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Experimental Investigation of TiO_2–Rhodamine 6G Hybrid Coating for Dye-Sensitized Solar Cell Applications

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Abstract. *This work presents an experimental study on the optical properties of TiO_2–Rhodamine 6G (R6G) hybrid systems with potential relevance to dye-sensitized solar cell applications. TiO_2 particles were prepared using pulsed laser ablation in liquid at different pulse numbers, while R6G dye solutions were prepared at various concentrations. The optical behavior of TiO_2, R6G, and their hybrid systems was investigated using UV–Vis absorption and fluorescence spectroscopy.This work presents an experimental study on the optical properties of TiO_2–Rhodamine 6G (R6G) hybrid systems with potential relevance to dye-sensitized solar cell applications. TiO_2 particles were prepared using pulsed laser ablation in liquid at different pulse numbers, while R6G dye solutions were prepared at various concentrations. The optical behavior of TiO_2, R6G, and their hybrid systems was investigated using UV–Vis absorption and fluorescence spectroscopy.These findings suggest that TiO_2–R6G hybrid coatings may improve visible light harvesting and could be considered for applications related to dye-sensitized solar cells.*

Keywords: *Titanium dioxide (TiO_2) nanoparticles; Rhodamine 6G (R6G) ; TiO_2–R6G hybrid system ; Optical properties.*

1. INTRODUCTION

Titanium dioxide, also abbreviated as TiO2, is identified as a metal oxide compound known for its versatility in different optical and catalytic applications. The scientific importance of this compound can be identified based on its chemical stability and peculiar electronic configuration. An extensive overview of this compound has been discussed by Chen and Mao [1]. It has been emphasized that different routes for the synthesis of this compound and its structure engineering are crucial for its optical and electronic properties. To further discuss this compound, Diebold discussed the surface science of this compound [6]. The importance of surface states and defects has been identified for its performance. Moreover, Chiodo et al. discussed the importance of this compound for different applications [2].discussed the compound from a theoretical point of view by investigating the effects of self-energy and excitonic effects in crystalline TiO2.Their work demonstrated that The role of electron–hole interactions and quasiparticle corrections is critical in understanding the actual band structure of the material. With these basic concepts in mind, a number of review articles, including those published by Schneider et al. [3], Pelaez et al. [4], and Nakata and Fujishima [5], focused on the mechanism of photocatalysis in TiO_2 and the ways in which it can be made active in the visible region.

Rhodamine 6G (R6G) is a popular xanthene dye with a strong absorption in the visible region of the spectrum and a high quantum yield of fluorescence. The spectroscopic characteristics of the dye are highly environment-dependent. Ogunsipe [7] showed the importance of the solvent environment in the absorption spectra of R6G, along with the role of molecular interactions in the excited-state dipole moments. Further understanding of the dye-matrix interaction was provided by Lewkowicz et al. in a study that showed the embedding of R6G in TiO2 and SiO2 nanolayers results in a concentration-dependent variation in the fluorescence intensity, emission, and structure.

Hybrid systems consisting of TiO_2 in combination with other organic dyes, including R6G, have also been studied for the improvement of the light harvesting properties of the system. Saeed et al. [9] have shown the potential of TiO_2-supported catalyst systems in the degradation of aqueous solutions of R6G under light exposure, thus emphasizing the interfacial interaction of the dye with the semiconductor surface. The results of the research conducted by Ameen et al. [10] have also shown the effect of the incorporation of R6G in the structure of TiO_2 thin films prepared using the sol-gel technique in conjunction with the dip-coating process, thus showing the changes in the optical density of the system. Seery et al. [11] have also shown the enhanced photocatalytic properties of the system under visible light exposure, including the degradation of R6G dye, thus emphasizing the importance of the modification of the TiO_2 structure for the improvement of the photocatalytic properties of the system **.**

In the present study, the focus will be on the optical analysis of the TiO2–Rhodamine 6G hybrid coatings, especially with respect to the use in solar cell technology. In the present work, the emphasis is not laid on the development of the entire solar cell device, including its electrical properties. Instead, the optical properties of the hybrid coating are examined. This is necessary for the understanding of the absorption properties and charge transfer, especially with respect to coated polycrystalline solar cells.

Based on the above-mentioned studies, the present research aims to prepare and investigate the optical properties of TiO_2 nanoparticles at different laser pulse numbers, Rhodamine 6G solutions with various concentrations, and TiO_2–R6G hybrid systems.

Dye-sensitized solar cells (DSSCs) have attracted considerable attention due to their low cost, simple fabrication, and ability to operate under low light conditions. However, their efficiency is still limited by factors such as charge recombination, insufficient light absorption, and instability of dye molecules. Hybrid systems combining semiconductor materials such as TiO_2 with organic dyes like Rhodamine 6G have been investigated to enhance light harvesting and improve interfacial charge transfer. Such systems may provide improved optical response and are therefore of interest for DSSC-related applications.

