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CIRCULAR ECONOMY IN ACTION: HIGH-PURITY NANOPARTICLES VIA WASTE VALORIZATION

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ABSTRACT

This research successfully presents a sustainable and eco-friendly method for synthesizing iron oxide nanoparticles (IONPs) using agricultural waste as a resource. The innovative approach utilizes the biochemical properties of agricultural by-products to achieve the production of high-purity, uniformly sized nanoparticles, which are poised to have vast implications across a multitude of applications. This study addresses the growing demand for green chemistry practices, showcasing how nanotechnology can align with environmental sustainability goals. The method outlined demonstrates the dual benefit of waste valorization and advanced material synthesis, turning agricultural residues into valuable raw materials for nanoscience. The resultant nanoparticles exhibit superior characteristics, such as consistent particle size distribution and high purity, making them suitable for use in areas like medicine, energy storage, catalysis, and environmental remediation. This study emphasizes the pressing need to adopt sustainable practices in technological advancements, with a focus on minimizing the environmental footprint of scientific processes. The use of agricultural waste not only promotes the reduction of waste accumulation but also aligns with circular economy principles by repurposing otherwise discarded materials. The findings also underline the importance of integrating renewable resources in nanotechnology innovations. Future directions for this research include further optimization of the synthesis process to maximize nanoparticle yield while maintaining quality. Advanced characterization techniques will be employed to refine the properties of the synthesized IONPs. Additionally, future investigations will expand on the exploration of practical applications, assessing the efficacy and performance of the nanoparticles in real-world scenarios such as targeted drug delivery, water purification, and advanced battery technologies. This study serves as a beacon for interdisciplinary collaboration, bridging the domains of green chemistry, material science, and environmental engineering. The insights gained extend beyond the immediate scope of iron oxide nanoparticles, offering a framework that can be replicated for other nanomaterials. This holistic approach to sustainable development highlights the potential for nanotechnology to provide innovative solutions to some of the most pressing environmental challenges of our time. By demonstrating the feasibility of using agricultural waste in high-tech applications, this research not only contributes to the growing body of knowledge in green nanotechnology but also inspires a shift toward more sustainable scientific methodologies. The integration of eco-friendly practices with cutting-edge technology has the potential to redefine the future of nanoscience, ensuring a more sustainable and environmentally conscious pathway forward.

Keywords: Sustainability, Nanotechnology, Iron Oxide Nanoparticles (IONPS), Agricultural Waste, Green Chemistry, Circular Economy, Environmental Remediation, Waste Valorization

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1. INTRODUCTION

The utilization of agricultural waste for synthesizing iron oxide nanoparticles (IONPs) marks a revolutionary and eco-conscious leap in the realm of nanotechnology. In an era where environmental concerns are paramount, there is a growing emphasis on sustainable and green chemistry practices for producing essential materials across diverse applications (Kaleem, M et al 2023). Conventional nanoparticle synthesis often relies on hazardous chemicals and energy-intensive processes, resulting in detrimental ecological consequences. (Abdullah, J. et al 2023). In contrast, the bio-synthesis of IONPs using agricultural waste not only mitigates these environmental challenges but also presents a creative solution to waste management. Agricultural by-products, often discarded as waste, can be repurposed as natural reducing and stabilizing agents in the liquid-phase synthesis of IONPs. (Zúñiga et al.2023)This sustainable method not only transforms unwanted agricultural residues into valuable resources but also aligns with the principles of green chemistry by minimizing reliance on harmful chemicals and reducing energy consumption during production (Panneerselvam, C et al 2024).

This innovative approach demonstrates the potential of agricultural waste to generate high-purity, uniformly sized IONPs, proving its feasibility as a practical, eco-conscious alternative to conventional methods (Abid, M. A et al 2021). By utilizing agricultural by-products, the nanoparticle synthesis process becomes inherently more environmentally friendly, contributing to waste valorization and supporting the concept of a circular economy (Abu-Serie, M. M et al 2022). The resulting IONPs have versatile applications, ranging from medicine to environmental remediation and electronic devices (Selvaraj, R, et al 2022). The benefits of this process are manifold. Beyond reducing environmental harm and providing a cleaner synthesis method, the use of agricultural waste addresses critical waste management issues by repurposing by-products that would otherwise contribute to pollution (Dowlath, M. J. H et al 2021). Agricultural residues possess natural properties that make them effective in nanoparticle synthesis, providing a low-cost, efficient, and sustainable pathway for producing high-quality materials (Kiwumulo, H. et al 2022).

