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Enhancing the Efficiency and Stability for Next-Generation Solar Energy Harvesting

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ABSTRACT

Scientific research is swiftly advancing to improve solar cell efficiency as a solution to environmental damage from fossil fuels. This study targets two main strategies: the production of nanostructured titanium dioxide (TiO_2 NPs) through electrochemical methods, chosen for its ease, speed, and cost-effectiveness, and the high efficiency of titanium dioxide as a luminous solar concentrator (LSC). X-ray diffraction (XRD), and transmission electron microscopy (TEM) confirmed the formation of titanium dioxide nanorods and spherical particles. The research also utilized Rhodamine B dye only to enhance solar cell efficiency. Combining 50% titanium dioxide with rhodamine dye yielded change in efficiency ($\Delta\eta$) of 70%, whereas individual dye application resulted in ($\Delta\eta$) of 20% for rhodamine dye. These findings mark significant progress toward clean, efficient, and sustainable energy solutions, highlighting the potential of nanotechnology and innovative dye applications to enhance solar cell performance and reduce environmental impact.

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تعزيز الكفاءة والاستقرار لحصاد الطاقة الشمسية من الجيل التالي

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الكلمات المفتاحية:

خلايا شمسية , كفاءة ثاني اوكسيد التيتانيوم النانوي , الطريقة الكهروكيميائية , صبغة الرودامين ب , مركز شمسي مضيء

الـــخُـــلاصـــة

في هذه الدراســه تم تصــنيع جزيئات نانويه كرويه من ثاني اوكســيد التيتانيوم (TiO_2) (27 نانو متر) باستخدام طريقة كهرو كيميائية وتم توصيفها باستخدام حيود الاشعة السينيه (XRD) والمجهر الالكتروني النافذ (TEM) ثم دمجت هذه الجســيمات النانويه مع صــبغة الرودامين ب لتصــنيع مركزشمسي مضيء(LSC) مصمم لتعزيز كفاءة تحويل الخلايا الشمسيه القائمه على السليكون . حقق خلط 50%من ثاني اوكسيد التيتانيوم (TiO_2) مع صبغة رودامين ب تحسنا ملحوظا في الكفاءة ($\Delta\eta$= 70% و η= 1.361), متجاوزا بذلك نسبة 20% الملاحظه مع صبغة الرودامين ب وحده .

تبرز هذه النتائج الية التعزيز تأزرية , مما يظهر امكانية تقنية النانووالتكامل الاستيراتيجي للصبغات في تطوير تقنيات الطاقة النظيفة والفعالة والمستدامة .ويؤكد العمل على جدوى الخلايا الشمسيه الكهروضوئية القائمه على ثاني اوكسيد التيتانيوم كحلول مبتكره لتحسين حصاد الطاقة الشمسية مع تقليل البصمات البيئية .

