Stain Removal Efficiency of TiO_2 Nanoparticles

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Abstract

This study focuses on the synthesis of titanium dioxide (TiO_2) nanoparticles (NP) using both chemical and green synthesis methods to evaluate their effectiveness in stain removal when applied to fabrics. The research aims to compare the detergency properties of TiO_2 nanoparticles synthesized through conventional chemical techniques and eco-friendly approaches. The performance of these nanoparticles is assessed based on their ability to break down stains, highlighting their potential for textile treatment and environmental cleaning. The findings emphasize the advantages of green synthesis, contributing to sustainable and efficient fabric care solutions.

Keywords: TiO_2 Nanoparticles, Green Synthesis, Chemical Synthesis, Stain Removal, Detergency, Textile Treatment, Environmental Cleaning.

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Introduction

Titanium dioxide (TiO_2) is perhaps one of the most-studied semiconducting materials and due to its excellent specific properties, which make them particularly useful in particular applications, especially on the environmental/industrial level. Its high refractive index and outstanding UV-blocking performance, making it a vital active ingredient in sunscreens and coatings [1]. Photocatalytic activity by which it catalyses to decompose the organic compounds on exposure to UV light [2]. Antibacterial activity for various applications including the medical device sector, coatings, and environmental sanitation [3]. High stability under a broad scope of applications makes them resistant for long-lasting functions [4]. Self-cleaning ability is realized due to the hydrophilicity and photocatalytic action on the decomposition of dirt and other organic stains due to light exposure and the wetting process of water [5] etc. However, one of the more promising applications of TiO_2 NPs is found in photocatalysis, where it can catalyse degradation of organic pollutants and stain removal from textiles. TiO_2 interacts with water and oxygen molecules under UV light and forms electron-hole pairs. Hydroxyl radicals and superoxide anions produced during this reaction are capable of breaking down any organic compound and can break any organic stain present. The photo reactivity of TiO_2 depends on a number of parameters like particle size, surface area, crystallinity, and presence of different crystalline phases namely anatase, rutile, and brookite [6].

Photocatalytic Properties of TiO_2

The photocatalytic activity of TiO_2 arises from the formation of electron-hole pairs by the interaction with ultraviolet light. The reactive oxygen species produced through the combination of these electron-hole pairs are highly reactive, particularly hydroxyl radicals that efficiently degrade organic compounds, which are often seen in stains found on fabrics. Therefore, although TiO_2 has been very important in purification of air and water, it is becoming a highly valued element for the treatment of fabrics. The catalytic performance of TiO_2 is highly dependent on the anatase form. Among them, the tetragonal crystal structure form exhibits high photocatalytic activity because it possesses a higher surface area and greater efficiency in producing ROS under UV irradiation, which can be used for stain removal and purification of the environment. Photocatalytic activity for the removal of stains from fabrics can be optimized if nanoparticles of NP can be synthesized in the anatase phase by tailoring the synthesis procedure of TiO_2.

Synthesis Methods

The synthesis method used for TiO_2 NP affects the photocatalytic properties. Two synthesis methods are presented here:

Chemical Synthesis Method

The conventional chemical process for the synthesis of TiO_2 nanoparticles (NP) involves the sol gel method, in which titanium tetra iso - propoxide (TTIP) is the precursor. Generally, it requires carefully controlled environments and reactants, such as ethanol and deionized water. TiO_2 nanoparticles (NP) produced by such methods can have property control with regard to diameter, aspect ratio, and crystalline phase. The main drawback for this method, however, involves the use of hazardous chemicals along with the toxic by-products. However, its ability to make precise control in nanoparticle properties makes it the most reliable high-performance TiO_2.

Eco-Friendly (Biologically, Green) Synthesis Method

The green synthesis method, on the other hand, incorporates plant extracts as reducing agents. Such extracts include bioactive compounds like polyphenols, flavonoids, and proteins that help in the formation of nanoparticles without the use of toxic chemicals [7]. Plants like Aloe vera and neem are the most common because of their antioxidant activities.

This method is environmentally friendly, cost-effective, and reduces the overall carbon footprint of TiO_2 synthesis. It is also less hazardous and avoids the disposal problems associated with chemical waste. However, the characteristics of the TiO_2 nanoparticles (NP) produced by green synthesis are typically less controlled, resulting in more variability in particle size and crystallinity. The most popular sources for such investigations are plants, including Tulsi, Aloe vera, Neem, and green tea due to the potential availability of considerable natural resources bearing strong reducing characters. Green synthesis is a procedure that not only is environmental but also economic. This process mainly uses low cost, renewable elements. Moreover, this synthesis path is quite suitable for mass scalability and is uncomplicated due to fewer steps generally involved in synthesizing the nanomaterial. The surface properties and biocompatibility of nanoparticles (NP) produced by green synthesis might differ, indicating improved performance in areas such as environmental remediation and biomedical fields.

