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A Study of Nanocomposite for Photocatalytic

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Abstract - This review article presents a comprehensive investigation of nanocomposites for efficient photocatalytic applications. The study focuses on the synthesis and characterization of nanocomposite materials comprising semiconductor nanoparticles and a matrix material. The nanocomposites exhibit enhanced photocatalytic activity due to synergistic effects. The structural, morphological, and optical properties of the nanocomposites are characterized using advanced analytical techniques. The photocatalytic performance of the nanocomposites is evaluated using model contaminants under simulated solar irradiation. The study investigates the influence of various parameters on photocatalytic activity and contributes to the development of advanced nanocomposites for sustainable energy and environmental remediation applications.

Keyword - Nanocomposites, Synthesis

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INTRODUCTION

Nanocomposites are composite materials made up of two or more nanoscale materials, each with its own unique physical, chemical, and mechanical characteristics. In recent years, nano-composites' potential uses in photocatalysis—the use of light energy to kickstart chemical reactions—have been the subject of intense research. Due to its great efficiency and lack of environmental impact, photocatalysis has been extensively employed for the elimination of organic contaminants in water and air.

When synthesizing nanocomposites for photocatalysis, one material is combined with another that can boost its photocatalytic properties. Among them is graphene oxide (GO), which excels at electron transport despite its small size and enormous surface area. Nanocomposites of GO and photocatalytic materials like titanium dioxide ($TiO2$) are simple to create by functionalization.

$TiO2$/GO nanocomposites are synthesized using the hydrothermal approach, which requires the application of both heat and pressure during the synthesis process. Methods including X-ray diffraction (XRD), transmission electron microscopy (TEM), Fourier transform infrared spectroscopy (FTIR), and ultraviolet-visible spectroscopy (UV-vis) are then used to describe the nanocomposites and verify their structure, morphology, and optical characteristics.[1]

NANOCOMPOSITES

A nanocomposite is a multiphase solid material with one, two, or three phases with diameters less than 100 nm, or structures with nano- size repetition intervals between the phases. This description may include porous media, colloids, gels, and copolymers in their widest meaning, although it is most often understood to refer to the solid combination of a bulk matrix and nano- sized phase(s) changing in characteristics owing to structural and chemical differences. There will be significant differences between the nanocomposite and its component materials in terms of mechanical, electrical, thermal, optical, electrochemical, and catalytic characteristics. It has been suggested that there is a minimum effect size of <5 nm for catalytic activity, <20 nm for softening a hard magnetic material, <50 nm for refractive index alterations, and <100 nm for creating super paramagnetism, mechanical strengthening, or inhibiting matrix dislocation movement.[2]

Nanocomposites are a class of materials that have seen rapid growth in interest in recent years as researchers discover their usefulness in a variety of contexts. A nanocomposite, in its most basic definition, is a composite material that includes a nanoscale filler substance. Nanocomposites have qualities that are a function of both their filler and matrix materials, as well as their interaction.

Nanocomposites can be classified into two main categories: polymer-based nanocomposites and inorganic nanocomposites. Polymer-based nanocomposites are made by incorporating nanoscale filler materials into a polymer matrix, while inorganic nanocomposites are made by incorporating nanoscale filler materials into an inorganic matrix. Both types of nanocomposites have unique properties that make them ideal for a wide range of applications.[3]

One of the main advantages of nanocomposites is their improved mechanical properties. The addition of nanoscale filler materials to the matrix can significantly improve the strength, stiffness, and toughness of the composite material. This is due to the high surface area-to-volume ratio of the nanoparticles, which allows them to interact more effectively with the matrix material and provide better reinforcement. Additionally, the small size of the nanoparticles can also prevent the formation of large cracks and defects in the material, further improving its mechanical properties.

Nanocomposites also have unique electrical and thermal properties that make them useful for a wide range of applications. For example, carbon nanotube-based nanocomposites have been shown to have excellent electrical conductivity, making them ideal for use in electronic devices and conductive coatings. Similarly, metal nanoparticle-based nanocomposites have excellent thermal conductivity, making them ideal for use in heat sinks and other thermal management applications.

