

RESEARCH ARTICLE

Studying the optical and electrical properties of thin films using Congo red dye doped with nanoparticles (TiO₂, MgO, SiO₂) in solar luminescent concentrator (LSC) applications

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ABSTRACT

This study investigates improving photovoltaic cell efficiency by developing luminescent solar concentrators (LSCs) based on an organic Congo red dye embedded in a polyvinyl alcohol (PVA) polymer matrix. Thin films were prepared with varying weight percentages of the dye, with the addition of fixed proportions of nanoparticles (SiO₂, MgO, TiO₂) to enhance the optical and electrical properties. Optical characterization results (UV-Vis and fluorescence) showed a steady increase in absorption and fluorescence emission intensity at a fixed wavelength (625 nm) with increasing dye and nanoparticle concentrations. Electrical measurements revealed a significant improvement in solar cell parameters, indicated by a reduction in the energy gap (E_g). Films doped with titanium dioxide (TiO₂) particles achieved the highest efficiency at 4.8%, followed by films doped with magnesium oxide (MgO) at 4.5%, and then films doped with silicon dioxide (SiO₂) at 3.8%, compared to 3.5% for the pure dye. These results demonstrate that incorporating nano-enhancers, particularly titanium dioxide, represents a promising strategy for improving the performance of solar photovoltaic concentrators and advancing renewable energy applications.

Keywords: Congo Red, PVA, Nanoparticles (SiO₂, MgO, TiO₂), Luminescent Solar Concentrator (LSC), Solar Cell Efficiency.

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1. Introduction

Solar energy is one of the renewable energy sources that provides heat and light ^[1]. Light travels from the sun to Earth in about 8 minutes and 9 seconds ^[2]. Solar energy is divided into two main groups based on its use: photovoltaic energy and solar thermal energy. The photovoltaic effect is the process by which sunlight is directly converted into electrical energy, as in photovoltaic (PV) cells. Solar thermal systems, on the other hand, are devices that utilize sunlight to produce thermal energy (such as heating water or air) ^[3]. Photovoltaic cells are a clean and environmentally safe energy source and an efficient and continuous source of electricity generation ^[4]. Many studies have been conducted to convert solar energy into electrical energy from heat and light ^[5]. Using photovoltaic cells, sunlight energy is converted into electrical energy. Many scientific studies and experiments have been conducted to improve the efficiency of solar cells. Some studies have focused on developing techniques for simple wet chemical etching processes to produce a Nanoscale porosity pattern on the silicon surface of photovoltaic cells ^[6]. The design and use of concentrators on solar cells has been an important topic in many studies. Some plastic and glass panels and dyes act as photo

concentrators, collecting sunlight and re-emitting it at longer wavelengths. Both organic and inorganic dyes can be used [7]. Organic dyes are natural compounds derived from plants, animals, or minerals. Organic dyes are readily available and easy to obtain, and they have high fluorescence, so they can be used as a light center for the thin layer of a solar cell [8].

1.1. luminescent solar concentrators (LSC)

To increase the efficiency of the solar cell, some photovoltaic (PV) cells are coupled with luminous solar concentrators (LSC). The plastic and glass sheets coated with luminous materials such as dyes that absorb sunlight of a certain wavelength and emit light of a longer wavelength are known as the luminous solar concentrator (LSC). Most of the light resulting from total internal reflection is surrounded before being directed to the edges of the luminous solar concentrator and into the solar cell.[7] Figure (1) depicts the layout of a luminescent solar concentrator (LSC).

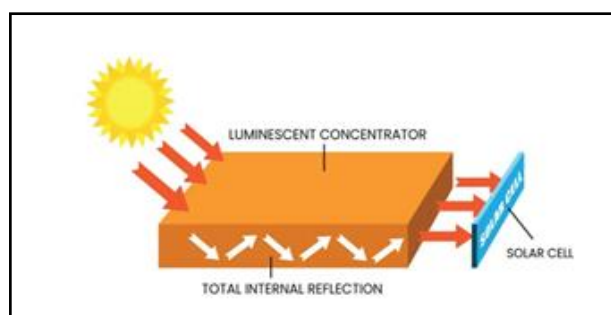


Figure 1. Luminescent Solar Concentrator

1.2. Organic dyes

A dye or colorant is a type of chemical substance that is either liquid or solid and dissolves in the medium to which it is added. It works to form a homogeneous mixture that changes the color of the medium it is in. Examples include ink, food additives, plastics, and many other materials in which it is used [9]. Figure (2)



Figure 2. shows the pigment colors

It is a substance that changes the color of the medium it enters and is soluble. The pigment can be of natural origin, whether animal, plant, or mineral, in which case, it is necessary to use separation methods such as distillation or solvent extraction. It can also be produced through chemical manufacturing. Pigments are found in food, especially in beverages and sweets. They are also used for dyeing clothes. Pigments are the main component of paints [9]. Natural dyes are renewable, biodegradable, and eco-friendly since they are derived from plant extracts, minerals, or animal sources. Furthermore, they frequently use fewer chemical procedures during manufacture, which lowers pollution [10]. While synthetic dyes are made from petrochemical materials that pollute the environment [11].

