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Research Article

Advancing Green Nanotechnology: Harnessing the Bio-reducing Properties of *Musa paradisiaca* Peel Extract for Sustainable Synthesis of Iron Oxide Nanoparticles

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Abstract
A green synthesis method utilizing *Musa paradisiaca* peel extract as a reducing and stabilizing agent was employed to produce iron oxide nanoparticles. The synthesized nanoparticles were extensively characterized using FTIR, XRD, DLS, SEM, EDX, and TEM techniques. FTIR analysis confirmed the presence of iron metal and functional groups derived from the peel extract. XRD results indicated the presence of magnetite (Fe_3O_4) and/or maghemite (γ-Fe_2O_3) phases, signifying a high degree of crystallinity. DLS analysis provided valuable insights into the size distribution and polydispersity of the nanoparticles, revealing an average particle diameter of 43.35 nm and a polydispersity index of 0.612. SEM examination uncovered the presence of aggregated formations, where irregularly shaped nanoparticles exhibited either close packing or loose association, resulting in the formation of larger aggregates. These environmentally friendly iron oxide nanoparticles could potentially hold great promise for a variety of biological applications, including the potential for drug delivery and antimicrobial applications.

Keywords: Iron oxide, nanoparticles, green approach, *Musa paradisiaca* peel

1. INTRODUCTION

The progress of scientific research in transitioning from studying microscopic subjects to exploring nanoscopic structures has gained significant momentum, thanks to the integration of scientific and technological advancements [1][2]. The manufacturing of nanostructures, which encompasses factors such as shape, size, porosity, chemical content, and other characteristics, within the nanoscale range of 1–100 nm, plays a crucial role in our life [3]-[5]. Nanostructures find extensive applications across diverse fields such as electrical instruments, engineering, environmental sciences, architecture, and various medicinal and biological domains [6][7].

Metal oxide nanoparticles have garnered significant attention among the various types of nanomaterials due to their distinctive characteristics, including (i) the ability to modify lattice symmetry and cell parameters, allowing for structural modifications; (ii) the alteration of electrochemical properties caused by the quantum confinement effect; and (iii) the changes to surface properties leading to a notable increase in the band gap [8]. Among these metal oxide nanoparticles, iron oxides stand out as highly biocompatible nanoparticles, primarily due to their exceptionally small physical properties such as super-paramagnetism, stability in liquid solutions, low susceptibility to oxidation, and adaptable surface chemistry [9][10]. Iron oxides find a wide range of applications including antibiotic degradation, dye adsorption, food processing, drug delivery, magnetic cell sorting, MRI, magnetic particle imaging, immunoassays, tissue engineering, stem cell tracking, hyperthermia treatment of cancer, bioengineering, cosmetics, biosensing, and antimicrobial activity against various pathogens such as fungi, bacteria, and viruses [11].

A multitude of metal and metal oxide nanoparticles have been synthesized through various chemical methods [12][13]. However, the utilization of such techniques raises concerns regarding toxicity and the potential generation of hazardous byproducts [14]. As a result, there is growing interest in exploring a "green technique" for nanoparticle synthesis, which offers a simple and economical alternative. Green synthesis of