As the global demand for eco-friendly technologies rises, adopting agricultural waste as a resource for nanoparticle synthesis marks a significant stride in advancing sustainable practices in nanotechnology (Yassin, M. T et al 2023). This approach not only addresses pressing environmental challenges but also contributes to the development of greener technologies, fostering innovation while safeguarding the planet. Furthermore, the versatility and eco-conscious appeal of this method underscore its potential to serve as a model for other sustainable technologies (Soltys, L, et al 2021). By transforming agricultural waste into high-value nanoparticles, this method exemplifies the principles of waste valorization and sustainability. It highlights the transformative power of innovative thinking in tackling two critical challenges—waste management and environmental impact reduction (Ndou, N et al 2023). As industries seek cleaner and more efficient ways to produce essential materials, methods like this will play a key role in driving the next generation of environmentally responsible technologies (Awais, S et al 2023). This advancement not only holds promise for nanotechnology but also sets a precedent for incorporating sustainability at the heart of scientific innovation.

The central hypothesis of this research is that agricultural waste materials such as rice husk, sugarcane bagasse, and banana peels can effectively function as reducing and stabilizing agents in the liquid phase synthesis of iron oxide nanoparticles (IONPS) (Aida et al 2023). This method aims to produce high-purity nanoparticles that prevent agglomeration and maintain uniform size. Moreover, it is hypothesized that this environmentally friendly approach will surpass traditional chemical synthesis methods in terms of sustainability and waste valorization (Khadka, D et al 2024). The synthesized iron oxide nanoparticles (IONPs) exhibit immense potential across a wide range of applications, reflecting the versatility and effectiveness of this green synthesis approach. A prominent application lies in drug delivery systems, where IONPs can act as carriers for targeted drug delivery (Saleem, S, et al 2022). This enhances the therapeutic impact of drugs while minimizing side effects, ultimately leading to improved patient outcomes. Additionally, IONPs play a vital role in magnetic resonance imaging (MRI) due to their magnetic properties. They serve as efficient contrast agents, significantly improving image clarity and aiding in accurate medical diagnoses. In cancer treatment, IONPs are utilized in hyperthermia therapy to selectively heat and destroy cancer cells, leaving healthy tissue unharmed. This non-invasive treatment option offers a promising alternative in oncology. IONPs are also highly beneficial in environmental applications, particularly in wastewater treatment. Their high surface area and reactivity make them effective in removing contaminants and pollutants from wastewater, contributing to cleaner and safer water resources. Furthermore, IONPs function as catalysts in various chemical reactions, including the Suzuki reaction, Friedel-Knorr reaction, thiolysis of epoxides, and dehydrogenation of ethylbenzene (Isik, Z et al 2022). They also support the synthesis of heterocycles, α-aminonitriles, sulphonamides, and quinoxalines, enhancing the efficiency and yield of these processes. Industrially, IONPs find applications in sectors such as plastics, steel, paint, and cosmetics, highlighting their economic significance. In agriculture, they can be employed as iron fertilizers to improve soil nutrient content, fostering plant growth and productivity (Yassin, M. T et al 2024). This not only supports sustainable farming practices but also addresses nutrient deficiencies in agricultural soils (Priya, N, et al 2021). The hypothesis driving this research emphasizes the transformative potential of agricultural waste in producing eco-friendly IONPs. By utilizing the natural reducing and stabilizing properties of agricultural by-products, this method provides an environmentally sustainable alternative to traditional chemical synthesis. It promotes waste valorization, reduces environmental impacts, and aligns with principles of green chemistry (Selvaraj, R, et al 2022). The broad array of applications for synthesized IONPs underscores their adaptability and far-reaching impact. From healthcare and environmental remediation to industrial and agricultural advancements, this innovative approach exemplifies the possibilities of sustainable technologies to reshape various industries while fostering environmental stewardship.

2. RESEARCH AND METHODOLOGY

The research methodology encompasses several critical steps, from the collection of agricultural waste to the characterization of the synthesized nanoparticles. The process is designed to leverage the biochemical properties of agricultural by-products, ensuring an eco-friendly and sustainable approach to nanoparticle synthesis.