2. MATERIALS AND METHODS

2.1. MATERIALS

Commercially available titanium dioxide (TiO_2) powder, purchased from a local market, was used as a base material for preparing the target pellet. Analytical-grade rhodamine 6G dye was used as an organic compound for hybrid formation. Deionized (distilled) water was used as a solvent during all steps of sample preparation.

2.2 PREPARATION OF TIO_2 NANOMATERIAL

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Titanium dioxide (TiO_2) powder was compressed in the form of a solid pellet using a mold made of stainless steel. The prepared pellet was then added to 10 mL of deionized water contained in a glass beaker. Laser ablation was carried out using an Nd:YAG laser with a fixed wavelength. The laser beam was focused onto the pellet under ambient conditions. To investigate the influence of the time of laser ablation on the formation of nanoparticles, the number of laser pulses was varied at 600, 900, and 1200 pulses. The prepared TiO_2 colloidal solutions were named according to the number of pulses used in the laser ablation process, i.e., TiO_2-600, TiO_2-900, and TiO_2-1200, and were contained in plastic tubes. The laser ablation process was carried out using an Nd:YAG laser operating at a fixed wavelength under ambient conditions. Although detailed parameters such as pulse energy and repetition rate were not recorded, the experimental conditions were kept constant throughout all measurements to ensure consistency and reproducibility of the results.

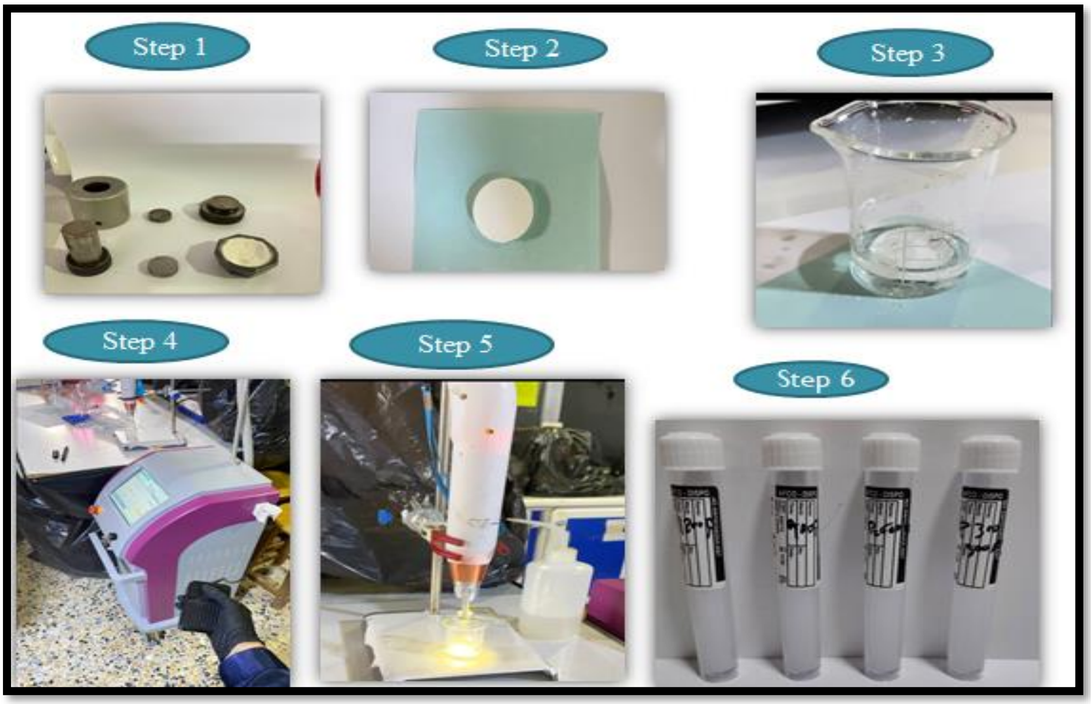

Fig. 1. Main steps of TiO_2 sample preparation in the laboratory.

2.3 PREPARATION OF RHODAMINE 6G (R6G) DYE SOLUTIONS

A certain amount of Rhodamine 6G (R6G) dye was accurately weighed using an analytical balance to obtain 0.1 mg of the pure compound. The measured amount of the compound was then dissolved in 20 mL of deionized water to obtain a stock solution with a concentration of 10^{-3} M. Thereafter, a number of diluted solutions with the following concentrations: 3 x 10^{-4}, 5 x 10^{-4}, and 7 x 10^{-4}, were obtained from the stock solution using the standard dilution relation, which is given by the equation: $C_1V_1=C_2V_2$.

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Fig.2. Main steps of R6G dye preparation in the laboratory, including weighing, dilution, and transferring the prepared solutions into labeled tubes.