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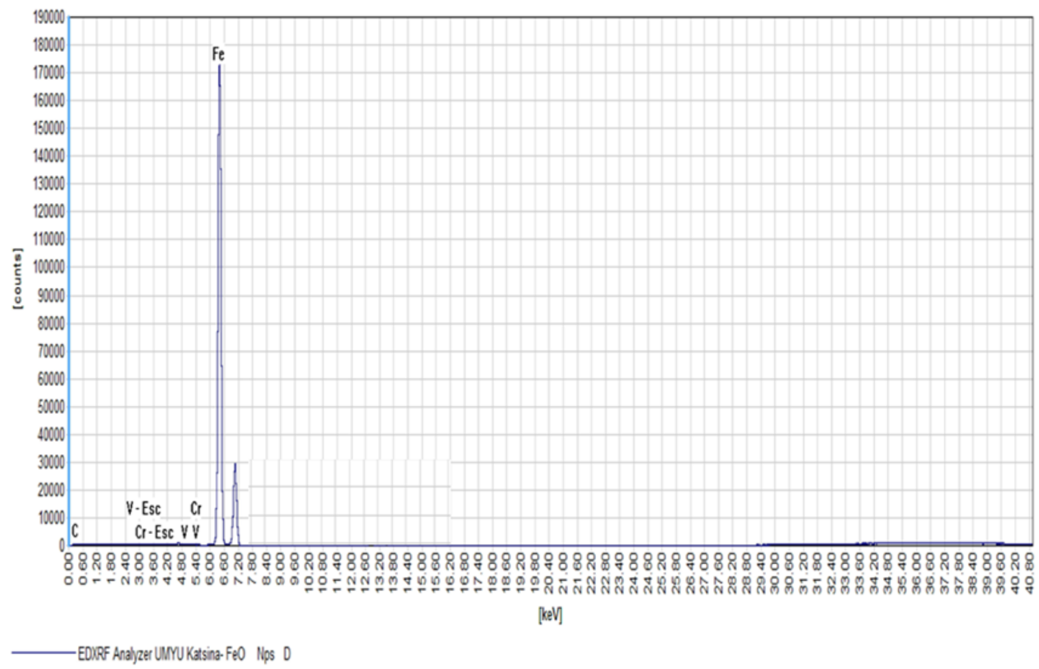

Figure 1. XRF spectra of iron oxide nanoparticles synthesized using *M. paradisiaca* peel extract.

nanoparticles is advantageous over chemical synthesis due to its cost-effectiveness, reduced toxicity, low production costs, labor efficiency, and greater stability [15].

As per a report, waste derived from plant-based sources, including *Musa paradisiaca* peel, fruit peel, and vegetables, is primarily categorized as low or no-value waste [16]. Only 5% of this waste is reportedly converted into compost, while the remaining portion ends up in landfills as refuse [16]. Consequently, this leads to the emission of unpleasant odors, as well as creating an unhealthy environment for market vendors and the surrounding areas. It is imperative to address the proper management of plant-based waste. One potential solution involves utilizing plant extracts, which are abundant and cost-effective sources of phytochemicals rich in polyphenols, such as terpenoids, phenolic acids, flavonoids, and ferulic acid. These compounds facilitate the reduction and synthesis of nanoparticles with exceptional stability [6]. The use of plant extracts also reduces the reliance on toxic reducing chemicals, thereby offering a more environmentally friendly approach [17].

Previous investigations have successfully utilized plant extracts from various sources to synthesize iron oxide nanoparticles [18]-[20]. However, there has been limited research exploring the utilization of *M. paradisiaca peel* extract specifically for this purpose. Thus, this study focused on the synthesis of iron oxide nanoparticles using *M. paradisiaca* peel extract as both a reducing and stabilizing agent. The nanoparticles were extensively characterized to understand their properties. This approach combined sustainable synthesis methods, capitalizing on the unique properties of iron oxide nanoparticles, and harnessing the phytochemical constituents present in *M. paradisiaca* peel extract. The research opens up possibilities for diverse applications in different fields while also emphasizing resource utilization and waste management.

2. MATERIALS AND METHODS

2.1. Chemicals

Analytical grade iron(II) sulfate heptahydrate ($FeSO_4 \cdot 7H_2O$) and sodium acetate ($NaC_2H_3O_2$) were purchased from Sigma Aldrich. All the chemicals were used without further purification.

2.2. Methods

2.2.1. Collection and Preparation of Plant Extract

The *M. paradisiaca* bunches were purchased from an outdoor market in Benin City, Edo State, Nigeria, and the peels were then collected. The *M.*

paradisiaca peels were properly cleaned with distilled water to get rid of any dirt particles. The peels were dried for about 14 d at ambient temperature and in a dust-free environment. The dried peels were crushed, and 10 g of the crushed peels were transferred to a round bottom flask that contained 200 mL of distilled water. With vigorous stirring, the mixture was refluxed for 60 minutes at 80 °C. The resultant extract, which was yellow in color, was filtered, cooled to ambient temperature, and then stored at 4 °C.

