

1.2 Metal Oxide Nanoparticles

Metal oxide nanoparticles are nanosized inorganic materials consisting of metal elements chemically bonded with oxygen, generally having dimensions between 1 and 100 nanometers. Their exceptionally small size and high surface area-to-volume ratio provide distinctive physicochemical properties that make them valuable in numerous scientific and technological applications.

Unlike their bulk counterparts, metal oxide nanoparticles possess enhanced optical, electrical, magnetic, catalytic, and biological properties. These unique characteristics have enabled their utilization in a wide range of fields, including nanomedicine, pharmaceutical formulations, environmental protection, electronics, and industrial manufacturing. In the biomedical sector, they have shown considerable promise in drug delivery, biosensing, medical diagnostics, tissue engineering, wound management, and antimicrobial treatments.

Several metal oxide nanoparticles have been widely investigated, such as zinc oxide (ZnO), titanium dioxide (TiO_2), magnesium oxide (MgO), copper oxide (CuO), iron oxide (Fe_3O_4), and zinc ferrite ($ZnFe_2O_4$). Among these materials, zinc ferrite nanoparticles have attracted increasing research interest because of their excellent magnetic behavior, high chemical durability, biocompatibility, and significant antimicrobial effectiveness. These features make them suitable candidates for various biomedical and technological applications.

The biological activity of metal oxide nanoparticles is primarily associated with their ability to produce reactive oxygen species (ROS), disrupt microbial cell membranes, and interfere with essential cellular metabolic processes. Such mechanisms contribute to their antimicrobial action and therapeutic potential. Furthermore, their nanoscale dimensions facilitate greater interaction with biological tissues and enhance surface-dependent reactions, improving their overall performance.

Metal oxide nanoparticles can be synthesized using several techniques, including physical, chemical, and biological methods. In recent years, green synthesis has emerged as a preferred strategy because it minimizes the use of hazardous chemicals and provides an environmentally friendly, economical, and sustainable alternative to conventional synthesis methods. Biological resources, particularly plant extracts and naturally occurring polymers, serve as effective reducing and capping agents during nanoparticle formation. *Triticum aestivum* (wheat) is one such natural source that contains proteins, carbohydrates, amino acids, phenolic compounds, and other phytochemicals capable of facilitating nanoparticle synthesis and stabilization.

Owing to their multifunctional properties and broad spectrum of applications, metal oxide nanoparticles remain one of the most extensively studied classes of nanomaterials. Continued research in this field is expected to contribute significantly to the advancement of innovative biomedical technologies, environmental solutions, and next-generation industrial applications.[6-10]