In addition to their improved mechanical, electrical, and thermal properties, nanocomposites also have other unique properties that make them useful in a wide range of applications. For example, some types of nanocomposites have improved barrier properties, making them ideal for use in food packaging and other applications where oxygen or other gases need to be kept out. Other types of nanocomposites have improved optical properties, making them useful in displays and other applications where high-quality optics are required.[4]

Despite their many advantages, there are still some challenges associated with the production and use of nanocomposites. One of the main challenges is achieving a uniform distribution of the nanoparticles throughout the matrix material. This is important for ensuring that the nanocomposite has consistent properties throughout its volume. Additionally, the use of nanoparticles can also raise concerns about their potential toxicity and environmental impact, although these concerns are still being studied.

Need for nanocomposites

Improvement of charge separation,life time of charge carrier,It can be achived interfacial charge transfer efficiency. Increase the photocatalytic performance avoid agglomeration and photo corrosion Charge recombination could be significantly reduced and high surface area could be maintained.In order to make semiconductor nanoparticles (ZnO or TiO_2) suitable for receiving and utilizing visible light with good efficiency.

NANOCOMPOSITES TYPES

1.Metal oxide-metal oxide-based nanocomposites

Sol-gel techniques may also be used to manufacture nanocomposites based on metal oxides. Due to their very porous nature, aerogels are excellent foundational components for nanocomposites. The timing of when the second phase is injected into the aerogel material determines the fabrication method for the resulting nanocomposites. During the sol-gel processing of the metal oxides (before to supercritical drying), the second component may be introduced. Aerogel particles may be chemically modified via reactive gas treatments or the vapor phase (after supercritical drying). Many different types of nanocomposites can be made using these overarching methods.

2. Polymer – based nanocomposites

Researchers are intrigued by the synergistic and hybrid features of polymer nanoparticle composite materials. It is possible to execute both the synthesis of polymer-based nanocomposite and the preparation of nanoparticles in a single process, or to do both processes sequentially in a single reactor (the in situ technique). Filler compatibility with the polymer matrix and filler dispersion are both improved by a simplified, one-step synthesis. Polymer nanocomposites with isotropic inorganic particles have been prepared via in situ synthesis of particles in a liquid media, as seen in Fig. It is possible to introduce the polymer after colloid synthesis has begun, or it may already be present. The polymer's effect on particle dispersion may be either destabilizing or stabilizing. In the former, the nanocomposite develops naturally by co-precipitation after colloid formation; in the latter, nanocomposites may be generated via the addition of a solvent that functions as a co-precipitation agent, casting followed by solvent evaporation, or spin coating.

Figure 1: Polymer-based nanocomposites

3. Carbon-based nanocomposites

From an application standpoint, carbon-based nanomaterials, such as fullerenes, single- and multi-walled carbon nanotubes, and carbon nanoparticles, are among the most promising candidates. Carbon nanotubes have been extensively explored since their discovery in 1991 by Sumio Iijima, as seen in Fig. .Potential future uses for these materials include polymer composites, electronics, and medication delivery because to their exceptional electrical and mechanical capabilities.[5]

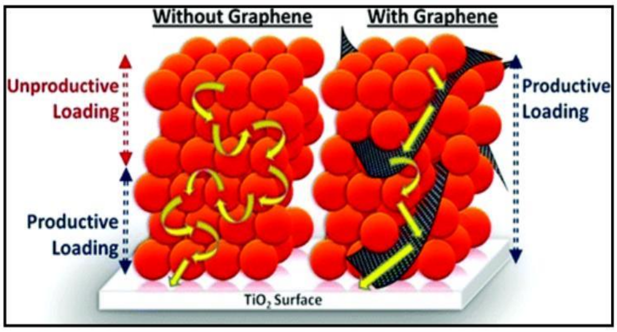


Figure 2: Carbon-based nanocomposites

4. Noble-metal–based nanocomposites

Because of their promise as nanostructured materials, noble metal nanoparticles (NMNPs) embedded in polymeric matrices have been the subject of much research. In this chapter, we'll look at how to make nanocomposites out of noble metals using photo-induced reduction processes under strict supervision. The role that reaction processes, circumstances, and the type of polymer matrices have in allowing for the regulation of the final NP shape is explored. Nanoparticle characteristics and composite qualities may be described using a variety of analytical methods. In the chemical production of metal colloids, polymeric materials have been widely used as NP stabilizers. Most methods for creating or incorporating NMNPs into polymers begin with the use of aqueous, polar (and often protic), or aqueous/polar/protic solvent combinations.[6]