Applications and Future Prospects

The synthesis of TiO_2 nanoparticles (NP) using eco-friendly methods opens an exciting possibility for expanding their applications. In the field of environmental cleanup, TiO_2-based photocatalysts have demonstrated success in breaking down pollutants in water, including heavy metals, dyes, and pharmaceutical residues. The adoption of green synthesis methods could further enhance these processes by reducing the environmental impact associated with nanoparticle production. for particular applications, and mass production to cater to the growing demand for sustainable nanomaterials. In addition, TiO_2 NP is being studied for antimicrobial purposes, self-cleaning surfaces, and energy conversion systems such as dye-sensitized solar cells. Future research should emphasize efficiency gains for green synthesis methodologies, including tailored nanoparticle properties. Green synthesis combined with TiO_2 photocatalysis will possibly pave the way to new approaches to environmentally sound technologies in the coming years.

Objectives

- Synthesis of TiO_2 nanoparticles (NP) using the chemical sol-gel method.
- Green synthesis methods with plant extracts for TiO_2 nanoparticles (NP).
- Application of the synthesized TiO_2 nanoparticles (NP) to muslin fabrics.
- Testing the efficiency of TiO_2 - muslin fabrics for stain removal at sunlight exposure.
- Testing the efficiency of TiO_2 NP on muslin fabrics for stain removal.
- Comparison of chemical and green-synthesized TiO_2 nanoparticles (NP) for stain removal.

Materials and Methods

Preparation of TiO_2 Nanoparticles (NP)

1. ***Chemical Synthesis Method***

Materials: TTIP, ethanol, deionized water.

Procedure

1 ml TTIP was dissolved in 9 ml ethanol. 5 ml of Deionized water was gradually added under constant stirring. The mixture was heated at 80°C for 2 hours to obtain a white precipitate. The precipitate was washed with ethanol and then deionized water, dried at 100°C, and then calcined at 500°C for 3 hours. Thus, TiO_2 nanoparticles (NP) from chemical synthesis (C) method was prepared [8].

2. ***Green Synthesis Method***

Materials: TTIP, plant extracts (e.g., Tulsi powder, Aloe vera, neem), deionized water.

Procedure

Plant leaves were washed with D/w and boiled in deionized water to prepare the extract.

The prepared TTIP solution was mixed with the plant extract and heated at 80°C for 2 hours.

The resulting precipitate was washed, dried at 100°C, and calcined at 500°C for 3 hours. Thus, TiO_2 nanoparticles (NP) from green synthesis (B) method was prepared.

Characterization of TiO_2 Nanoparticles (NP)

Characterization of the synthesized TiO_2 nanoparticles (NP) is carried out using techniques like X-ray diffraction (XRD) from Pune University, Department of Physics. UV-Visible spectroscopy to confirm their phase composition, morphology, and light absorption properties. The characterized curve shows that the nanoparticles (NP) are of TiO2.

Application of TiO_2 Nanoparticles on Muslin Fabrics

Materials: Muslin fabric, synthesized TiO_2 nanoparticles (NP), polyvinyl alcohol (PVA) binder.

Procedure

The prepared TiO_2 nanoparticles (NP) were dispersed in water with a binder (1% starch solution).

Solutions for two different concentrations were prepared i) 33% TiO_2 NP solution + 67% binder & ii) 50% TiO_2 NP solution + 50% binder solution.

Muslin fabric was cut in 5 equal pieces namely, C1 [soaked in (i)], C2 [soaked in (ii)], B1[soaked in (i)], B2 [soaked in (ii) & control Co (not soaked in NP).

The muslin fabric was soaked in different concentrations of nanoparticles (NP) for 30 minutes, dried at 60°C for 1 hour to ensure proper adhesion of the nanoparticles (NP).

Stain Removal Test

Materials: Common stains (ink), TiO_2 - coated muslin fabric, sunlight, and normal water.

Procedure

Stain was applied to the cotton fabric and dried for 24 hrs. at Room temperature.

The fabric (C1, C2, B1, B2 and Co) was washed with detergent and dried. (C & B indicates chemical synthesis & green synthesis method).