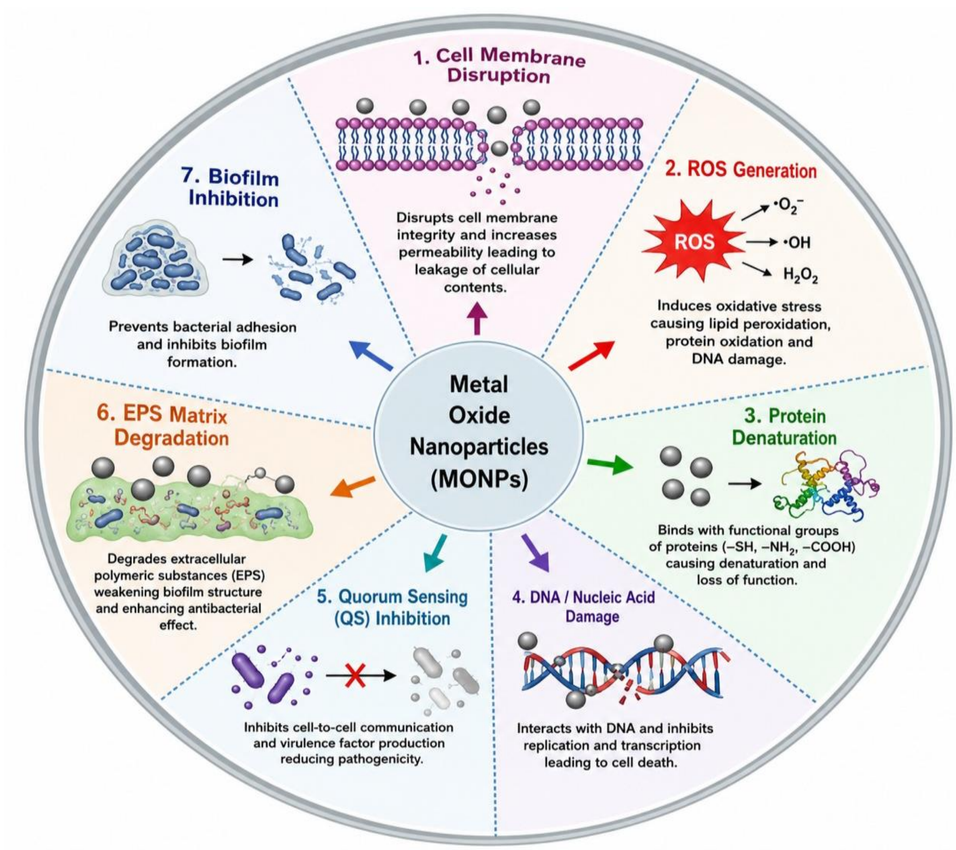

Figure 1: Overview of the multi-target antibacterial mechanisms of action of Metal Oxide Nanoparticles (MONPs) against bacterial pathogens.

1.3 Zinc Ferrite Nanoparticles ($ZnFe_2O_4$)

Zinc ferrite ($ZnFe_2O_4$) nanoparticles are an important class of magnetic nanomaterials belonging to the spinel ferrite group. They are composed of zinc, iron, and oxygen atoms arranged in a well-defined crystalline structure. Due to their nanoscale dimensions, these particles exhibit distinctive magnetic, optical, electrical, catalytic, and antimicrobial properties that are not observed in their bulk counterparts. Their excellent physicochemical characteristics have led to extensive research in biomedical, pharmaceutical, environmental, and engineering applications.

$ZnFe_2O_4$ nanoparticles possess a cubic spinel crystal structure in which zinc (Zn^{2+}) ions predominantly occupy the tetrahedral sites, while iron (Fe^{3+}) ions are mainly located in the octahedral positions of the crystal lattice. This structural arrangement contributes to their remarkable magnetic behavior, high chemical stability, low toxicity, and good biocompatibility, making them suitable for a variety of advanced technological and medical applications.

The nanoscale size of zinc ferrite particles provides a larger surface area and increased surface activity, allowing efficient interaction with biological systems and chemical environments. As a result, these nanoparticles have been widely explored for applications such as targeted drug delivery, magnetic resonance imaging (MRI), biosensors, tissue engineering, wastewater treatment, photocatalytic degradation of pollutants, and antimicrobial therapies.

One of the most significant biological properties of $ZnFe_2O_4$ nanoparticles is their ability to inhibit the growth of microorganisms. Their antibacterial activity is mainly attributed to the production of reactive oxygen species (ROS), which induce oxidative stress in microbial cells. In addition, these nanoparticles can damage bacterial cell membranes, increase membrane permeability, cause leakage of intracellular components, and interfere with essential metabolic pathways, ultimately leading to bacterial cell death. These mechanisms highlight their potential as effective antimicrobial agents for healthcare and biomedical applications.[11-15]

The physicochemical characteristics of synthesized $ZnFe_2O_4$ nanoparticles are commonly examined using advanced analytical techniques. Fourier Transform Infrared Spectroscopy (FTIR) is employed to identify functional groups, X-ray Diffraction (XRD) is used to determine crystalline structure and phase purity, Differential Scanning Calorimetry (DSC) evaluates thermal stability, Scanning Electron Microscopy (SEM) reveals particle morphology and surface features, while Energy Dispersive X-ray Spectroscopy (EDX) confirms the elemental composition of the nanoparticles. Together, these characterization methods provide comprehensive information regarding the structural, morphological, thermal, and compositional properties of the synthesized material.