2.1. COLLECTION AND PREPARATION OF AGRICULTURAL WASTE

The project began with the collection of agricultural waste banana peels. The materials were selected based on their availability and biochemical composition, which included compounds that could act as reducing agents (Kharey, P et al 2022). The collected agricultural waste was then dried and powdered to enhance the extraction of bioactive compounds. The drying process ensured the removal of moisture, which could have interfered with the extraction and synthesis processes. The powdered waste was subjected to solvent extraction using water, a green solvent, to obtain a bio-extract rich in reducing agents.

Figure1 banana peel extract

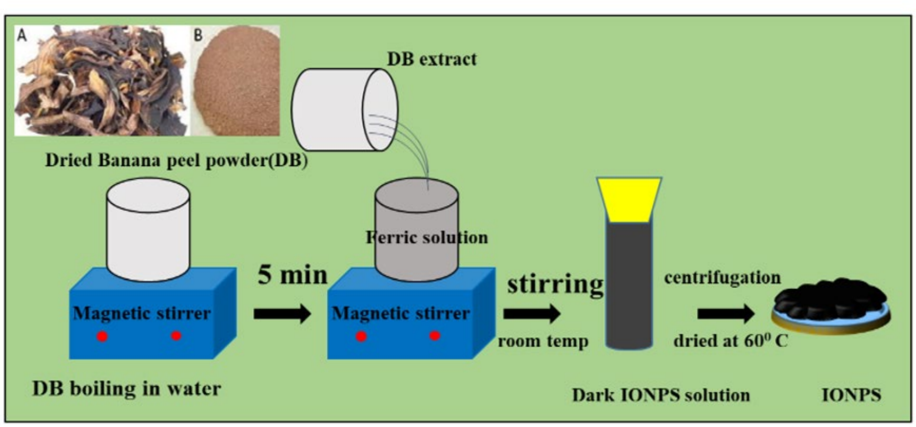

Figure 2 Synthesis of iron oxide Nano particles

The synthesis of IONPS involves several key steps:

1) **Preparation of Extract:** First, the banana peels were washed, dried at 35°C for 96 hours, and then crushed into a powder. 10 mg of the powder is mixed with 100 ml of water and heated to extract bioactive compounds at 80oC on a magnetic stirrer with continuous stirring. This step ensures the solubilisation of compounds that will act as reducing agents during nanoparticle synthesis.
2) **Formation of IONPS:** The prepared dried banana peel extract (DB) extract is added to 100 ml of an iron salt solution (0.01 M FeCl3) and 5ml of 0.1 M NaOH in 100ml:120 ml (5), 100ml:110ml (4), 100ml:100ml (3), 100ml:90ml (2) and 100ml:80ml (1) ratio under constant stirring. Appearance of black colour indicates the bioactive compounds in the extract reduced the iron ions to iron oxide, forming nanoparticles (Alamu, G. A. et al 2024). The stirring process ensures uniform mixing and prevents the agglomeration of nanoparticles.
3) **Purification:** The resulting nanoparticles were washed and centrifuged multiple times with a 1:1 ethanol and water solution to remove impurities. This purification step is crucial to ensure the high purity of the synthesized nanoparticles.

2.2. CHARACTERIZATION

The synthesized IONPS were characterized using various techniques to determine their size, shape, and composition. X-ray diffraction (XRD) was employed to analyse the crystalline structure of the nanoparticles, while scanning electron microscopy (SEM) provided detailed images of their morphology. Fourier-transform infrared spectroscopy (FTIR) was used to identify the functional groups present on the surface of the nanoparticles, confirming the role of bioactive compounds in reduction and stabilization

3. ANALYSIS OF DATA AND FINDINGS (RESULTS AND DISCUSSIONS)

The experimental observations and data analysis indicate the successful synthesis of iron oxide nanoparticles using agricultural waste. The key findings of the study are summarized as follows:

3.1. HIGH PURITY AND DESIRABLE PHYSICAL PROPERTIES

The synthesized IONPS exhibit high purity, as confirmed by XRD and SEM analyses. The nanoparticles demonstrate a uniform size distribution and crystalline structure, indicating the effectiveness of the synthesis process.