1. INTRODUCTION

Nanoscience has witnessed remarkable advancements over the past three decades, emerging as one of the most impactful scientific disciplines due to its transformative applications across diverse sectors. These include, but are not limited to, industry, agriculture, medicine, national security, and energy management, among other critical fields [1]. Nanomaterials are specifically characterized by structural dimensions within the nanoscale range (1–100 nm). This precise scale provides them with unique properties—such as enhanced chemical reactivity, exceptional electrical conductivity, and superior mechanical strength—distinguishing them from conventional materials and enabling their interdisciplinary utility. Their superior surface area, high flexibility and hardness, tensile strength, and superior optical and magnetic properties when compared to their counterparts of bulk materials. All these positive characteristics make nanomaterials the ideal solution to enhance the efficiency of solar cells in general, as they are highly efficient semiconductors, and in particular as luminescent solar concentrators (LSC) to enhance light harvesting and reduce light waste [2, 3]. As global efforts are focused to address environmental crises through sustainable energy solutions, photovoltaic (PV) systems have positioned themselves in an advanced stage in renewable energy innovation, offering scalable pathways to mitigate carbon emissions [4]. The rapid adoption of solar power stems from mounting concerns over the ecological damage caused by conventional fossil fuels, coupled with solar energy's inherent reliability and near-limitless availability. Solar cells, recognized as a practical method for investing this energy, capitalize on Earth's substantial solar influx. Scientific estimates indicate that the atmosphere receives approximately 1367 W/m² of solar irradiance, with global absorption rates reaching 1.8×10^{11} MW a capacity far exceeding current worldwide energy demands [5]. In solar cell research, titanium dioxide (TiO_2) nanoparticles have garnered significant attention as a multifunctional n-type semiconductor. With a bandgap energy between 3.2 and 3.35 eV, TiO_2 is widely integrated into photocatalysis, electronic devices, and renewable energy systems. Beyond energy applications, its commercial versatility extends to coatings, polymer composites, cosmetic sunscreens, and printing technologies. This material exists in multiple crystalline phases (e.g., anatase, rutile, and brookite) and can adopt both ordered and disordered atomic configurations [6,7]. To optimize solar energy utilization and minimize losses, researchers have turned to advanced technologies such as

luminescent solar concentrators (LSC). These systems enhance photovoltaic efficiency by concentrating diffuse sunlight, thereby improving energy conversion rates while reducing material waste a critical advancement in sustainable energy infrastructure[8,9]. Furthermore, Rhodamine B is utilized due to its high molar absorptivity ($\varepsilon \approx 106{,}000\ M^{-1}\ cm^{-1}$ in ethanol at 543 nm). The reported fluorescence quantum yields (Φ_f) range from 0.3 to 0.66 [10], depending on the solvent. Fluorescence lifetimes (ϲ) also vary significantly with the solvent, ranging from 3.2 ns in octanol to just 1.5 ns in water. This variation is primarily due to changes in non-radiative relaxation rates. The fundamental reason behind this is not well understood, but one clear trend is that as the polarity of the solvent mixture increases, the quantum yield of Rhodamine B decreases. Some studies have also identified solvent viscosity as a contributing factor in Rhodamine B solvent sensitivity; in high viscosity solvents, the motion of the flexible diethylamino groups on the xanthene ring is restricted, potentially lowering non-radiative decay rates. However, other studies have not found a direct dependence of non-radiative decay rates on solvent viscosity. Specific mode coupling between vibrations of Rhodamine B and those of interacting solvent molecules has also been suggested to explain the large variation in non-radiative decay rate. Additionally, the solvent affects the position of the absorption and emission maxima for Rhodamine B. For cationic Rhodamine B in methanol, these values are 552 nm and 577 nm, respectively, whereas in water, there is a small red-shift of the respective maxima to 557 nm and 580 nm. This red-shift is attributed to a greater stabilization of the highly polarizable excited state due to more favorable interactions between the dye and polar solvents, leading to a decrease in the S0 → S1 energy level gap.2[11,12,13]

2. Experimental details:

2.1 Nanofabrication of Titanium Dioxide TiO_2:

Nanofabrication of titanium dioxide TiO_2 is performed using an electrochemical cell. This method is characterized by its simplicity, productivity, and low cost. Two facing electrodes are immersed in a pre-prepared potassium chloride salt solution (KCl), with one electrode larger than the other. The potassium chloride solution was prepared by dissolving (10) g of potassium chloride in (100) ml of deionized water, from which 5 ml were taken. Additionally, the solution contains a polyvinylpyrrolidone stabilizer (PVP), which helps to maintain the nanoparticle stability and prevent their re-aggregation. This stabilizer was prepared by dissolving (10) g of polyvinylpyrrolidone in (100)ml of deionized water, from which (10) ml were drawn and were added to the cell. The solution volume was then adjusted to 200 ml. Titanium electrodes were immersed and connected to a constant voltage source ranging from 0 to 30 volts, with a current of 0 to 5 amperes. The current was set to 0.05 Am, and the immersion ratio of the electrodes was 1:2. The cell was placed on a hot plate

to stir the solution and ensure uniform electrical conductivity. After one hour, the voltage was removed, and the solution is collected, then centrifuged and washed with deionized water, followed by absolute ethanol. The nanoparticles were then dried in an oven at 70 degrees Celsius for one hour. Subsequently, the collected nanomaterial was calcined in a furnace at 700 degrees Celsius for one hour.