2.4 PREPARATION OF HYBRID TIO_2–R6G SAMPLES

Hybrid nanofluids were prepared by physically mixing the TiO2 colloidal suspensions prepared using various numbers of laser pulses with the solutions containing the Rhodamine 6G (R6G) dye at various concentrations. The hybrid nanofluids prepared were TiO_2(300P) + R6G (3×10^{-4} M), TiO_2(600P) + R6G (7×10^{-4} M), TiO_2(900P) + R6G (5×10^{-4} M), and TiO_2(1200P) + R6G (1×10^{-4} M).). Each solution was manually shaken for a period of 3-5 minutes to ensure that there was adequate dispersion and coloring. The hybrid solutions that were obtained were then packed in closed containers and stored in an environment that is not exposed to direct light.

Fig. 3. TiO_2–R6G hybrid sample preparation.

It should be noted that the characterization of the prepared TiO_2 particles in this study is mainly based on optical measurements. No structural or morphological characterization techniques such as scanning electron microscopy (SEM), transmission electron microscopy (TEM), or X-ray diffraction (XRD) were performed. Therefore, the nanoscale nature of the particles is inferred from the preparation method and optical behavior rather than being directly confirmed.

3. INSTRUMENTS USED

Two main instruments were used to determine the optical properties of the prepared samples:

- The absorption spectra were recorded using a UV–Vis spectrophotometer (Shimadzu UV-1800, Japan) operating in the wavelength range of 300–900 nm, with measurements carried out in 1 cm quartz cuvettes. Distilled water was used as the reference for baseline correction.

Fig. 4. UV–Vis spectrophotometer used for recording the absorption spectra of TiO_2, R6G, and TiO_2–R6G hybrid samples.

- Flluorescence measurements were carried out using a fluorescence spectrometer (Perkin Elmer LS-55 or similar model) to record the emission spectra for the dye Rhodamine 6G and the hybrid material TiO2-R6G. The excitation wavelengths are chosen according to the absorption maxima for the dye. The measurements are carried out at room temperature..

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Fig.5 fluorescence spectrometer (PerkinElmer LS-55 or similar model)

4. RESULTS AND DISCUSSION

4.1 OPTICAL PROPERTIES OF TIO_2 NANOPARTICLES

The optical absorption of the TiO2 nanoparticles, which have been synthesized by varying the number of laser pulses, has shown considerable absorption in the ultraviolet region. After that, a gradual decrease in intensity with an increase in wavelength has been observed. An increase in the number of pulses has shown considerable enhancements in intensity with regard to the optical absorption. This may be due to an increase in the concentration of the nanoparticles and/or a decrease in their size. From the results obtained, it may be noted that the optical properties of the TiO2 nanoparticles are largely dependent on the laser ablation.

The optical absorption properties of the TiO_2 nanoparticles, which were synthesized by employing different numbers of pulses, are shown in Figure 6(a) and 6(b). As can be seen from Figure 6a, all the samples show high absorption in the ultraviolet region, while the absorption decreases gradually as the wavelength is increased. Moreover, it is noted that the absorption coefficient is enhanced by increasing the number of pulses. From the results obtained in Figure 6b, which are associated with the absorbance of the samples, the effect of the laser ablation process is noted. The increase in absorption may be related to changes in particle concentration and size with increasing laser pulses.