1.3. Nanomaterial's

They are materials whose dimensions typically range between (1 and 100) nm and are known as nanomaterial's (NMs) [12]. Nano materials are characterized by their small size and large surface area, which

confers them some distinctive properties and behaviors. Therefore, they are used in many different fields, such as environmental research, electronics, energy, and medicine [13].

1.4. Linear optical properties

The study of linear optical properties involves examining how a material interacts with the electric field of light, which is directly proportional to the material's properties such that its constants, like refraction and absorption, are independent of the incident light intensity, as expressed by the relationship:

$$P = \epsilon_0 \chi^{(1)} E \quad (1)$$

Where: (P) Polarization, (ϵ_0) Permittivity of space, ($\chi^{(1)}$) Linear electrical susceptibility, (E) Applied electric field [14].

1.5. Organic Congo Red Dye

It is an anionic organic dye belonging to the azo dye class, containing two azo groups (N = N) linking aromatic rings. It is a solid with a red color due to its absorption of light at approximately 500 nm wavelengths within the visible spectrum. Its molecular formula is $C_{32}H_{22}N_6Na_2O_6S_2$. It exhibits high chemical stability, making it suitable for Stokes displacement applications. This allows it to be used as a photo-center in low-voltage solar cells (LSC). Experiments have shown that when combined with certain polymer materials such as (PVA), it acquires high fluorescence properties [15].

1.6. Fluorescence

Fluorescence is a form of photoluminescence, where molecules absorb photons of light, which leads to their excitation, i.e., their transition from lower levels to levels with higher electronic energy. This is followed by a rapid temporary relaxation process, after which the molecule loses part of its energy and descends to the ground levels. This process is accompanied by the emission of a photon of light, and the process takes place at a short time rate. The photoluminescence process begins with the absorption of a photon by the molecule, which leads to a transition from the ground state (s_0) to higher levels (s_1 and s_2). Upon reaching the excited state, it undergoes a short vibrational relaxation, losing some of its energy through non-radiative collisions, and descends to the lowest vibrational level. Electrons can also lose their energy in another way through internal transformation [16].

1.7. Photovoltaic cell parameters:

The study includes some of the photovoltaic characteristics of the solar cell in terms of its efficiency, the amount of energy it produces, the packing factor, as well as the open-circuit voltage and short-circuit current.

1.7.1. Current and voltage characteristics (VOC).

The open-circuit voltage (V_{OC}) can be defined as the maximum achievable voltage of a solar cell under zero load current [17]. when ($R_L = \infty$). Its value can be calculated mathematically using the following relationship:

$$V_{OC} = \frac{kT}{q} \ln \left(\frac{I_L}{I_0} + 1 \right) \quad (2)$$

Where: (k) Boltzmann's constant, (T) absolute temperature, (q) charge of the electron, (I_L) incident light current, (I_0) reverse saturation current.

1.7.2. Short circuit current (Isc):

The short-circuit current (I_{sc}) is defined as the maximum current generated by a solar cell at zero voltage ($v = 0$). It is directly proportional to the incident light intensity and the surface area of the solar cell [18], and is expressed by the following equation:

$$I_{sc} = I_0 \left(e^{\frac{qV_{oc}}{KT}} - 1 \right) \quad (3)$$

$$I = I_L = I_{sc} \quad (4)$$

1.7.3. Solar Cell Efficiency (η)

The efficiency of solar cells (η) is defined as the ratio of the electrical power produced to the power of the incoming solar radiation, and is given by the following relationship: ^[19]

$$\eta = \frac{P_{out}}{P_{in}} = \frac{V_{oc} I_{sc} FF}{P_{in}} \quad (5)$$

To calculate the efficiency of a solar cell when adding photovoltaic concentrators (LSC), this efficiency improvement ($\Delta\eta$) is calculated by comparing the efficiency of the solar cell after the addition ($\eta\%$)_{LSC} to the efficiency of the solar cell in isolation ($\eta\%$)_{bare}, using the following relationship: ^[20]

$$\Delta\eta = \frac{(\eta\%)_{LSC} - (\eta\%)_{bare}}{(\eta\%)_{bare}} \times 100\% \quad (6)$$

The resulting ratio is considered a measure of the effectiveness of the photocenter.