2.2 Characterizations of the synthesized TiO_2

The results of X-ray diffraction showed the formation of titanium dioxide nanoparticles, with Miller indices of (111, 101, 103, 004, 112, 200, 105, 211, 213, 116, 200, 107, and 115) for the 2-theta angle ranging from 20 to 80 degrees, forming a tetragonal shape with an average crystal size of 27 nanometers, as shown in the table 1. The Miller indices were plotted against the 2-theta angle on the x-axis and the intensity on the y-axis that shown in figure 2. The results were seen o be matched with the reference card number (JCPDS Card number: 01-073-1764) [14]. Furthermore, the TEM results revealed nanoparticle agglomerations in the forms of spherical-like structures, as seen in the images in Figures 3.

Table 1 *X-Ray Diffraction data of TiO_2 NPs.*

2-Theta	FWHM	hkl	Geometric shape	D nm
25.692	0.413	101	tetragonal	19.72937
27.806	0.361	110	tetragonal	22.6705
36.476	0.42	101	tetragonal	19.91543
38.192	0.307	110	cubic	27.38406
41.61	0.378	111	tetragonal	22.48262
44.402	0.404	210	tetragonal	21.23863
48.462	0.437	111	cubic	19.93551
54.679	0.882	105	tetragonal	10.13973
55.471	0.441	200	cubic	20.35267
56.983	0.28	220	tetragonal	32.28223
63.074	0.459	002	tetragonal	20.30713
69.192	0.35	211	cubic	27.57365
70.534	0.345	220	tetragonal	28.20302
75.46	0.391	215	tetragonal	25.68946
76.37	0.261	202	tetragonal	38.72413

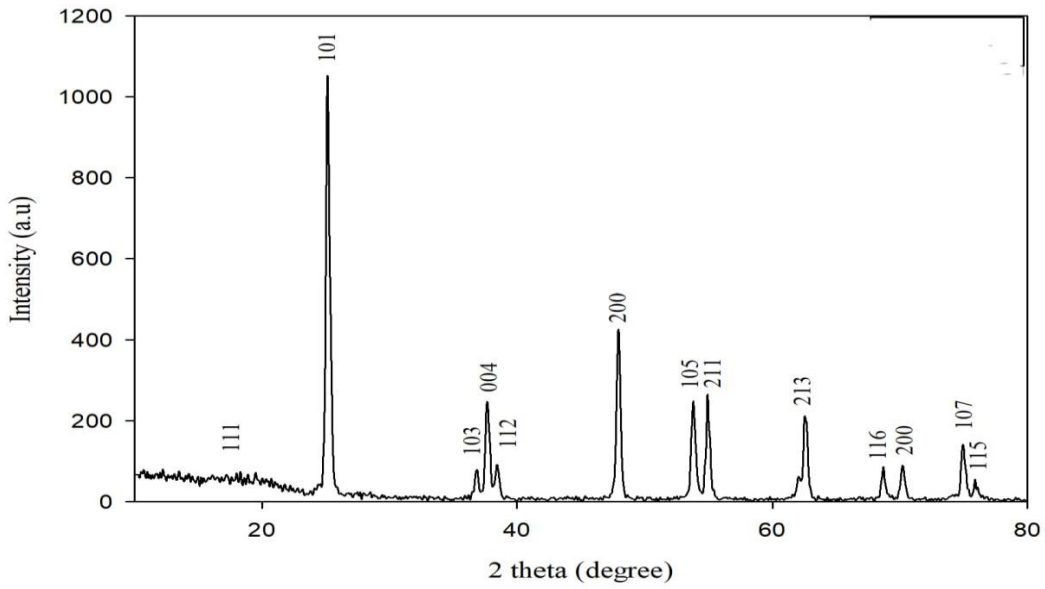


Figure.1 X-Ray Diffraction pattern of TiO_2 NPs.