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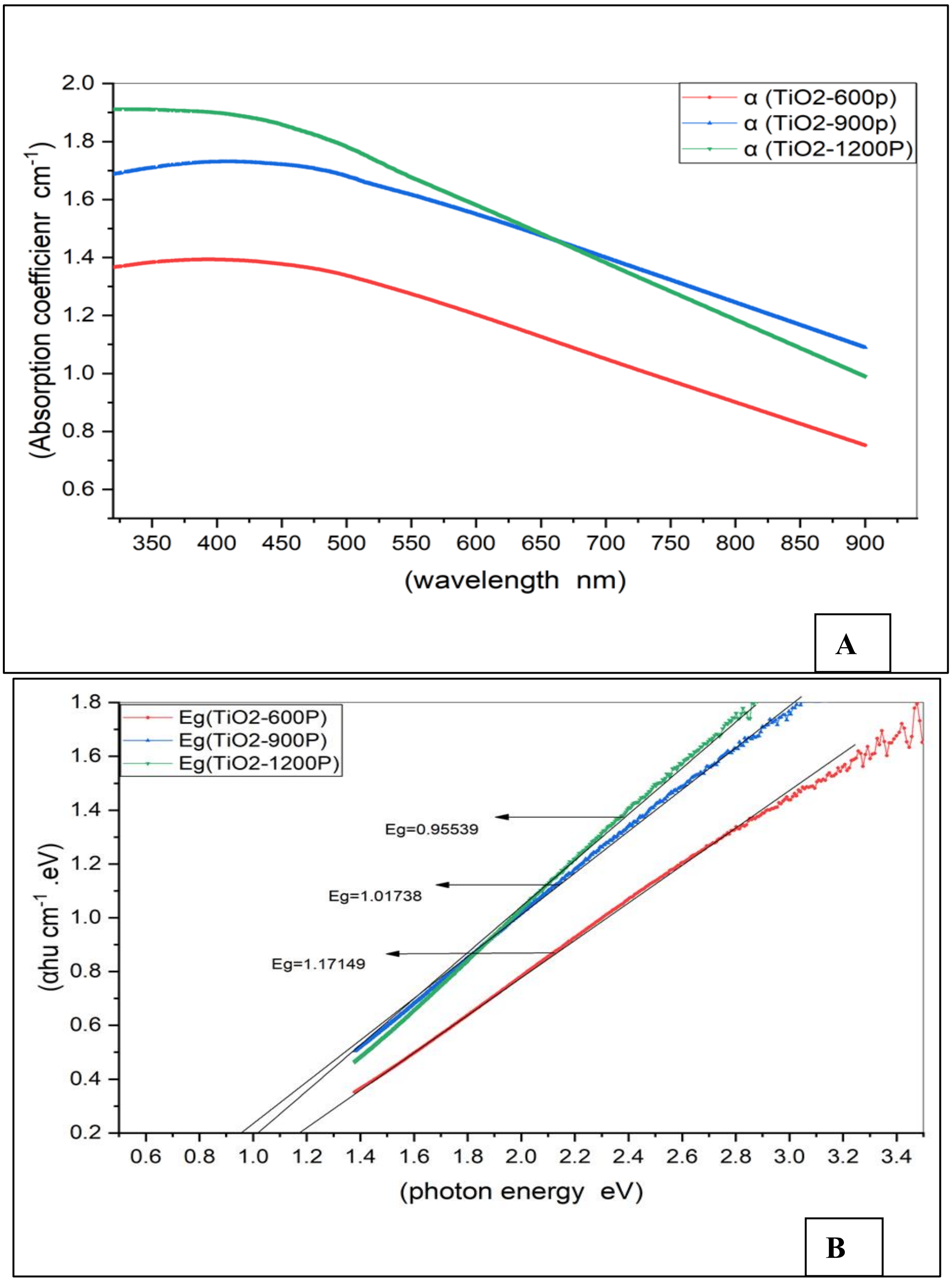


Fig. 6. (a) Absorption coefficient and (b) absorbance spectra of TiO_2 nanoparticles prepared at different laser pulse numbers

4.2 OPTICAL PROPERTIES OF RHODAMINE 6G

The absorption band of Rhodamine 6G has a strong intensity in the visible region with a wavelength range of 520-530 nm, corresponding to π-π* transitions. The intensity of absorption increases with increasing dye concentration, whereas the wavelength remains nearly constant. This suggests that the dye has good optical stability. The applicability of Beer-Lambert's law has also been verified with this range of dye concentrations. The absorption spectra have also been verified with the transmission spectra.Figures 7(a) and 7(b) show the absorption coefficient spectra and extinction coefficient spectra of

Rhodamine 6G dye with various concentrations. From these spectra, it has been verified that a strong absorption peak exists in the visible region with a wavelength range of 520-530 nm. The intensity of absorption increases with increasing dye concentration. The stable peak position indicates good optical stability of the R6G dye at the studied concentrations.