The XRD analysis was conducted within a 2θ range of 10° to 80° to determine the crystalline structure and crystal size of the synthesized IONPS. The XRD pattern of IONPS prepared with DB extract (Fig.3) revealed diffraction peaks at 2θ values of 33.5o, 35.5°, 42.6o, 49o, 54o, 57.5o , 64.2o and 65°, indicating the presence of predominantly iron oxide Nano particles. Additionally, low-intensity peaks between 2θ values of 20° and 25° were observed, attributed to the organic matter coating on the IONPS surface, enhancing particle stability. Using the peak broadening profile at a 2θ value of 34.5°, the approximate size of IONPS was calculated using the Scherrer formula:

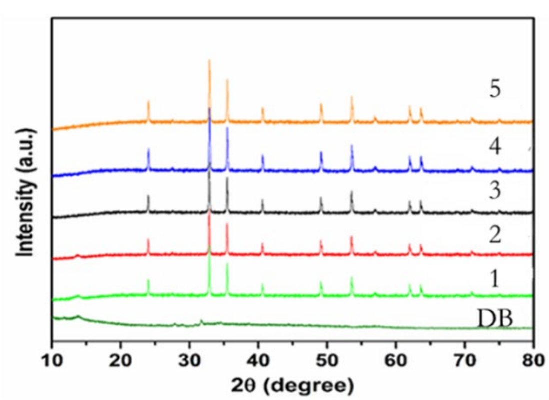

Figure 3 XRD pattern of Iron oxide Nano particles

$$d = 0.94(\lambda)/\beta \cos \Theta$$

where λ is the wavelength (1.5418 Å) and β is the full-width at half maximum (FWHM) of the corresponding peak. The size of the synthesized IONPS was determined to be 60 nm using Scherrer's equation.

SEM analysis was conducted to investigate the morphology, crystal growth, and approximate size of IONPS. As shown in Fig.4, the SEM micrograph reveals that the IONPS particles are predominantly spherical, though some are irregular in shape. The particles exhibit polydispersity with sizes ranging from 50 nm to 90 nm. Notably, slight agglomeration is observed in the SEM images of IONPS synthesized using DB extracts, likely due to magnetic interactions among the nanoparticles.