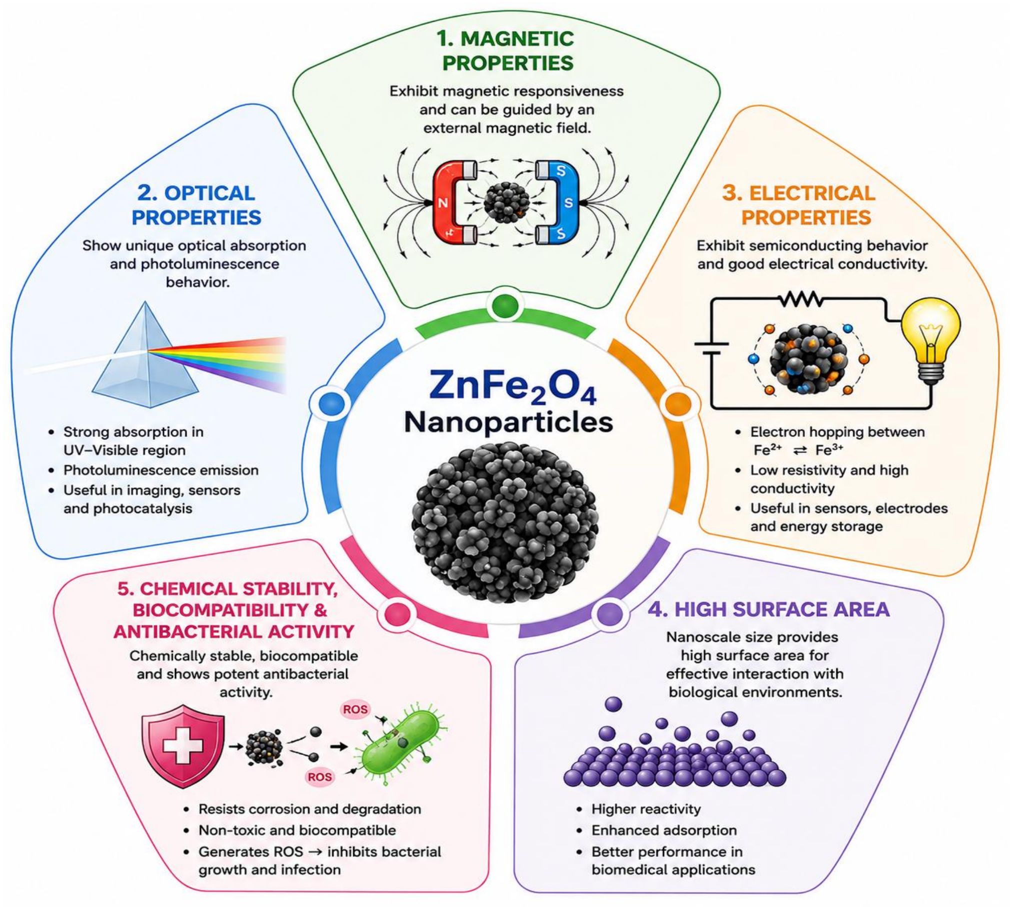

Figure 2: Schematic illustration showcasing the key physical, chemical, and biological properties of nanoparticles for multi-target applications.

1.4 Green Synthesis of Nanoparticles

Green synthesis is an environmentally sustainable approach for the preparation of nanoparticles using biological resources as alternatives to conventional chemical reagents. Plant materials, microorganisms, natural polymers, and agricultural products can provide bioactive constituents that participate in nanoparticle formation. Compared with conventional methods, biological synthesis can reduce the use of hazardous chemicals and provide a relatively simple, economical, and environmentally friendly route for nanoparticle preparation.

Plant-mediated nanoparticle synthesis is facilitated by naturally occurring biomolecules such as proteins, carbohydrates, amino acids, phenolic compounds, flavonoids, and other phytochemicals. These constituents can interact with metal ions and contribute to nucleation, particle growth, surface modification, and stabilization of the resulting nanoparticles. The nature and concentration of these biomolecules, together with the reaction conditions, can influence the structural and morphological characteristics of the synthesized material.

Triticum aestivum (wheat) is a readily available plant source containing various biological constituents, including starch, proteins, carbohydrates, amino acids, phenolic compounds, and minerals. These components make wheat-derived materials suitable for plant-assisted nanoparticle synthesis. The use of *Triticum aestivum* provides a renewable and economical biological source for the preparation of nanomaterials while reducing dependence on conventional chemical additives.