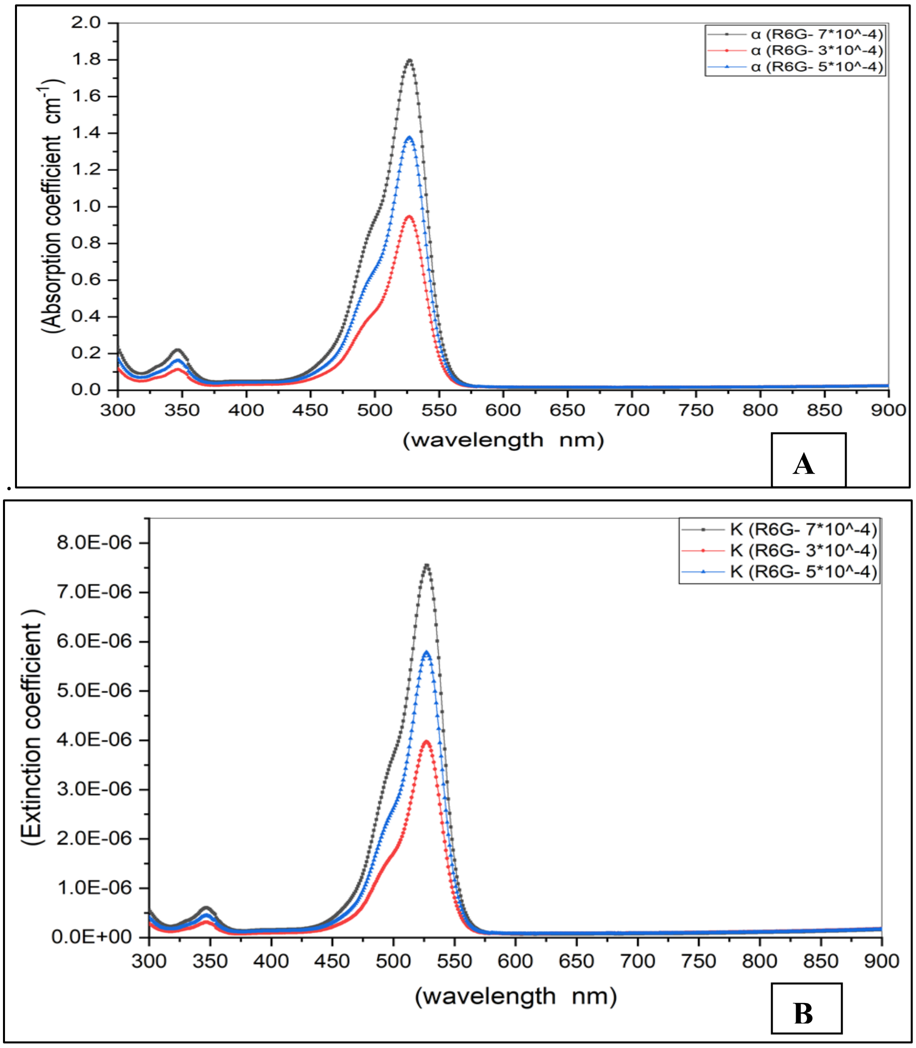


Fig. 7,(a) Absorption coefficient and (b) extinction coefficient of Rhodamine 6G at different dye concentrations.

The UV–Vis absorbance spectra of Rhodamine 6G solutions at different concentrations are shown in Figure 8. The absorbance intensity increases proportionally with dye concentration, indicating compliance with the Beer–Lambert law and confirming the optical stability of the dye.

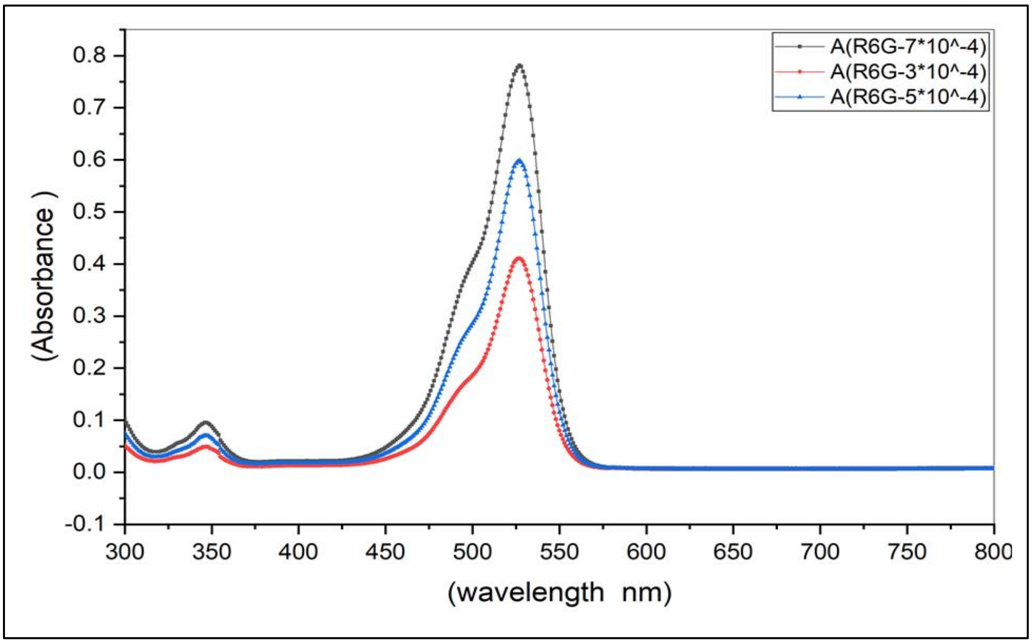


Fig .8 ,UV–Vis absorbance spectra of Rhodamine 6G solutions at different concentrations.

Figure 9 shows the transmission spectra of Rhodamine 6G solutions at various concentrations. A significant decrease in transmission is observed near the absorption maximum, reflecting the inverse relationship between absorbance and transmission.