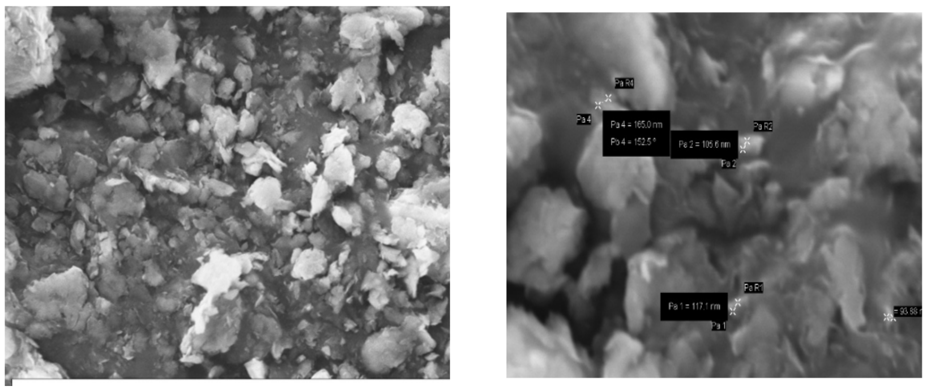

Figure 4 SEM Images of Iron oxide Nano particles

3.2. ROLE OF BIOACTIVE COMPOUNDS

FTIR analysis reveals the presence of polyphenol functional groups on the surface of the IONPS. These groups are indicative of the bio-extract's role in reducing and stabilizing the nanoparticles. The presence of such functional groups ensures the prevention of agglomeration and enhances the stability of the nanoparticles. The FT-IR spectrum of DB extract and IONPS stabilized in DB extract (Fig.5) provides information about the formation and stabilization of iron oxide nanoparticles, revealing interactions among the biomolecules of the DB extract and metal ions. The FT-IR spectral analysis of DB extract (Fig.5) shows a peak at 3359 cm^{-1} due to -OH and -NH stretching vibrations, and peaks at 1641 cm^{-1} and 1239 cm^{-1} indicate the presence of an amide group. Additionally, the peak at 1083 cm^{-1} indicates the presence of -OH bending and C-O-C stretching modes. These absorption peaks suggest the presence of polyphenols in the DB extract. In the FT-IR spectrum of the colloidal solution of IONPS stabilized in the DB extract, it is observed that the peak at 3359 cm^{-1} shifts to 3361 cm^{-1} and the peak at 1641 cm^{-1} shifts to 1642 cm^{-1} with increasing intensity. Similarly, the peaks at 1239 cm^{-1}, 1083 cm^{-1}, 976 cm^{-1}, and 923 cm^{-1} shift to 1231 cm^{-1}, 1081 cm^{-1}, 977 cm^{-1}, and 922 cm^{-1}, respectively. It is also noted that the peaks at 873 cm^{-1} and 680 cm^{-1} are completely absent in the IONPS colloidal solution. The shift in the peak from 3359 cm^{-1} to 3361 cm^{-1} suggests that phenolic species present in the DB extract may be involved in the formation of IONPS. Previous reports also indicate that polyphenols are responsible for the reduction of Fe. Therefore, from the FT-IR spectral analysis, it is concluded that polyphenols in the DB extract are responsible for the reduction and stabilization of IONPS (Muzafar, W et al 2022).

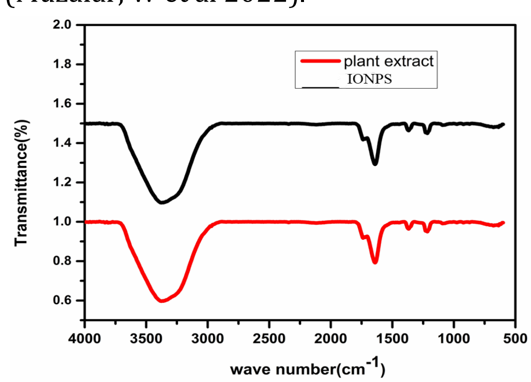

Figure 5 FTIR of DB extract and Iron oxide Nano particles

3.3. ENVIRONMENTAL AND ECONOMIC BENEFITS

The use of agricultural waste in the synthesis process offers significant environmental benefits by reducing the reliance on hazardous chemicals and minimizing waste. Additionally, this method promotes the valorization of agricultural by-products, converting them into valuable materials with wide-ranging applications (Alexeree, S et al 2024). The utilization of agricultural waste in the synthesis process presents substantial environmental advantages by decreasing dependence on harmful chemicals and reducing waste production (Zafar, S, et al 2024). This innovative approach encourages the valorization of agricultural by-products, transforming them into valuable materials with diverse applications.

By incorporating agricultural waste, the synthesis process becomes more sustainable and eco-friendly. This method not only mitigates the environmental impact of hazardous chemicals but also addresses the issue of waste disposal in the agricultural sector (Al-Karagoly et al 2022). Utilizing waste materials helps in conserving natural resources and minimizes the environmental footprint of various industrial processes. Moreover, this approach promotes a circular economy, where waste products are repurposed and reintroduced into the production cycle. This not only adds value to the agricultural by-products but also creates new opportunities for economic growth and job creation in rural areas. The resulting materials can be used in a wide range of applications, including biofuels, bioplastics, and other bio-based products, further contributing to the reduction of fossil fuel dependence and greenhouse gas emissions (Guo, S et al 2022). In conclusion, the use of agricultural waste in synthesis processes offers a sustainable and innovative solution to environmental challenges while simultaneously promoting economic growth and resource conservation. This approach exemplifies the potential of green chemistry and circular economy principles in addressing global environmental issues.

4. CONCLUSION AND SUGGESTIONS

This project successfully demonstrates a viable and sustainable method for synthesizing iron oxide nanoparticles using agricultural waste. The eco-friendly approach leverages the biochemical properties of agricultural by-products to produce high-purity, uniformly sized nanoparticles with wide-ranging applications. The study highlights the importance of green chemistry in advancing nanotechnology and promoting environmental sustainability. Future work will focus on optimizing the synthesis process to enhance the yield and quality of the nanoparticles. Additionally, further research will explore the practical applications of the synthesized IONPS in greater detail, assessing their performance in real-world scenarios. The insights gained from this study can be applied to other areas of Nano Science offering innovative solutions for sustainable development.

CONFLICT OF INTERESTS

None.

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