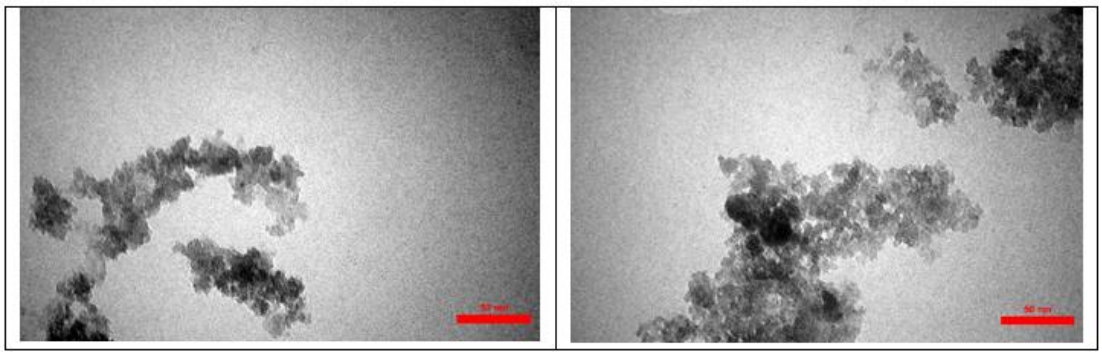
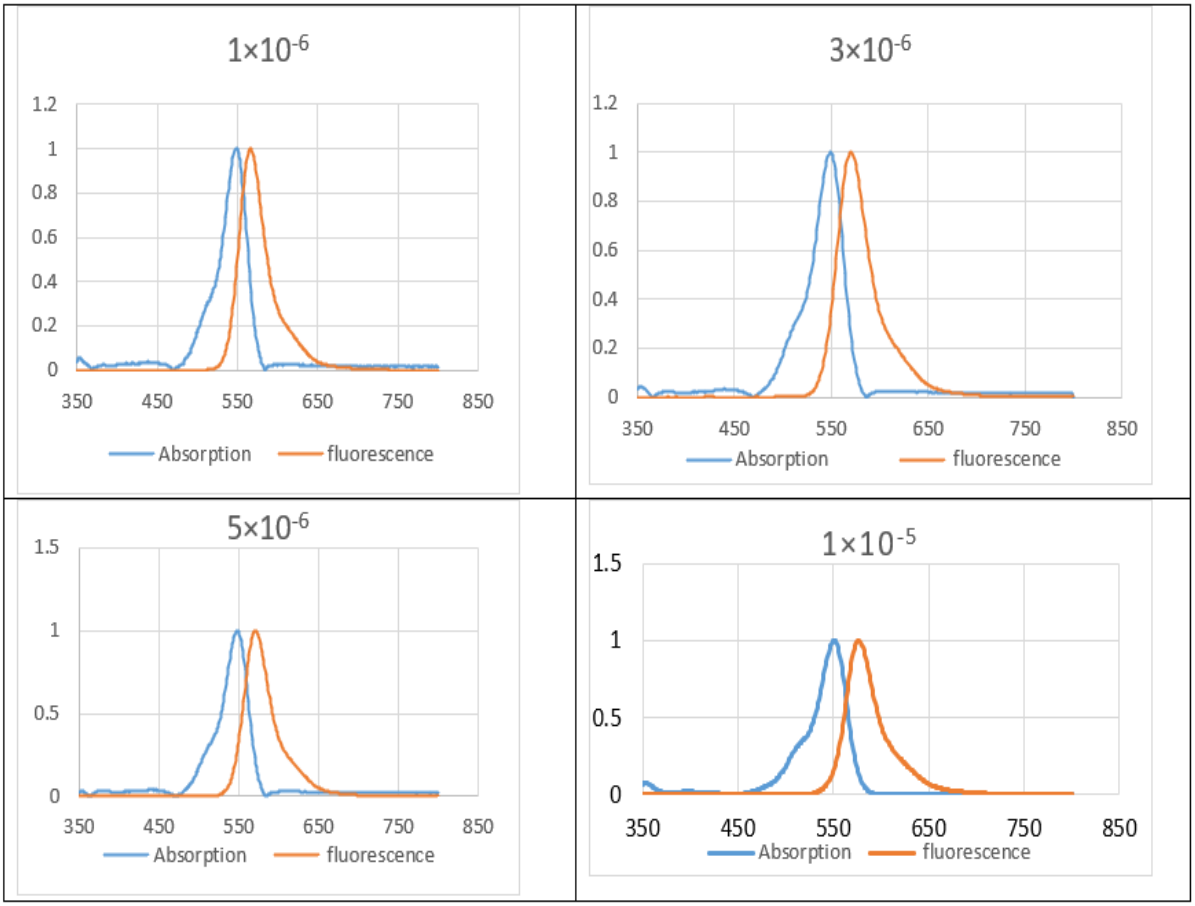