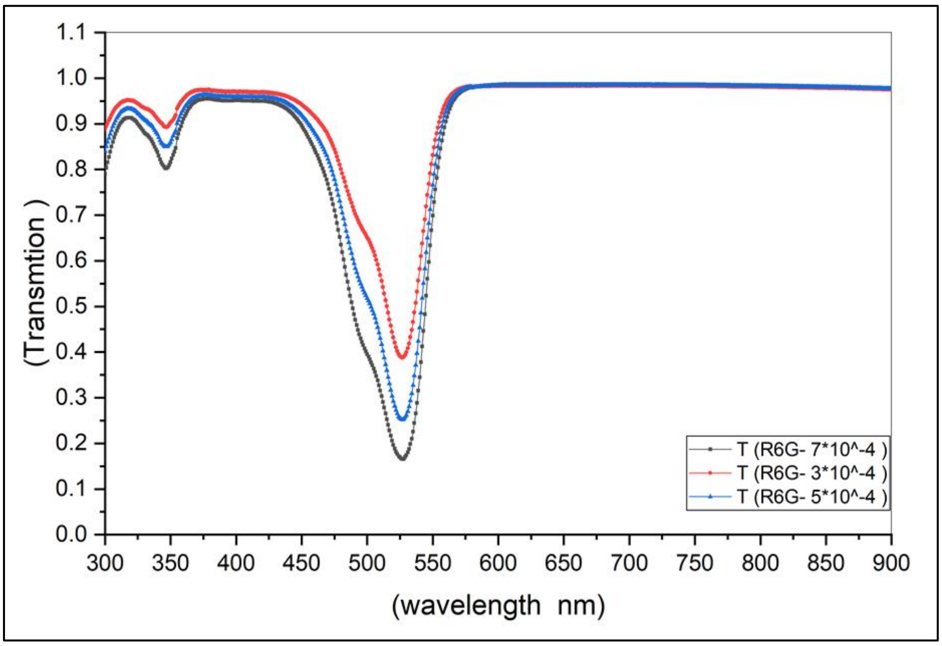
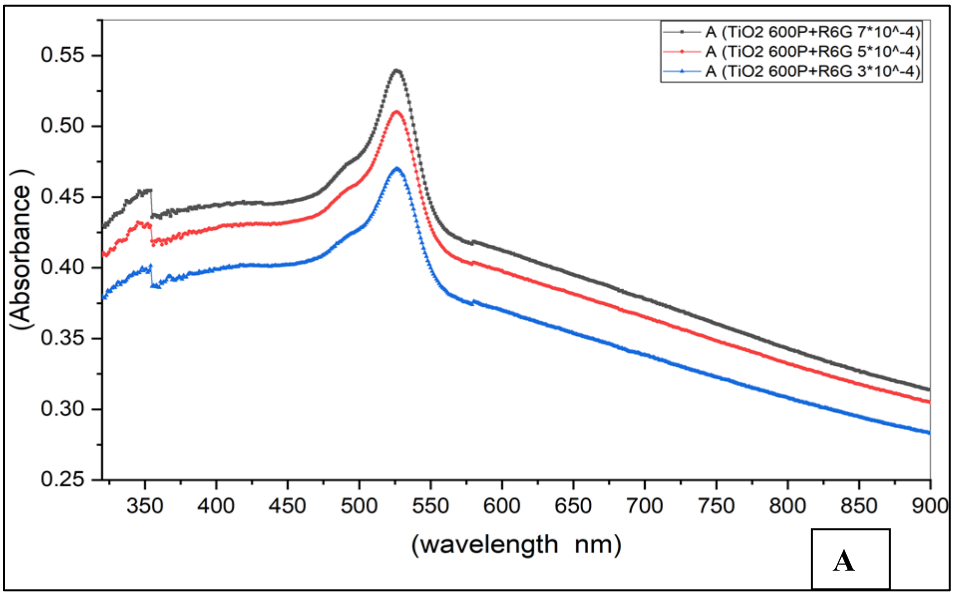
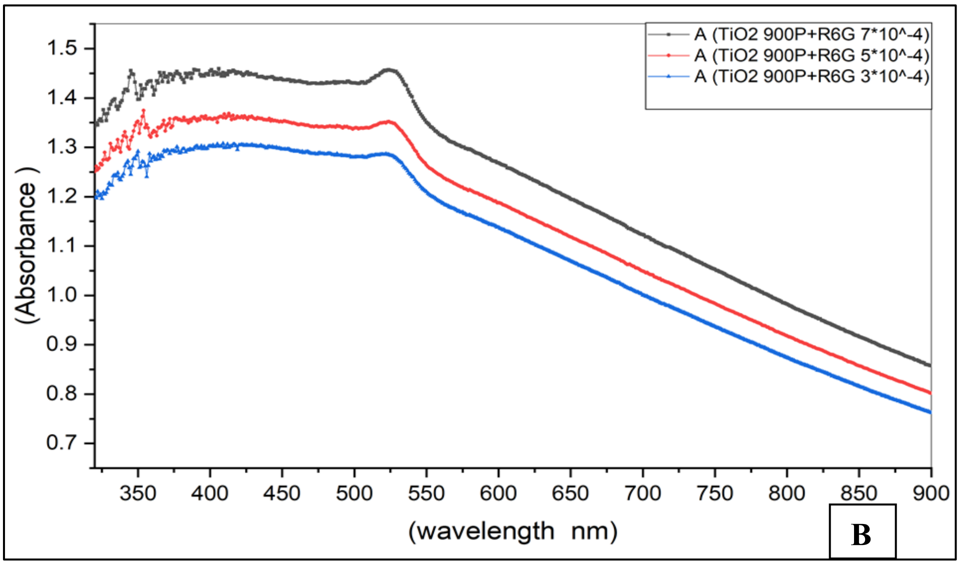