In the present study, *Triticum aestivum* powder was employed as a plant-derived component in the sol-gel-assisted synthesis of zinc ferrite ($ZnFe_2O_4$) nanoparticles. The synthesized material was subsequently characterized using XRD, FTIR, DSC, and SEM to investigate its crystalline, functional, thermal, and morphological properties. This approach was explored as a simple and sustainable route for the preparation of $ZnFe_2O_4$ nanoparticles.[16-20]

1.5 *Triticum aestivum* (Wheat) and Its Role in Nanoparticle Synthesis

Triticum aestivum, commonly referred to as wheat, is one of the most widely cultivated cereal grains and serves as a major source of nutrition worldwide. It contains a wide range of naturally occurring constituents, including starch, carbohydrates, proteins, amino acids, polysaccharides, vitamins, minerals, and phenolic compounds. Because of the abundance of these bioactive molecules, wheat has become an attractive biological material for the eco-friendly synthesis of nanoparticles.

In green nanoparticle synthesis, wheat-derived biomolecules play multiple roles during the formation process. Compounds such as starch, proteins, and polysaccharides act as natural reducing agents by converting metal ions into nanoparticles. At the same time, these biomolecules function as stabilizing and capping agents, preventing particle aggregation and improving the stability and biocompatibility of the synthesized nanomaterials.

The application of wheat in nanoparticle synthesis provides several benefits compared with conventional chemical methods. As a renewable, biodegradable, non-toxic, inexpensive, and readily available natural resource, wheat offers a sustainable alternative for nanoparticle production. Its utilization also minimizes the dependence on hazardous chemicals, making the synthesis process safer for both human health and the environment.

Numerous studies have demonstrated the successful use of wheat and its derivatives in the synthesis of metal and metal oxide nanoparticles. During the synthesis process, the phytochemicals and other bioactive constituents present in wheat interact with metal precursors, facilitating nanoparticle formation while influencing their size, morphology, crystallinity, and biological activity. These interactions contribute to the production of nanoparticles with improved physicochemical and functional properties.[21-23]

Figure 3: Morphological characteristics and field overview of green wheat (*Triticum aestivum*) at the spike development stage.

2 METHODS AND MATERIALS

Materials

Zinc sulphate ($ZnFe_2O_4$), ferric chloride, and citric acid ($C_6H_8O_7$) as the major materials involved in the synthesis process. *Triticum aestivum* (wheat powder) was used as a natural plant-derived material during the green sol–gel synthesis. All the chemicals and materials used in the experiment were of suitable analytical grade and were used without further purification. Distilled water was used as the solvent for the preparation of the reaction mixture. The materials used in the synthesis were zinc sulphate, ferric chloride, citric acid, and *Triticum aestivum* (wheat powder). other chemicals were obtained from Sigma-Aldrich., India. All other chemicals purchased were of analytical grade.

3. Green Synthesis of $ZnFe_2O_4$ Nanoparticles Using *Triticum aestivum* (Wheat) by the Sol–GelMethod

$ZnFe_2O_4$ nanoparticles were synthesized by the green sol–gel method using *Triticum aestivum* (wheat powder) as a natural reducing and stabilizing agent. Zinc sulphate and ferric chloride were used as the precursor materials for the synthesis. The required quantities of zinc sulphate and ferric chloride were dissolved in 100 mL of distilled water with continuous stirring until a homogeneous solution was obtained.

To the above solution, 15 g of citric acid was added gradually and stirred continuously until it dissolved completely. Citric acid acted as the chelating agent, facilitating the formation of a homogeneous sol by complexing the metal ions. Subsequently, a sufficient quantity (q.s.) of *Triticum aestivum* (wheat powder) was added to the reaction mixture with continuous stirring. The phytochemical constituents present in wheat powder assisted in the formation of the sol and promoted the green synthesis of $ZnFe_2O_4$ nanoparticles.

Continuous stirring resulted in the gradual conversion of the reaction mixture into a thick gel. The gel was shaped into a compact mass (ball) and allowed to dry under laboratory conditions.

The dried gel was transferred to a china dish and subjected to calcination in a muffle furnace at 700°C for 8 hours. During the calcination process, the gel initially converted into charcoal and, upon complete combustion of the organic constituents, formed a brown-coloured ash, indicating the formation of $ZnFe_2O_4$ nanoparticles.[24-30]

The obtained ash was washed thoroughly with distilled water to remove any remaining impurities. Finally, the washed material was dried in a hot air oven at 150°C for 1 hour to obtain a fine brown $ZnFe_2O_4$ nanoparticle powder. The synthesized powder was collected, stored in an airtight container, and used for further characterization by X-ray Diffraction (XRD) and Fourier Transform Infrared (FTIR) spectroscopy, followed by evaluation of its antibacterial activity.