2.2.2. Green Synthesis of Iron Oxide Nanoparticles

The iron oxide nanoparticles were synthesized through an eco-friendly approach from *M. paradisiaca* peels as reported by a published procedure with slight modifications [21]. In a typical experiment, 2.16 g of $FeSO_4 \cdot 7H_2O$ and 6.56 g of $NaC_2H_3O_2$ were dispersed into a beaker containing 40 mL of *M. paradisiaca* peel extract solution with vigorous stirring for 2 h at 70 °C. After 2 h, a homogeneous dark reddish-brown color formed, providing confirmation of the presence of iron oxide nanoparticles. The resultant mixture was then cooled to room temperature. The synthesized product was purified by using a centrifuge machine, neutralized with distilled water/ethanol, and dried in a vacuum oven for 12 h at 90 °C.

2.2.3. Characterization Techniques

The comprehensive analysis of the synthesized iron oxide nanoparticles involved an array of sophisticated characterization techniques, each contributing to a holistic comprehension of their properties and potential applications. Fourier transform infrared (FTIR) spectroscopy, for instance, played a pivotal role in unveiling the molecular intricacies of the synthesized iron oxide nanoparticles. In this process, potassium bromide (KBr) was used to create pellets, allowing us to identify specific functional groups by scrutinizing the characteristic absorption bands in the FTIR spectrum. This approach facilitated the identification of molecular structures and chemical bonds, shedding light on the composition of the nanoparticles. Transitioning to microscopy techniques, both transmission electron microscopy (TEM) and scanning electron microscope (SEM) played integral roles in unravelling the morphological aspects of the nanoparticles. TEM provided high-resolution images, unravelling internal microstructure, particle size distribution, and morphology. Conversely, SEM offered a broader perspective on surface features. This twofold approach provided a comprehensive understanding of the nanoparticles' physical attributes. Dynamic light scattering (DLS) was instrumental in deciphering the nanoparticles' traits within the solution. By analyzing the scattered light, DLS offered insights into surface charge, average particle diameter, and the polydispersity index (PDI). This data critically contributed to assessing the nanoparticles' stability and uniformity when suspended. Turning to elemental insights, energy dispersive spectroscopy (EDS) was employed to shed light on the chemical composition. By measuring X-ray emissions generated from interactions between the nanoparticles and an

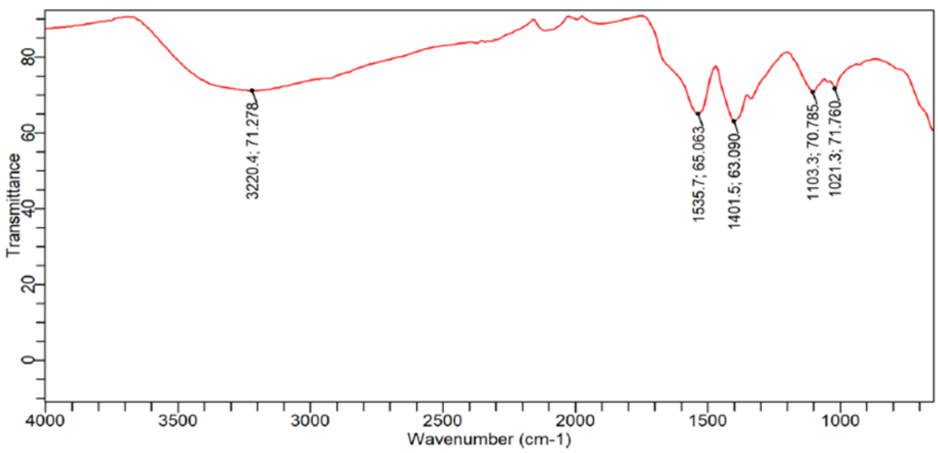

Figure 2. The FTIR spectrum of the synthesized *M. paradisiaca* peel based-iron oxide nanoparticles.