Fig .9,Transmission spectra of Rhodamine 6G solutions at different concentrations.

4.3 OPTICAL PROPERTIES OF TiO_2–R6G HYBRID SYSTEMS

The TiO_2–R6G hybrid systems show improved absorption of visible light compared to pure TiO_2 and R6G, with an increase in absorption intensity with an increase in concentration. The difference in absorption with varying numbers of laser pulse intensity indicates that the structural properties of TiO_2 play an important role. The absorbance spectra of TiO_2–R6G hybrid systems with varying numbers of laser pulse intensity are shown in Figure10(a, b, c). The TiO_2–R6G hybrid systems show improved absorption compared to pure TiO_2 and pure R6G. The intensity of absorption increases with an increase in concentration. The improved absorption in the hybrid system indicates enhanced interaction between TiO_2 and R6G.





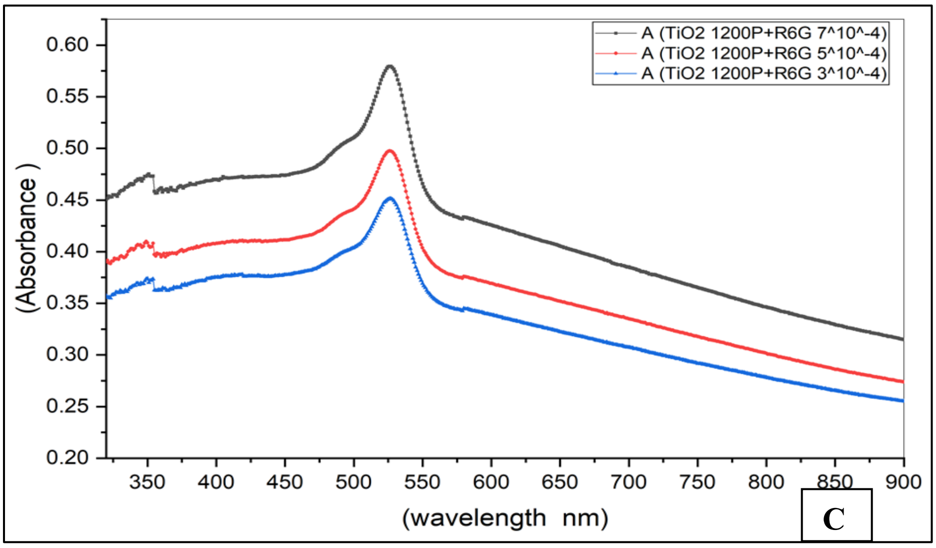


Fig. 10. (a) Absorbance spectra of TiO_2–R6G hybrid system prepared at 600 pulses, (b) 900 pulses, and (c) 1200 pulses at different Rhodamine 6G concentrations.

The enhanced absorption observed in the TiO_2–R6G hybrid systems suggests improved interaction between the dye molecules and TiO_2 particles. This behavior may be attributed to interfacial charge transfer processes. However, further structural and electrical characterization is required to confirm the exact mechanism.

4.4 FLUORESCENCE QUENCHING IN TIO_2–R6G HYBRIDS

In pure form, Rhodamine 6G shows intense fluorescence emission bands around 550-560 nm. Upon doping with TiO2 nanoparticles, it has been observed that the intensity of the fluorescence emission bands decreases significantly, and this effect becomes more pronounced with an increase in the number of laser pulse. This observation indicates that there is a significant amount of non-radiative charge transfer from the excited state dye molecules to TiO2. Figure 11 shows a comparison of the fluorescence emission spectra of pure Rhodamine 6G and TiO2-R6G hybrid systems. The intensity of the fluorescence emission bands decreases significantly, and this effect becomes more pronounced with an increase in the number of laser pulse. The fluorescence reduction in the hybrid samples may be attributed to charge transfer between R6G and TiO_2.