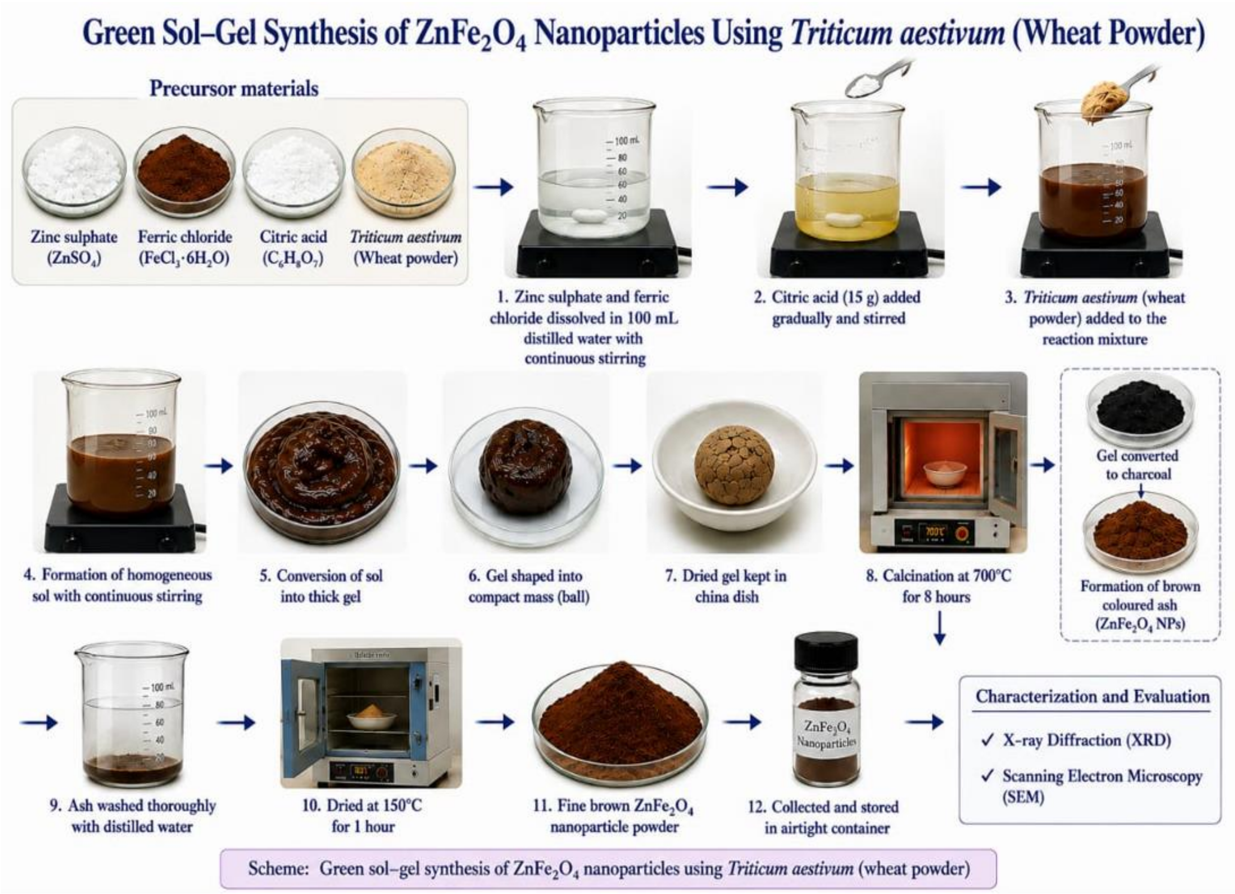

Figure 4: Experimental Procedure for the Green Sol–Gel Synthesis of Zinc Ferrite ($ZnFe_2O_4$) Nanoparticles.

4. Characterization

4.1 Surface Morphology by SEM

The surface morphology and microstructural characteristics of the synthesized $ZnFe_2O_4$ nanoparticles were examined using scanning electron microscopy (SEM). SEM analysis was performed to evaluate the particle morphology, surface characteristics, degree of agglomeration, and approximate particle-size distribution. The obtained micrographs provided information about the shape and arrangement of the synthesized $ZnFe_2O_4$ nanoparticles and their tendency to form aggregates.