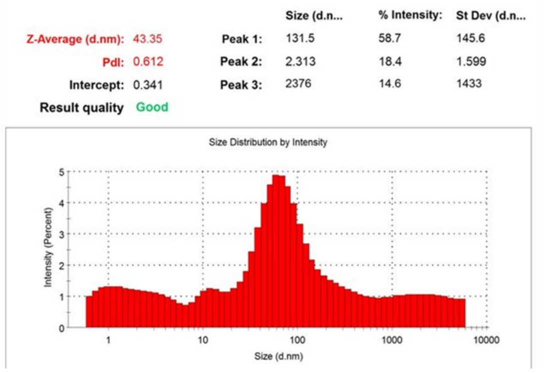

Figure 3. DLS analysis of iron oxide nanoparticles synthesized using *M. paradisiaca* peels.

electron beam, XRF provided a detailed understanding of the elemental constituents. This analysis greatly facilitated insights into the chemical properties of the nanoparticles. Finally, the X-ray diffraction (XRD) analysis proved pivotal in unravelling the nanoparticles' crystalline structure. By interpreting diffraction patterns resulting from X-ray interactions, this technique offered invaluable insights into crystal phases, lattice parameters, and overall crystallinity. This understanding was paramount in evaluating the nanoparticles' structural attributes. Together, these advanced characterization techniques formed a coherent tapestry of analysis, allowing us to comprehensively explore the synthesized iron oxide nanoparticles across various dimensions. This detailed investigation encompassed functional groups, morphology, surface characteristics, elemental composition, and crystalline structure. This multidimensional understanding lays a robust foundation for discerning the nanoparticles' potential applications and behavior in diverse scenarios.

3. RESULTS AND DISCUSSIONS

3.1. The Potential of Utilizing M. paradisiaca Peel Extract as a Bio-reducing Agent in the Sustainable Synthesis of Iron Oxide Nanoparticles

Due to its abundant bioactive compounds including phenolic compounds, flavonoids, tannins, and alkaloids, *M. paradisiaca* peel extract has shown promise as a bioreducing agent for the eco-friendly production of iron oxide nanoparticles [22][23]. These bioactive compounds possess both reducing and stabilizing properties, enabling them to donate electrons to iron ions and facilitate their conversion into nanoparticles [24]. These compounds act as green reducing agents, eliminating the need for toxic or hazardous chemicals commonly used in conventional synthesis methods [25][26].

Furthermore, the bioactive compounds in *M. paradisiaca* peel extract also contribute to the stabilization of the synthesized iron oxide nanoparticles [27][28]. Through electrostatic or steric interactions, these compounds form a protective layer on the nanoparticle surface, preventing their agglomeration and ensuring their stability [29][30]. In addition to their reducing and stabilizing properties, the bioactive compounds in *M. paradisiaca* peel extract can act as chelating agents for iron ions. By forming complexes with iron ions, these compounds enhance the reduction efficiency and prevent the precipitation of nanoparticles [31].

The antioxidant activity of *M. paradisiaca* peel extract is another important aspect that aids in the green synthesis of iron oxide NPs. Phenolic compounds present in the extract exhibit strong antioxidant properties, scavenging free radicals and preventing the oxidation of nanoparticles [31][32]. This antioxidant activity ensured the quality and stability of the synthesized iron oxide nanoparticles. Moreover, the use of *M. paradisiaca* peel extract as a bioreducing agent aligned with the principles of green chemistry. It is derived from a natural and renewable source, making it an eco-friendly alternative to conventional reducing agents [33]. This biocompatibility of the extract opened up potential applications of the synthesized iron oxide nanoparticles in various fields, including biomedicine, catalysis, and environmental remediation [34][35]. While these studies provide insights into the potential mechanistic role of *M. paradisiaca* peel extract in the green synthesis of iron oxide nanoparticles, it is important to note that further research is needed to fully understand the underlying mechanisms and optimize the synthesis process.

3.2. The Elemental Composition of the Iron Oxide Nanoparticles Synthesized Using Green M. paradisiaca peel Extract

The XRF analysis of the green *M. paradisiaca* peel extract-synthesized iron oxide nanoparticles revealed the presence of iron content. This analytical technique is widely used for elemental analysis and provides valuable information about the composition of materials. By subjecting the synthesized nanoparticles to XRF analysis, the specific characteristic X-ray emissions associated with iron were detected and quantified. This analysis confirmed the successful incorporation of iron within as the dominant peak (Figure 1). The XRF analysis provides important insights into the composition of the nanoparticles, further supporting the validity of the biosynthesis process using green *M. paradisiaca* peel extract.

Furthermore, the negligible presence of impurities in the nanoparticles suggests the effectiveness of the *M. paradisiaca* peel extract in providing a clean synthesis environment. The reducing and stabilizing agents present in the extract likely contributed to the prevention of impurity formation during nanoparticle synthesis. These agents might have acted as chelating agents, selectively binding to impurities, and preventing their incorporation into the growing nanoparticles.

