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HAEMATITE NANOPARTICLES AS A VERSATILE MATERIAL WITH DIVERSE APPLICATIONS: REVIEW

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Abstract

Haematite nanoparticles (α-FeO_3) have drawn attention due to their special qualities and versatility across a range of sectors. These nanoparticles are a good choice for commercial and scientific applications because of their remarkable chemical stability, cost-effectiveness, and environmental compatibility. They have special electrical, optical, and magnetic properties due to their nanoscale size, which are enhanced by high surface energy and quantum confinement events. Haematite nanoparticles' efficient absorption of visible light, chemical inertness and biocompatibility make them especially valuable in photoelectrochemical water splitting, pollutant degradation, and biomedical applications. The size, shape, and surface characteristics of haematite nanoparticles can be exquisitely controlled by advanced synthesis techniques such sol-gel method and hydrothermal, co-precipitation, microwave-assisted synthesis, and sonochemical processes, which makes them perfect for certain applications. Among its many advantages are scalability, energy efficiency, and high purity, there are drawbacks including limited scalability and high equipment expenses. To enhance the performance of haematite nanoparticles in a variety of applications, ongoing research focused on resolving charge transport and morphological issues. Their quantity, usefulness, and adaptability make them essential for advancing sustainable technology and addressing global issues.

Keywords: Haematite, nanoparticles, co-precipitation, photoanode, sonochemical,

Introduction

Haematite (α-Fe_2O_3), the most thermodynamically stable form of iron oxide under ambient conditions, has drawn many study groups due to its substantial interest in nanotechnology, unique features, and wide variety of uses. This material has outstanding chemical stability, environmental friendliness, and cost-effectiveness, making it an ideal contender for a variety of industrial and scientific applications. Haematite nanoparticles (α-Fe_2O_3) have high surface area-to-volume ratios, improved catalytic activity, and significant magnetic characteristics. They can be used in various domains, including catalysis, environmental remediation, biological applications, and energy storage.[1, 2].

The nanoscale dimension of haematite imparts specific electrical, optical, and magnetic properties that differ from its bulk counterpart. These features are attributed to quantum confinement phenomena and the high surface energy of nanoparticles. Haematite nanoparticles (α-Fe_2O_3) have showed potential in photoelectrochemical water splitting, pollutant degradation, and targeted drug delivery systems due to their effective visible light absorption, chemical inertness, and biocompatibility. [3,4].

Haematite's nanoscale dimension gives specific electrical, optical, and magnetic properties that differ from the bulk counterpart. These qualities are linked to quantum confinement phenomena as well as nanoparticles' high surface energy. Haematite nanoparticles (α-Fe_2O_3) offer potential in photoelectrochemical water splitting, pollutant degradation, and targeted drug delivery systems due to their effective visible light absorption, chemical inertness, and biocompatibility.[5].

Methods of Preparation of Haematite Nanoparticles

The synthesis of haematite nanoparticles (α-Fe_2O_3) is a critical step in tailoring their size, morphology, and surface properties for specific applications. Various methods, ranging from conventional chemical routes to advanced techniques, have been developed to produce (α-Fe_2O_3) with precise control over their structural and functional characteristics. Here are some synthesis methods discussed below.

Sol-gel method

The sol-gel method is a widely used approach for synthesising haematite nanoparticles (α-Fe_2O_3) due to its feasibility, simplicity, and ability to control particle size and morphology. In this process, an iron precursor, typically Fe^{3+}, is hydrolysed in the presence of a strong base like ammonia, sodium hydroxide, etc. The resulting gel is dried and calcined at high temperatures to produce haematite nanoparticles. There are also some disadvantages, like long reaction time and agglomeration during drying. [2]

Hydrothermal and solvothermal methods

Hydrothermal and solvothermal methods involve the crystallisation of haematite nanoparticles (α-Fe_2O_3) under high temperature and pressure in an aqueous or non-aqueous medium. These methods allow the synthesis of haematite nanoparticles with controlled morphology, energy-efficient scalability, and also well-defined shapes, such as rods, cubes, or spheres. But this method required specialised equipment, i.e., an autoclave. [3]

Co-precipitation method

This is one of the simplest, feasible, scalable, and most cost-effective methods for synthesising haematite nanoparticles (α-Fe_2O_3). It involves the co-precipitation of iron salts Fe^{2+} and Fe^{3+} in the presence of a strong base. The precipitate is washed, dried, and calcined at high temperature to obtain haematite nanoparticles. Its disadvantage is poor control over morphology and particle size. [4]

Microwave-assisted synthesis

Microwave-assisted synthesis is a rapid and energy-efficient technique for preparing haematite nanoparticles (α-Fe_2O_3). In this method, a microwave radiation source heats the reaction mixture, leading to the formation of nanoparticles with controlled size and morphology. Advantages of this method are high yield, uniform heating, and fast synthesis. also some disadvantages like limited scalability and high equipment cost. [5]

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Thermal decomposition

Thermal decomposition involves the decomposition of iron precursors like iron carbonyl or iron salts at high temperatures to form haematite nanoparticles (α-Fe_2O_3). The process is usually carried out in the presence of a stabilising agent to control particle size and prevent agglomeration. High crystallinity and uniform size distribution are some advantages, while some disadvantages are producing toxic by-products and requiring high temperatures.[1]