4.2 X-ray diffraction (XRD)

The crystalline structure and phase characteristics of the synthesized $ZnFe_2O_4$ nanoparticles were investigated using X-ray diffraction (XRD). XRD analysis was performed to determine the crystalline nature, phase formation, and structural characteristics of the synthesized material. The obtained diffraction pattern was analysed based on the position and intensity of the characteristic diffraction peaks. The crystallite size can also be estimated from the full width at half maximum (FWHM) of the prominent diffraction peak using the Scherrer equation. The XRD results provide important information regarding the formation and crystalline characteristics of the synthesized $ZnFe_2O_4$ nanoparticles.[31-35]

5. RESULTS AND DISCUSSION

5.1 Scanning electron Microscopy

The SEM micrographs of the synthesized $ZnFe_2O_4$ nanoparticles at 20.00 kX magnification (scale bar: 1 µm) revealed an irregular, highly agglomerated and porous morphology. Fine particles in the range of approximately 100–300 nm were observed along with larger fused structures. Well-defined faceted, octahedral-like crystalline structures measuring approximately 4–5 µm were also evident. The observed particle agglomeration and neck formation may be attributed to particle growth and sintering during calcination. Overall, the SEM images demonstrate a heterogeneous morphology with both fine particles and larger crystalline aggregates.

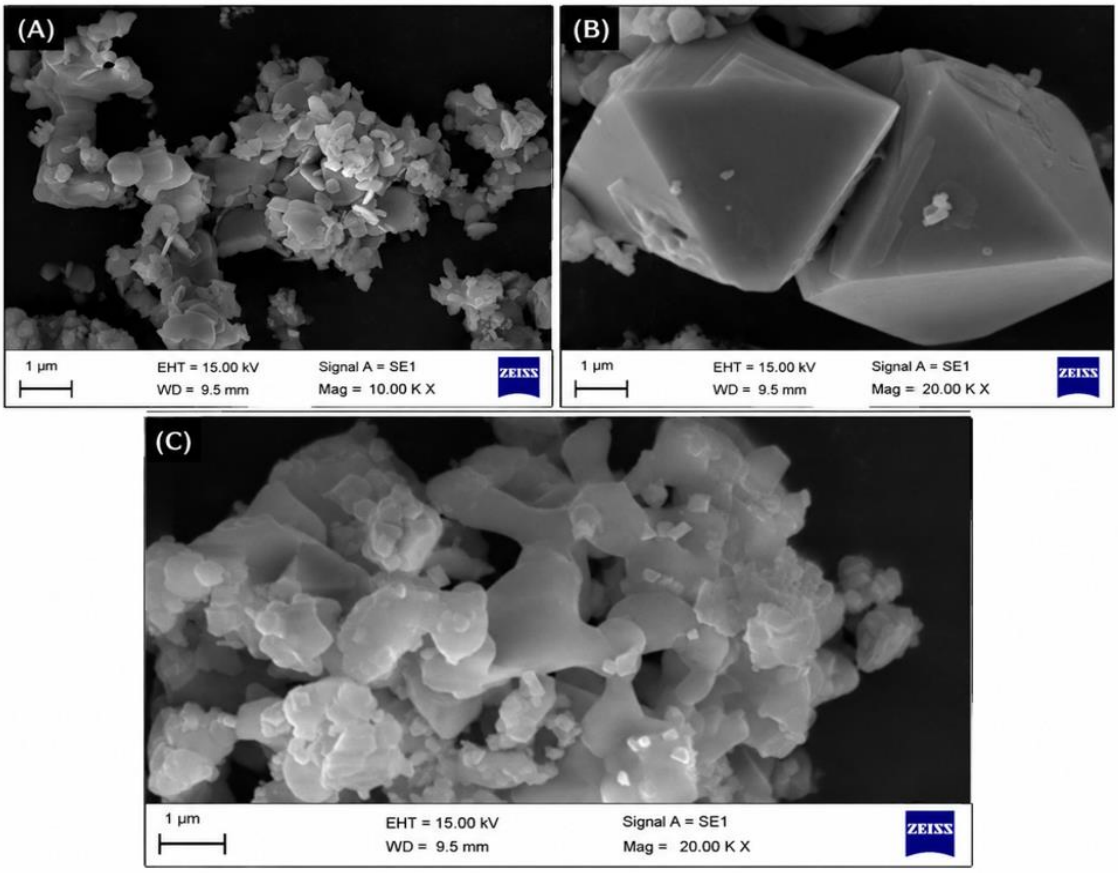

Figure 5: SEM micrographs of green synthesized $ZnFe_2O_4$ nanoparticles.