Figure.2 *TEM images of TiO_2 NPs.*

2.3 The quantum efficiency Φ_{fm} for five concentrations of Rhodamine B Dye

Five concentrations of Rhodamine B dye (BDH Chemicals Ltd Poole England) were prepared, namely (1×10^{-5}M, 2×10^{-5}M, 5×10^{-5}M, 1×10^{-4}M, 3×10^{-4}M). The absorption spectra were recorded using a UV-visible spectrophotometer (SCINCO mega-2100) and the fluorescence spectra using a spectrofluorometer (F96PRO from Shanghai Kingdak). Figure (4) included the graph from which the followings were calculated: maximum wavelength of absorbance (λ_{Amax}), maximum wavelength of fluorescence (λ_{Fmax}), Stokes shift ($\Delta\lambda = \lambda_{Fmax} - \lambda_{Amax}$), fluorescence lifetime (τ_{fm}), radiative lifetime (τ_f), and quantum efficiency (Φ_{fm}) for all five prepared concentrations.



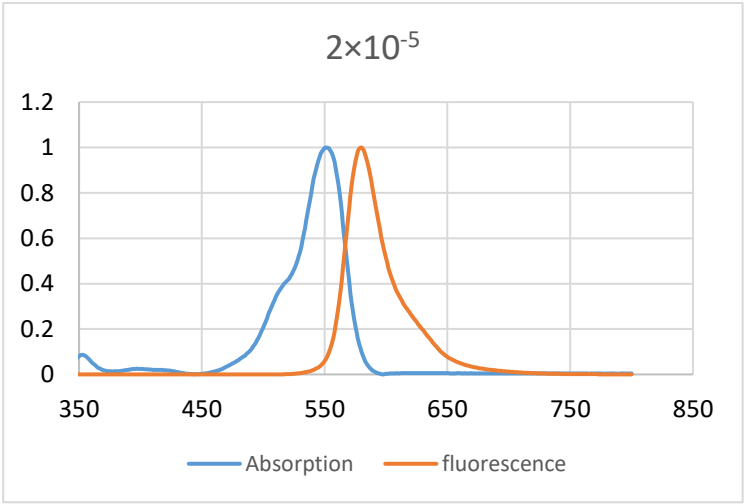


Figure.3 *Absorption and fluorescence plots for the five concentrations.*

Table. 2 *Absorption and fluorescence parameters.*

Concentration (mol/L)	λAmax (nm)	λ Fmax (nm)	Stock Shift Δλ=λflo-λabs (nm)	The radiated Life time τfm(n sec)	The fluorescence Life time τf (n sec)	The quantum efficiency% Φfm
1×10^{-6}	550	566	16	3.8948	3.8309	98.36
3×10^{-6}	549	570	21	3.8575	3.8205	95.55
5×10^{-6}	548	571	24	3.9869	3.8617	96.86
1×10^{-5}	551	576	25	3.8251	3.6549	99.04
2×10^{-5}	551	580	29	3.4525	3.0548	88.48