Results

Preparation of TiO_2 Nanoparticles (NP) (Chemical and Biological)

Figure 1: Preparation of chemically synthesized TiO_2 Nanoparticles (NP).

Figure 2: Preparation of biologically synthesized TiO_2 Nanoparticles (NP).

Characterization of TiO_2 Nanoparticles (NP)

X -Ray Characteristic

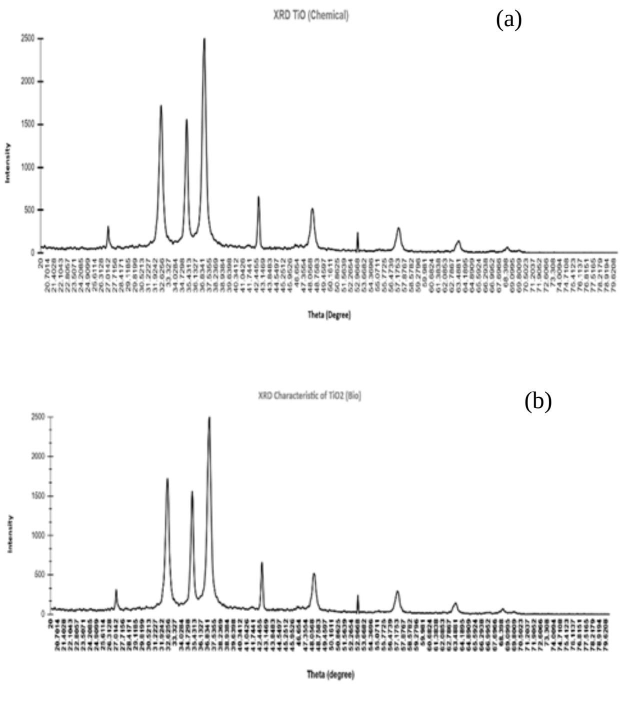


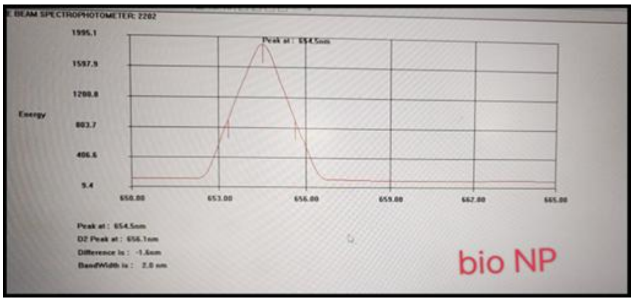
Figure 3: XRD analysis of the synthesized TiO_2 Nanoparticles. (a) XRD characterization for chemically synthesized TiO_2 nanoparticles. (b) XRD characterization for biologically synthesized TiO_2 nanoparticles

The TiO_2 Nanoparticle (NP) (Chemically synthesized and biologically synthesized) displayed nearly identical diffraction angles, suggesting that both methods produced TiO_2 with similar crystal structures. The intensity values are also closely matched, further indicating that the crystal formation and size may be consistent across both synthesis methods. There are small variations in intensity at specific angles like (36.80 & 37.140), which may indicate slight differences in crystal quality or the presence of impurities from the Aloe vera synthesis process. High-intensity peaks suggest a high degree of crystallinity in the material. The more crystalline the sample, the more coherent and sharper the diffraction patterns, leading to higher intensities at specific angles (peaks). From the X- Ray diffraction pattern figure 3 (a), (b), biologically synthesized nanoparticles are slightly more crystalline as compared to chemically synthesized nanoparticles.

UV characteristic

Figure 4. (a), (b) shows the UV characteristic of chemically synthesized and biologically synthesized nanoparticles with slight variation in the band gap energy.

(a)

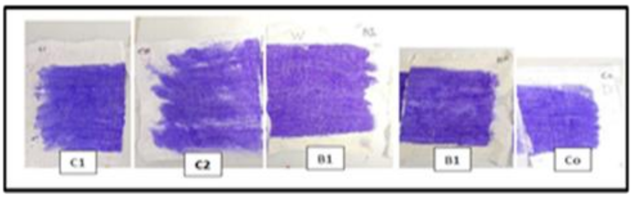


(b)

Figure 4: UV characterization of synthesized TiO_2 Nanoparticles. (a) UV characterization for chemically synthesized TiO_2 nanoparticles. (b) UV characterization for biologically synthesized TiO_2 nanoparticles.