3.3. The Analysis of Functional Groups in The Synthesized Iron Oxide Nanoparticles Using M. paradisiaca peel Extract

Figure 2 illustrates the FTIR spectrum of the iron oxide nanoparticles synthesized utilizing *M. paradisiaca* peel extract. The FTIR spectrum of the iron oxide nanoparticles revealed characteristic absorption peaks that correspond to specific vibrational modes of various functional groups [36]-[38]. For example, the presence of broad absorption bands of 3220.4 cm^{-1} can be attributed to the stretching vibrations of hydroxyl groups (-OH) present in phenolic compounds and flavonoids within the *M. paradisiaca* peel extract. These hydroxyl groups are known to contribute to the reducing and stabilizing properties of the extract during the nanoparticle synthesis. Furthermore, the appearance of absorption peaks in the range of 1535.7-1401.5 cm^{-1} indicates the presence of carbonyl groups (C=O) associated with organic compounds present in the extract. These organic compounds, such as polysaccharides and proteins, may have participated in the formation and stabilization of the iron oxide nanoparticles [36]-[38]. The FTIR analysis also revealed the presence of absorption bands in the fingerprint region, which provided information about the specific bonds and functional groups in the nanoparticles. These bands can be attributed to vibrations of metal-oxygen (M–O) bonds, characteristic of iron oxide nanoparticles [36]-[38].

In general, the FTIR analysis of *M. paradisiaca* peel extract-based iron oxide nanoparticles elucidated the involvement of various functional groups and molecular interactions in the synthesis process, highlighting the role of the *M. paradisiaca* peel extract as a reducing and stabilizing agent.

3.4. The Particle Size and PDI of the Iron Oxide Nanoparticles Synthesized Using M. paradisiaca peel Extract

Figure 3 shows the results of the DLS analysis performed on iron oxide nanoparticles synthesized with *M. paradisiaca* peels. DLS analysis of *M. paradisiaca* peel extract-based iron oxide nanoparticles with an average particle diameter of 43.35 nm and a PDI value of 0.612 provided important insights into the size distribution and polydispersity of the nanoparticles. DLS is a widely used technique for characterizing the size of nanoparticles in solution by measuring the intensity fluctuations of scattered light caused by Brownian motion. The obtained average particle diameter of 43.35 nm suggests the mean size of the nanoparticles in the sample. The nanoparticles are likely to be predominantly around this size. However, the polydispersity index of 0.612 indicates that there is a range of particle sizes

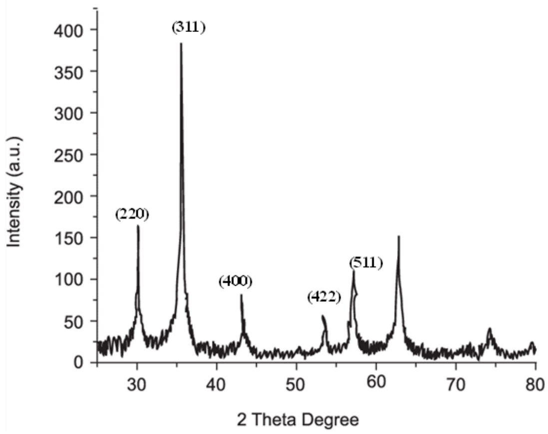

Figure 4. The XRD spectrum of the synthesized *M. paradisiaca* peel based-iron oxide nanoparticles.