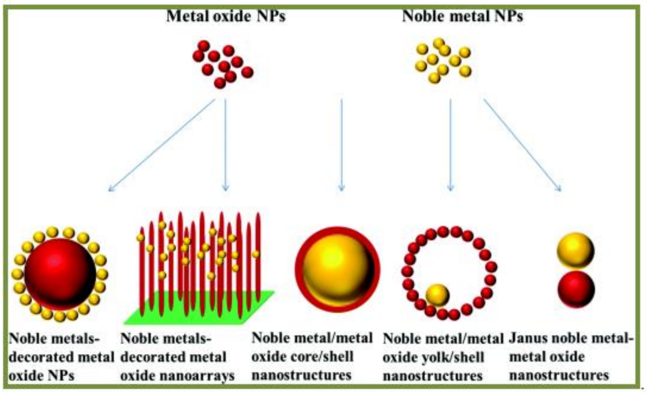
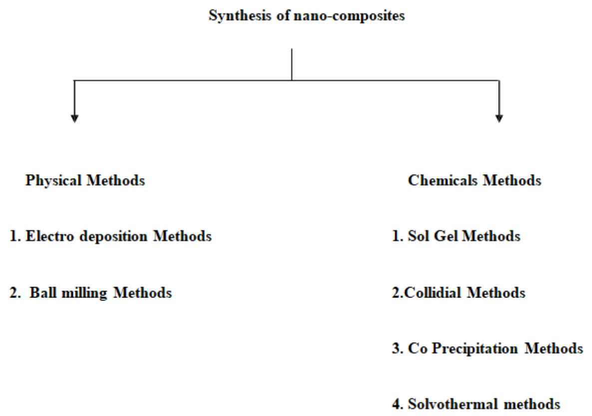


Figure 3: Noble-metal-based nanocomposites

SYNTHESIS OF NANOCOMPOSITES

1. Electrodeposition of Metal Matrix Nanocomposites



Research into the preparation of nanocomposite coatings, by electrochemically co-deposition of fine particles with metal from electrolytic solutions. Electrodeposition method meets some of these requirements, since it is an economical and versatile technique compared to other preparation techniques. Moreover, it is quickly scaled up to industrial production, offering an inexpensive method to produce large area samples. The occlusion electrodeposition, or electrochemically co deposition method, where the particles incorporation occurs simultaneously with the metal ions reduction, uses a precursor bath loaded with the particles to be occluded. This technique is widely used to obtain metal matrix composites due to its ease of preparation, low cost and versatility. The concentration of particles suspended in solution varies from 2 up to 200 g/L producing composites with typically 1-10 vol % of embedded particles. With the increasing availability of nanoparticles, the interest of the low-cost and low-temperature composite electroplating is continuously growing, with the major challenge being the achievement of high co-deposition rates and homogenous distribution of the particles in the metallic matrix.[7]

PHOTOCATALYSIS

The Greek roots of the English term "photocatalytic" may be traced back to the prefix "photo" (phos: light) and the word "catalysis" (katalyo: break apart, breakdown). Light is utilized to stimulate a material in the photocatalysis process without actually participating in the chemical change. The capacity of the catalyst to produce free radicals (such as super oxides or hydroxyl radicals) that may participate in secondary reactions is crucial to the photocatalytic activity. Organic synthesis, water and air purification, renewable fuel generation, etc. are all outcomes of photocatalysis. Fig 1.10 shows a comparison between plant photosynthesis and photocatalytic destruction of organic contaminants.[8] Two distinct types may be identified depending on the photocatalyst's condition:

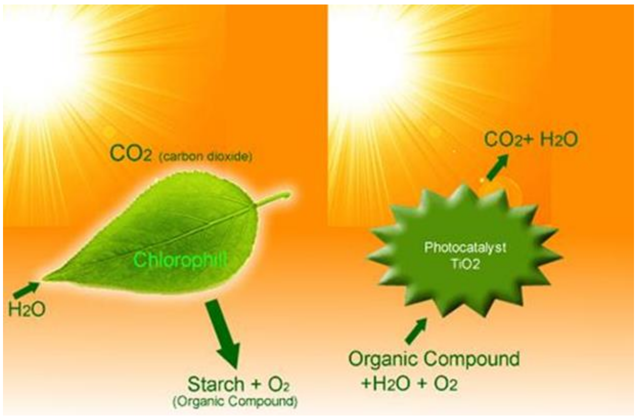


Figure 4: Photosynthesis and Photocatalysis

1. Homogeneous Photocatalysis

Homogeneous photocatalysis involves a single phase containing both the reactants and the photocatalysts. Homogeneous photocatalysis may be seen in ozone and photo-Fenton systems (Fe+ and Fe+/H2O2). In homogeneous catalysis, OH is the reactive species. There are two possible mechanisms by which ozone generates hydroxyl radicals.

$$O_3 + h\nu \rightarrow O_2 + O\ (1D) \qquad (1)$$

$$O(1D) + H_2O \rightarrow {}^{\bullet}OH + {}^{\bullet}OH \qquad (2)$$

$$O(1D) + H_2O \rightarrow H_2O_2 \qquad (3)$$

$$H_2O_2 + h\nu \rightarrow {}^{\bullet}OH + {}^{\bullet}OH \qquad (4)$$

However, there are significant drawbacks associated with homogeneous photocatalysis that have restricted its application. To begin, the catalysts are only stable under moderate circumstances, severely limiting their usefulness. Second, the catalysts are mixed together with the reactant, products, and solvents in the same phase. The final separation is a time-consuming and costly step. The catalyst is often lost and cannot be retrieved.

2. Heterogeneous Photocatalysis

Heterogeneous reactions include the separate presence of the reactant, the product, and the catalyst. Most heterogeneous photocatalysts are either transition metal oxides or semiconductors. An electron is stimulated from the valence band to the conduction band when a semiconductor absorbs a photon with more energy than the band gap of the material. It causes a positive hole to be created in the valence band. The electron in the conduction band is highly reducing, whereas the hole in the valence band is strongly oxidizing. Water, hydroxide ion (OH), organic compounds, and oxygen are only some of the adsorbed species that might participate in redox reactions with the excited electron and hole at the external surface. The hydroxyl radical (OH) is formed when water or OH is oxidized by the hole. Pollutants in both the air and water are quickly neutralized by hydroxyl radicals. Adsorbed oxygen is reduced to O2• by an electron from the conduction band. Therefore, the accumulation of oxygen radical species due to electron recombination with the hole can also contribute to the attack on contaminants.[9]

3. Mechanism of Photocatalysis

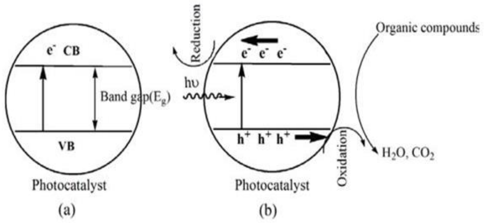


Figure 5: Schematic representations of (a) photocatalyst and (b) photocatalysis

A simple description of photocatalysis involves photon absorption, electronic excitation from VB to CB, electron-hole (e^{-}- h^{+}) formation, recombination of e^{-}- h^{+} pair, charge transport, water absorption, formation of free radicals, degeneration/disinfection of contaminations etc. The valence band hole acts as a powerful oxidant (+1.0 to +3.5 V vs NHE (normal hydrogen electrode) and the conduction-band electron acts as a good reductant (+0.5 to -1.5 V vs NHE) depending on the semiconductor and pH. The formed e^{-}-h^{+} pair may recombine and dissipate the stored energy if there is no separating force. Otherwise, they react with surface adsorbed (e^{-}donar and e^{-} acceptor) species or within the surrounding electrical double layer of charged particles. The recombination can be prevented or reduced in the presence of suitable scavenger or surface defect state to trap the e^{-} or h^{+}. Free radicals are formed during electron transfer processes that take place from water molecule to the photocatalyst and from photocatalyst to the dissolved oxygen. The formed free radicals ($O_2^{\cdot -}$, $^{\cdot}OH$ etc) result in the decomposition of organic compounds in water. The whole process is given equation (1) to (13).