Biologically synthesized TiO_2 nanoparticles show a slight lower band gap as compared to chemically synthesized TiO_2 nanoparticles. A lower band gap indicates that the sample can absorb light in the visible range more effectively which enhances the photocatalytic activity in broader light conditions. A higher absorption peak, especially in the UV or visible range, suggests better utilization of light for photocatalysis. This translates to higher efficiency in generating reactive oxygen species (ROS), which are crucial for breaking down stain molecules.

Application of TiO_2 Nanoparticles on Muslin Fabrics



(a)

(b)

(c)

Figure 5: Application of TiO_2 on muslin fabric (a) Muslin fabric before washing. (b) Muslin fabric washed with water (c) Muslin fabric wash with detergent

Visual assessments showed that the surfaces were treated with biological TiO_2 nanoparticles appeared significantly cleaner. This enhanced stain removal capability is likely due to the unique properties of the biologically synthesized nanoparticles, suggesting their potential as a more environmentally friendly and efficient alternative for cleaning applications.

Discussion

Chemical and Biological (green synthesis) methods successfully produced TiO_2 nanoparticles. Efficient removal of the stain by the biologically synthesized TiO_2 nanoparticles can be attributed to their enhanced surface reactivity and larger effective surface area, which likely facilitate more efficient interactions with the stain molecules.

Biologically synthesized TiO_2 nanoparticles are slightly more crystalline and have a lower band gap energy as compared to chemically synthesized TiO_2 NP. A material with high crystallinity is one in which the atoms are arranged in a regular, repeating pattern, thereby forming a well-ordered crystal lattice, is a basic concept in materials science and solid-state physics. [9, 10]. For biologically synthesized TiO_2 nanoparticles, the XRD analysis shows sharper and more intense diffraction peaks than chemically synthesized TiO_2. This reflects that the structure of biologically synthesized TiO_2 crystals is more uniform, ordered, with fewer lattice distortions and defects. This indicates that a better crystallinity condition is favorable in order to be stable for good physical and chemical properties such as photocatalytic efficiency. A more crystalline material will interact better with light and make electron transition during photocatalysis more effective, which is quite crucial for their application in stain removal.

This energy difference between the valence band, where the electrons are resting, and the conduction band, where electrons are free to move, is called the band gap of the material. The amount of energy required for an electron to jump from being stationary to moving freely is the energy difference between these two bands; this is how the material will conduct electricity or facilitate chemical reactions. TiO_2 is a semiconductor, and the band gap is very important for its photocatalytic activity. The band gap of TiO_2 is typically about 3.2 eV, which means it absorbs mainly UV light. However, a lower band gap means that the material can absorb visible light in addition to UV light, making it more efficient at using sunlight or artificial light for photocatalytic reactions. Biologically synthesized TiO_2 nanoparticles, owing to their method of synthesis, inherently usually have a smaller band gap compared to chemically synthesized ones. This occurs due to organic molecules or impurities that may get incorporated within the biological synthesis process, thereby slightly changing the electronic material structure. Biologically synthesized TiO_2 has a lower band gap, which means it can absorb a larger part of the light spectrum, especially in the visible region. This improves the photocatalytic activity because more light energy can be utilized to produce reactive species that break down stains, pollutants, or organic compounds. The higher crystallinity of biologically synthesized TiO_2 provides more stable and organized structures for photocatalysis, while the lower band gap allows for more effective light absorption, particularly in the visible range. Together, these properties make biologically synthesized TiO_2 more efficient in applications like stain removal compared to chemically synthesized TiO_2.

Authors should discuss the results and how they can be interpreted from the perspective of previous studies and of the working hypotheses. The findings and their implications should be discussed in the broadest context possible. Future research directions may also be highlighted.

Conclusion

This work highlights the potential of TiO_2 nanoparticles for environmentally friendly stain removal on muslin fabrics, leveraging photocatalytic activity under sunlight. Both chemical and green (biological) synthesis methods successfully produce TiO_2 nanoparticles, but biologically synthesized TiO_2 shows superior properties in terms of crystallinity and band gap energy. The higher crystallinity in biologically synthesized TiO_2 indicates a more uniform and stable crystal structure, leading to better performance in photocatalytic applications like stain removal. Additionally, the slightly lower band gap of biologically synthesized TiO_2 enables more efficient light absorption, especially in the visible range, making it more effective at generating reactive species for breaking down stains. Therefore, biologically synthesized TiO_2 nanoparticles are more efficient for stain removal applications than chemically synthesized ones due to their enhanced structural and optical properties.

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