3. Results and Discussion

Before utilizing the prepared LSC in this study, the solar cell exhibited a baseline efficiency of 3.45%. Following the integration of the Rhodamine B dye-TiO_2 system, the efficiency significantly enhanced to 77%, driven by the synergistic improvements in light harvesting and charge dynamics**.** The Stokes shift results for Rhodamine B dye exhibited values ranging from 16 to 29 for the concentrations listed in Table 2, indicating excellent quantum efficiency outcomes, with a concentration of 1×10^{-5} recorded the highest quantum efficiency of 99.04%, highlighting the first improvement. The second improvement was achieved by adding 50% of previously prepared and characterized nanometric titanium dioxide (TiO_2) to the dye, which significantly enhanced the solar cell conversion efficiency, with a concentration of 2×10^{-5} achieving the highest efficiency of 70.76%, as shown in Table 4. Additionally, the increase in efficiency can be attributed to Rhodamine B dye's broad spectral range, extending from 450 to 575 nm for visible light. The presence of the nanomaterial improved solar cell conversion efficiency by scattering incident light onto the light center, thereby increasing light harvesting toward the solar cell and reducing light losses.

Table 3 *solar cell parameters for Rhodamine B only*

Concentration (mol/L)	Imax (mA)	Vmax (Volt)	FF	η%	Δη%
1×10^{-5}	360.7	0.414	0.658	0.957	20.07
2×10^{-5}	321.9	0.455	0.508	0.938	17.69

5×10^{-6}	307.6	0.429	0.730	0.873	9.53
3×10^{-6}	284.9	0.469	0.631	0.915	14.88
1×10^{-6}	339.3	0.429	0.598	0.925	16.06

Table 4 *solar cell parameters for Rhodamine B with TiO_2 NPS*

Concentration (mol/L)	Imax (mA)	Vmax (Volt)	FF	η%	Δη%
1×10^{-5}	514.5	0.403	0.587	1.329	66.75
2×10^{-5}	506.8	0.419	0.642	1.361	70.76
5×10^{-6}	460.1	0.452	0.644	1.011	26.86
3×10^{-6}	513.0	0.423	0.627	1.025	28.67
1×10^{-6}	475.8	0.432	0.542	1.070	34.30

The addition of 50% titanium dioxide (TiO_2) nanoparticles combined with rhodamine dye to a silicon-based solar cell achieves a 77% efficiency enhancement through synergistic mechanisms: enhanced light absorption occurs as rhodamine captures underutilized visible wavelengths, while TiO_2 high surface area improves dye binding and photon harvesting via photosensitization, further supported by reduced reflective loss due to TiO_2 high refractive index [15]. Efficient charge transfer was enabled by TiO_2 crystalline structure and conduction band alignment, which rapidly shuttles excited electrons from the dye to silicon, minimizing electron-hole recombination [16, 17]. This is complemented by TiO_2 nano-scale properties, which amplify photocatalytic activity, electron-hole pair generation, and light scattering to prolong photon interaction. Crucially, the 50% TiO_2 ratio optimizes light utilization and charge transport without introducing resistance or light-blocking effects [18], collectively overcoming silicon's inherent spectral limitations and charge losses to deliver the

observed 77% efficiency improvement.

4.Conclusion

The resulted data revealed that electrochemical method adopted in this work was seen to be successful in synthesizing nanomaterials with a size scale led, together with using a rhodamine B dye in luminous solar concentrator (LSC) , to a marked increase in solar cell efficiency.

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