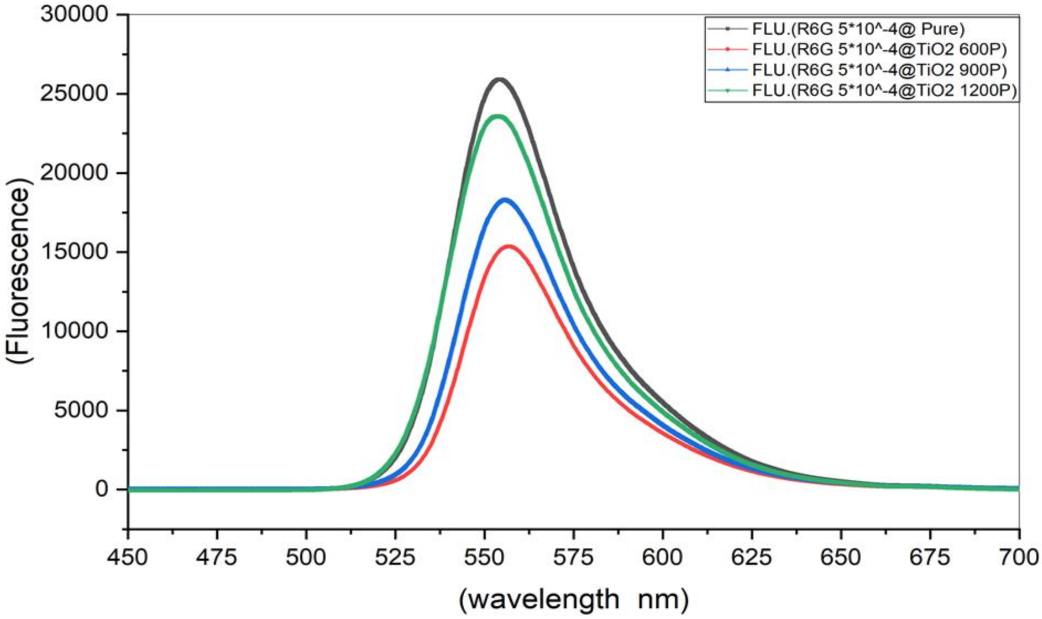


Fig.11 Fluorescence emission spectra of pure Rhodamine 6G and TiO_2–R6G hybrid systems prepared at different laser pulse numbers.

4.5 POTENTIAL APPLICATION OF TIO_2–R6G HYBRID COATINGS IN SOLAR CELLS

The TiO_2–R6G hybrid coatings demonstrate enhanced optical absorption in the visible region, which may contribute to improved light harvesting when applied to solar cell surfaces. This behavior is attributed to the interaction between TiO_2 nanoparticles and Rhodamine 6G molecules, which may facilitate charge transfer processes. However, it is important to note that no electrical measurements were performed in this study. Therefore, the effect of the hybrid coating on the actual performance of solar cells remains a prospective assumption and requires further investigation.

5. CONCLUSIONS

In this present research, the synthesis of TiO2 nanoparticles by pulsed laser ablation in liquid with various pulse numbers was successfully achieved, and the optical properties of the nanoparticles were examined. Based on the findings, it was revealed that an increase in pulse numbers has a significant impact on the optical properties of TiO2, resulting in improved absorption in the ultraviolet region due to changes in concentration, size, and surface characteristics following laser ablation.

The optical properties of Rhodamine 6G dye have been studied for different concentrations of the compound. The compound shows good absorption in the visible region at 520-530 nanometers. The intensity of absorption increases with the increase in concentration while maintaining the peak. The compound shows good optical stability in the extinction and transmission spectra. The intensity of absorption and transmission is inversely proportional according to the Beer-Lambert law.

Hybrid TiO2-R6G systems were successfully synthesized through the combination of TiO2 nanoparticles and Rhodamine 6G dye molecules. Enhanced absorption in the visible region was observed in the hybrid systems, as compared to the absorption of TiO2 and Rhodamine 6G dye individually, indicating the presence of strong interactions between the dye molecules and the semiconductor nanoparticles. The optical properties of the hybrid systems were found to be dependent on the concentration of the dye and the number of laser pulses used to prepare the TiO2 nanoparticles.

From the fluorescence analysis, a high quenching effect was observed in the TiO2-R6G hybrid systems in comparison to the quenching effect of Rhodamine 6G. The quenching effect has been observed to increase with an increase in the number of laser pulses.

The results obtained suggest that the TiO2–Rhodamine 6G hybrid coatings could be used as potential optical coatings for solar cell devices, especially for polycrystalline solar cells.

In conclusion, it can be said that the results have effectively verified that it is possible to control the optical properties of TiO2 and its interaction with Rhodamine 6G using the parameters of laser ablation and concentration. The absorption of visible light and charge transfer in TiO2-R6G hybrid materials have shown that it has potential use in the field of photocatalysis.

Further structural and electrical characterization is required to confirm the applicability of the hybrid system in solar cell devices.

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