Electrochemical Method

This method is environmentally friendly and obtains high purity. Haematite nanoparticles (α-Fe_2O_3) are synthesised through electrochemical reactions involving iron electrodes in an electrolyte solution. The deposition of iron oxides occurs at the cathode, and the precipitate is subsequently calcined at high temperature. But disadvantages are low yield and require some precise control over reaction conditions. [6]

Sonochemical method

Sonochemical synthesis uses ultrasonic waves to generate localised high-temperature and high-pressure conditions, which promote the formation of haematite nanoparticles (α-Fe_2O_3). In this method, fast reaction and unique particle morphology are some advantages, and high-cost equipment and limited scalability are disadvantages. [7]

Flame spray pyrolysis method

Flame spray pyrolysis is a high-temperature synthesis method where a precursor solution is atomised and combusted in a flame, producing haematite nanoparticles (α-Fe_2O_3). It is a continuous and high production rate process, but it is energy intensive and requires specialised equipment. [8]

Applications of Haematite Nanoparticles

Haematite nanoparticles (α-Fe_2O_3) exhibit a range of properties, including high chemical stability, unique magnetic behaviour, and excellent catalytic activity. These properties make them versatile materials for applications across various fields such as environmental remediation, energy storage, biomedical sciences, and catalysis. Below we discuss some detailed accounts of their applications one by one:

Environmental Remediation

Haematite nanoparticles are widely used for environmental clean-up due to their ability to degrade organic pollutants and adsorb heavy metals. It acts as photocatalysts under visible light for the degradation of organic pollutants like dyes and pesticides, making them valuable in wastewater treatment [3], and the high surface area and adsorption capacity of haematite nanoparticles (α-Fe_2O_3) enable them to bind with heavy metals such as arsenic, chromium, and lead, effectively removing these contaminants from water [1].

Energy Storage and Conversion

Haematite nanoparticles (α-Fe_2O_3) are integral to renewable energy technologies due to their semiconducting properties and stability. It's used as photoelectrochemical**.** Water-splitting is employed as photoanodes for hydrogen production through water splitting, leveraging their strong light absorption in the visible spectrum [5]. Used in lithium-ion batteries as electrode materials, offering high theoretical capacity and good cycling stability [4].

Catalysis

Haematite nanoparticles (α-Fe_2O_3) serve as catalysts or catalyst supports in various chemical reactions like the Fenton Reaction to generate hydroxyl radicals, which are potent oxidising agents for breaking down organic compounds [9]. And also heterogeneous catalysts**,** due to their high surface area and thermal stability, make them suitable for catalysing industrial reactions, including Fischer-Tropsch synthesis [10].

Biomedical Applications

The biocompatibility and magnetic properties of haematite nanoparticles make them attractive for biomedical uses, as drug delivery haematite nanoparticles (α-Fe_2O_3) can be functionalised to carry and release drugs at targeted sites, minimising side effects [11]. And Magnetic Resonance Imaging **(**MRI**)** enhances contrast scans due to their superparamagnetic properties [12] also used in Hyperthermia Therapy**,** where haematite nanoparticles (α-Fe_2O_3) generate localised heat under an alternating magnetic field, helping to treat cancer cells without damaging healthy tissue [13].

Sensors

Haematite nanoparticles (α-Fe_2O_3) are utilised in sensor technology for detecting gases, biomolecules, and environmental contaminants. In gas sensors**,** haematite nanoparticles (α-Fe_2O_3) exhibit high sensitivity to gases such as CO_2 and H_2 due to their excellent catalytic activity and electrical conductivity [14]. And in biosensors**,** haematite nanoparticles (α-Fe_2O_3) are functionalised to detect specific biomolecules, including glucose and DNA, for diagnostic applications [15].

Pigments and Cosmetics

Haematite nanoparticles (α-Fe_2O_3) are used as pigments due to their vibrant red colour and stability. Haematite nanoparticles (α-Fe_2O_3) are widely used in paints, ceramics, and plastics to achieve a stable red hue that resists fading [16]. Due to their non-toxic nature, haematite nanoparticles (α-Fe_2O_3) are incorporated into cosmetic products for colour and UV protection [17].

Magnetic Applications

The magnetic properties of haematite nanoparticles enable their use in data storage and magnetic devices like

Haematite nanoparticles (α-Fe_2O_3) are employed in magnetic recording media due to their high coercivity and stability [18]. It's used in smart fluids that alter viscosity in response to magnetic fields, with applications in braking systems and dampers [19].

Conclusion

Haematite nanoparticles (α-Fe_2O_3) are a flexible and sustainable material with numerous uses in science, industry, and technology. The material is appropriate because of its stability, environmental friendliness, cost-effectiveness, and nanoscale features, which position it as a cornerstone material for expanding applications such as catalysis, environmental remediation, health sciences, energy storage, and more. The development of precise synthesis methods has enabled tailored control over their morphology, size, and surface characteristics, optimising their performance in targeted applications like water purification and pollutant degradation, uses in renewable energy and biomedicine. Haematite nanoparticles demonstrate remarkable potential to address pressing global challenges due to their adaptability to various fields, cosmetics, and sensor technologies, further highlights.

Despite these applicability, some challenges, such as scalability, cost-effectiveness, and performance enhancement. Continuously research work needs to improve synthesis procedures and application possibilities. It will be critical to realising the full promise of haematite nanoparticles. Haematite nanoparticles are poised to be a promising material for the further research for sustainable solutions and new technologies.

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