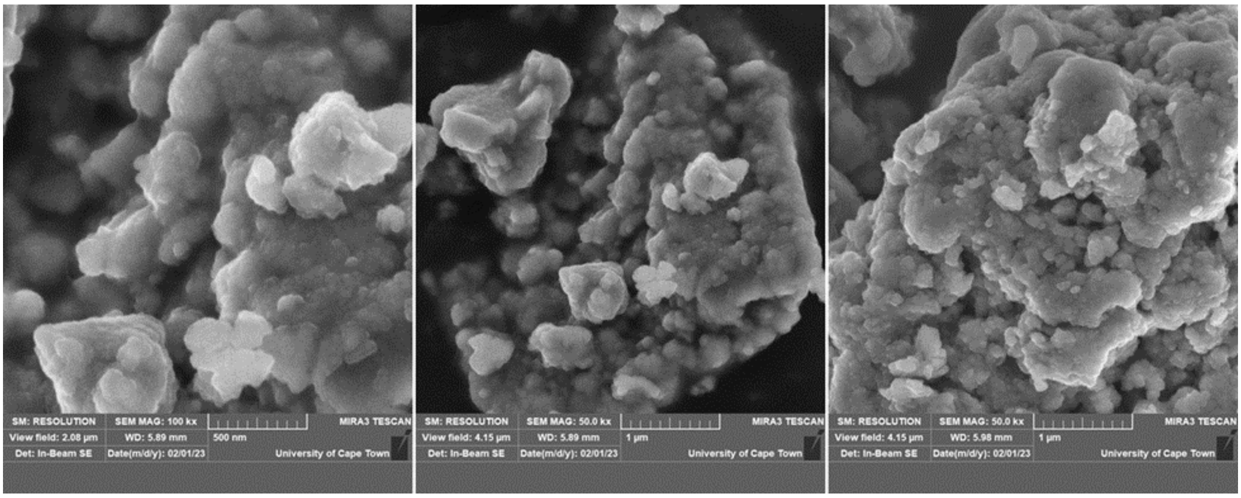

Figure 5. SEM micrographs of iron oxide nanoparticles synthesized using *M. paradisiaca* peel extract.

within the sample.

Comparing these results with other related studies, it is important to note that each synthesis method and extract used may yield different results. For instance, the synthesis of iron oxide nanoparticles using different plant extracts was investigated in a previous study [39]. Their findings revealed variations in particle sizes and PDI depending on the plant extract used. Additionally, another study focused on the synthesis of iron oxide nanoparticles using fruit peel extracts [40][41]. They reported similar DLS analysis results, with average particle sizes ranging from 30 to 60 nm and PDI indicating polydispersed samples.

Comparisons across studies highlighted the influence of different plant extracts and synthesis methods on the particle size and polydispersity of iron oxide nanoparticles. While the average particle diameter of 43.35 nm and PDI of 0.612 in the *M. paradisiaca* peel extract-based nanoparticles obtained in this study indicated a specific size range and moderate polydispersity, it is essential to consider these factors when evaluating the nanoparticles' properties and potential applications.

The utilization of *M. paradisiaca* peel extract in synthesizing iron oxide nanoparticles offers great promise for diverse applications, including biomedicine, magnetic resonance imaging, catalysis, and environmental remediation, among others. This potential is attributed to the nanoparticles' average particle diameter of 43.35 nm and a PDI of 0.612 [42]-[48]. The specific values of particle size and PDI are crucial factors that can impact their efficacy in various fields.

It is important to note that while the polydisperse nature of the nanoparticles can offer advantages in certain applications, it may also introduce variability in their performance. Further research and optimization are necessary to understand and harness the potential benefits of polydispersity in specific applications.

3.5. The XRD Spectrum of the Iron Oxide Nanoparticles Synthesized with M. paradisiaca Peel Extract

Figure 4 illustrates the XRD spectrum of the iron oxide nanoparticles synthesized using *M. paradisiaca* peel extract. The XRD spectrum of *M. paradisiaca* peel extract-based iron oxide nanoparticles provided valuable information about their crystal structure and phase composition. The XRD pattern revealed distinct diffraction peaks that correspond to specific crystal planes and lattice spacings of the nanoparticles. By analyzing the positions and intensities of these peaks, it is possible to determine the crystal structure and phase of the synthesized nanoparticles [49]. The appearance of diffraction peaks at characteristic angles, such as 2θ = 30°, 35°, 43°, 53°, and 57°, can be attributed to the presence of iron oxide phases, such as magnetite (Fe_3O_4) and/or maghemite (γ-Fe_2O_3), in the nanoparticle sizes [49]. These peaks corresponded to the (220), (311), (400), (422), and (511) crystal planes, respectively, which are commonly observed in iron oxide materials. The broadening and shape of the diffraction peaks provide insights into the particle size and crystallinity of the nanoparticles. A broader peak indicates smaller particle size, while a sharper peak suggests larger particles or higher crystallinity [50]. The observed aggregated formations in SEM images (Figure 4) can be linked to the crystalline arrangement and orientation of nanoparticles within these aggregates. The extent of aggregation might impact the preferred orientations of crystal planes, influencing the intensity of the corresponding XRD peaks. Additionally, the size distribution within aggregates could lead to shifts in peak positions due to size-related effects. The presence of any additional peaks or shifts in the XRD spectrum can indicate the presence of impurities or the formation of secondary phases during the nanoparticle synthesis.