$$\mathrm{SC} \longrightarrow e^{-} + h^{+} \quad \ldots\ldots\ldots\ldots (1)$$

$$h^{+} + OH^{-} \longrightarrow OH^{\cdot} \quad \ldots\ldots\ldots\ldots (2)$$

$$h^{+} + H_2O \longrightarrow OH^{\cdot} + H^{+} \quad \ldots\ldots\ldots\ldots (3)$$

$$O_2 + e^{-} \longrightarrow O_2^{-} \quad \ldots\ldots\ldots\ldots (4)$$

$$O_2^{-} + H^{+} \longrightarrow HO_2^{-} \quad \ldots\ldots\ldots\ldots (5)$$

$$HO_2 + HO_2 \longrightarrow H_2O_2 + O_2 \quad \ldots\ldots\ldots\ldots (6)$$

$$O_2^{-} + HO_2 \longrightarrow HO_2^{-} + O_2 \quad \ldots\ldots\ldots\ldots (7)$$

$$HO_2^{-} + H^{+} \longrightarrow H_2O_2 \quad \ldots\ldots\ldots\ldots (8)$$

$$H_2O_2 + O_2^{-} \longrightarrow OH^{\cdot} + OH^{-} + O_2 \quad \ldots\ldots\ldots\ldots (9)$$

$$H_2O_2 + e^{-} \longrightarrow OH^{\cdot} + OH^{-} \quad \ldots\ldots\ldots\ldots (10)$$

$$H_2O_2 \xrightarrow{h\nu\ \text{catalyst}} OH + OH \quad \ldots\ldots\ldots\ldots (11)$$

$$^{\cdot}OH + \text{Pollutant} \longrightarrow \text{Pollutant intermediate(s)} \quad \ldots\ldots\ldots\ldots (12)$$

$$^{\cdot}OH + \text{Pollutant intermediate(s)} \longrightarrow CO_2 + H_2O \quad \ldots\ldots\ldots\ldots (13)$$

Photocatalysis is applied in environmental clean-up especially of water and air by decomposing organic compounds and bacteria into carbon dioxide and water. Heterogeneous photocatalysis has been emerged as an important degradation technology for the mineralization of organic pollutants.[10] The advantages of heterogeneous photocatalysis process over other conventional methods can be summarized as follows:

- The processes can be carried out under ambient condition of temperature and pressure.
- The process uses atmospheric oxygen as oxidant and no other expensive oxidizing chemical is required.
- The oxidant is strong and less selective which leads to complete mineralization of organic pollutants.
- This process is known as green technology because the degradation product (carbon dioxide, water and mineral acids) shows moderate toxicity.
- The photocatalysts are cheap, non-hazardous, stable, biologically and chemically inert and reusable.

Summing up all these benefits and advantages, heterogeneous photocatalysis provides a cheap and effective alternative to clean water remediation.

CONCLUSION

In conclusion, the study of nanocomposites for photocatalytic applications has shown promising results in the development of efficient and sustainable materials for various environmental and energy-related processes. By incorporating semiconductor nanoparticles into a matrix material, the nanocomposites exhibit enhanced photocatalytic activity, thanks to the synergistic effects between the components. The synthesis and characterization of these nanocomposites have provided valuable insights into their structural, morphological, and optical properties, which directly influence their photocatalytic performance. Through rigorous evaluation using model contaminants and simulated solar irradiation, the photocatalytic efficiency and reaction kinetics have been assessed, highlighting the potential of nanocomposites for effective pollutant degradation. Furthermore, the study has investigated the influence of various parameters on photocatalytic activity, aiding in the optimization of nanocomposite design for specific applications. Overall, this research contributes to the advancement of nanocomposite materials and opens new avenues for sustainable energy conversion, water purification, air pollution control, and other environmentally beneficial processes.

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