5.2 X-Ray Diffraction (XRD)

The XRD pattern of the synthesized $ZnFe_2O_4$ nanoparticles exhibited several sharp and distinct diffraction peaks, indicating the crystalline nature of the synthesized material (Figure 6). The maximum diffraction intensity was approximately 2200 counts. The observed diffraction pattern suggests the formation of a crystalline $ZnFe_2O_4$ phase. However, definitive confirmation of the crystal phase and phase purity requires comparison of the observed diffraction peaks with standard JCPDS/ICDD reference data. The crystallite size was not determined in the present study due to the unavailability of the required FWHM values. Overall, the XRD findings confirm the crystalline nature of the synthesized $ZnFe_2O_4$ nanoparticles.

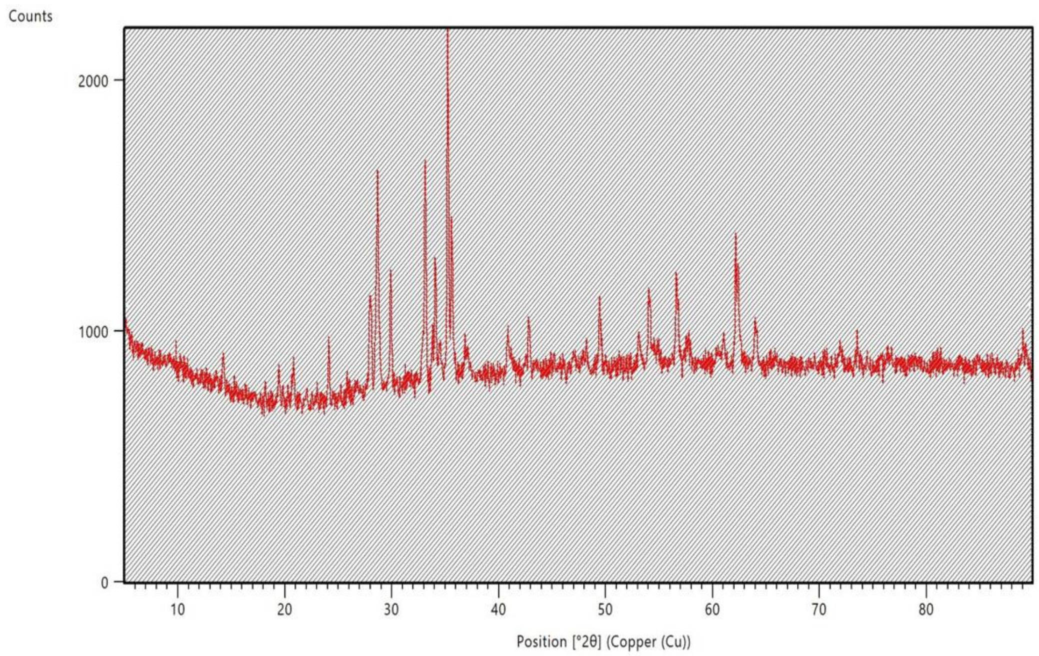

Figure 6: XRD Spectrum of Synthesized $ZnFe_2O_4$ nanoparticles.

6. CONCLUSION

The present study successfully demonstrated a green sol–gel-assisted approach for the synthesis of $ZnFe_2O_4$ nanoparticles using *Triticum aestivum* (wheat) as a plant-derived material. The synthesized product was subjected to physicochemical characterization using SEM and XRD. SEM analysis revealed an irregular, agglomerated and porous morphology, with fine particles and larger faceted crystalline structures. XRD analysis showed several sharp and distinct diffraction peaks, confirming the crystalline nature of the synthesized material. The findings indicate that *Triticum aestivum* can be utilized as a readily available and economical biological material for the preparation of $ZnFe_2O_4$ nanoparticles. Overall, the study provides a simple and environmentally sustainable approach for the synthesis of zinc ferrite nanoparticles and establishes their preliminary structural and morphological characteristics. Further studies involving detailed phase identification, crystallite-size determination, elemental analysis, and additional physicochemical and biological evaluations are recommended to establish their potential pharmaceutical and biomedical applications.

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