3.6. Morphological Analysis of the M. paradisiaca Peel Extract Based-Iron Oxide Nanoparticles

The morphological analysis of the *M. paradisiaca* peel extract-based iron oxide nanoparticles revealed their size, shape, and surface characteristics. This analysis provided valuable insights into the synthesis process and aids in understanding the potential applications of these nanoparticles. Figure 5 depicts SEM showcasing iron oxide nanoparticles that were synthesized utilizing extract from M. paradisiaca peels. The SEM examination unveiled the existence of aggregated formations, where the irregularly shaped nanoparticles exhibited either close packing or loose association with each other, resulting in the formation of larger aggregates. These irregularities are likely attributed to factors such as synthesis conditions, crystal growth dynamics, and surface interactions during nanoparticle formation [51]. The nanoparticles within the clusters exhibited variations in size, resulting in a distribution of particle sizes. Some nanoparticles appeared larger, while others were smaller, indicating a polydisperse nature. This finding aligned with the DLS result depicted in Figure 3. The size range and distribution provided insights into the synthesis method and the control of particle growth [52]. Moreover, the clustered morphology resulted in a porous structure with voids or gaps between individual nanoparticles. This porosity can have implications for applications such as catalysis and drug delivery [53]. Additionally, the surface of the nanoparticles and clusters exhibited roughness, likely due to variations in particle size and shape.

The presence of clustered nanoparticles suggests the existence of interparticle interactions. Van der Waals forces, magnetic interactions, or electrostatic forces may be responsible for holding the nanoparticles together within the clusters [54]. Understanding these interactions is crucial for controlling aggregation behavior and achieving desired dispersibility.

The presence of irregularly shaped aggregated formations in the synthesized iron oxide nanoparticles, characterized by both close packing and loose association, presents substantial potential for a wide range of applications. These unique configurations offer exciting possibilities for harnessing the properties of the nanoparticles in diverse scientific and technological domains. The formation of larger aggregates contributes to unique properties and characteristics that can be utilized in different fields. These aggregated formations offer new opportunities for the application of iron oxide nanoparticles, leveraging their specific structural arrangements to enhance performance and functionality in diverse scientific and technological domains. For example, in the field of biomedical engineering, these aggregated formations have been utilized in targeted drug delivery systems due to their ability to form stable carriers for therapeutic agents [55]. Similarly, in the field of environmental remediation, the unique structural arrangements of these nanoparticles have been employed in the removal of heavy metals from contaminated water sources of the aggregated nanoparticles have been harnessed to enhance the efficiency of catalytic reactions [50][56].

4. CONCLUSIONS

This study successfully demonstrated the green synthesis of iron oxide nanoparticles using *M. paradisiaca peel* extract as a reducing and stabilizing agent. The comprehensive characterization of the synthesized nanoparticles provided a profound understanding of their properties. The analysis of functional groups revealed that the peel extract served as a capping agent for the nanoparticles, potentially contributing to their increased stability. The synthesized samples exhibited highly crystalline magnetite and/or maghemite phases, indicating the formation of structurally well-defined nanoparticles. The average particle diameter of 43.35 nm and a PDI of 0.612 indicated a relatively uniform size distribution with moderate dispersity for the synthesized nanoparticles. Additionally, morphological examination revealed the formation of larger aggregates, attributed to the irregular shape of the nanoparticles. These environmentally friendly iron oxide nanoparticles exhibit immense potential for various applications, particularly in the fields of drug delivery and antimicrobial agents. The green synthesis approach utilizing *M. paradisiaca* peel extract not only offers a sustainable and eco-friendly production method but also opens up new avenues for the development of functional nanoparticles in diverse scientific and technological domains.

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Conflicts of Interest

The author(s) declare no conflict of interest.

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