1.8. Results and Discussion:

Thin nanofilms with a thickness of 130 μm were prepared by adding 1g of polyvinyl alcohol (PVA) to 30 mL of distilled water. Three different weights of Congo Red dye (0.002, 0.004, and 0.006 g) were also added to these prepared films. The optical properties (absorption) were investigated using UV spectroscopy (Figure 3), and the emission spectroscopy (transmittance) was investigated using fluorescence spectroscopy (Figure 4).

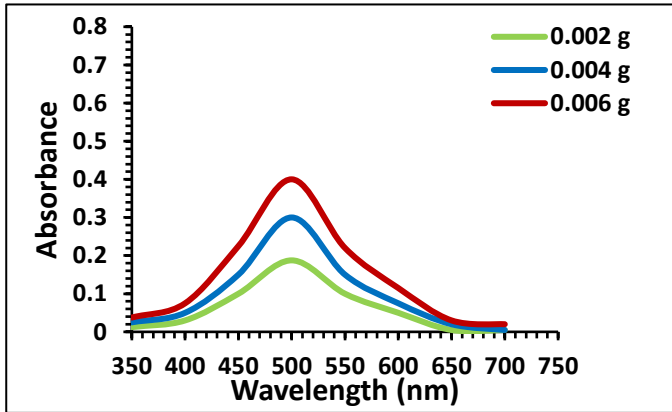


Figure 3. Absorption spectrum of PVA/Congo red dye films at different weights.

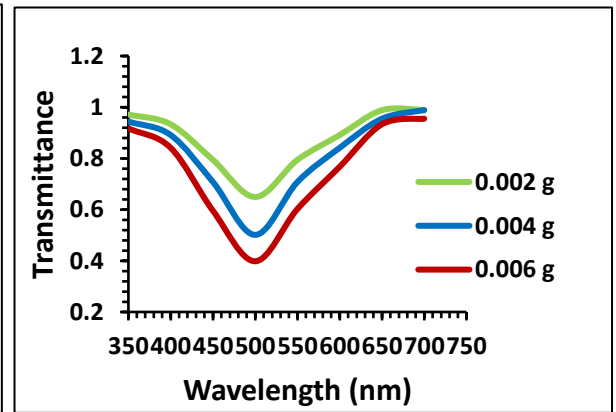


Figure 4. Emission spectrum of PVA/Congo red dye films at different weights.

The results showed an increase in absorbance A , reflectance R , absorption coefficient α , and extinction k , as well as a clear decrease in energy gap values E_g and a clear and significant decrease in transmittance with increasing weight percentages of the dye, Table (1).

Table 1. Optical properties of (PVA) films prepared with different weights of Congo red dye.

Weight (g) (CR)	A	T	R	$\alpha(\text{cm}^{-1})$	$K(4 \times 10^{-4})$	n	$E_g(\text{ev})$
0.002	0.213	0.613	0.174	57.7	2.52	2.43	2.15
0.004	0.331	0.467	0.202	89.6	3.92	2.63	2.02
0.006	0.401	0.389	0.210	108.6	4.75	2.69	1.88

A fixed weight percentage of silicon dioxide nanoparticles (SiO₂) was added to those nanofilms prepared with different weight percentages of dye (0.002, 0.004, and 0.006 g). The absorption spectrum was studied using ultraviolet spectroscopy (Figure 5), and the emission spectrum was studied using a fluorescent device (Figure 6).

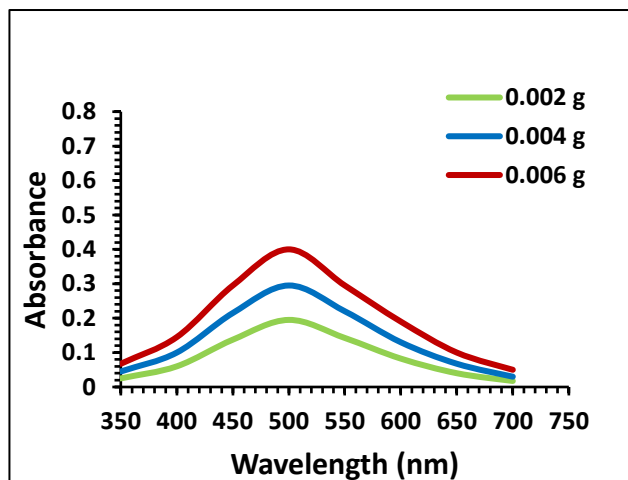


Figure 5. Absorption spectrum of (PVA/Congo red dye) films with added SiO₂ at different weights.

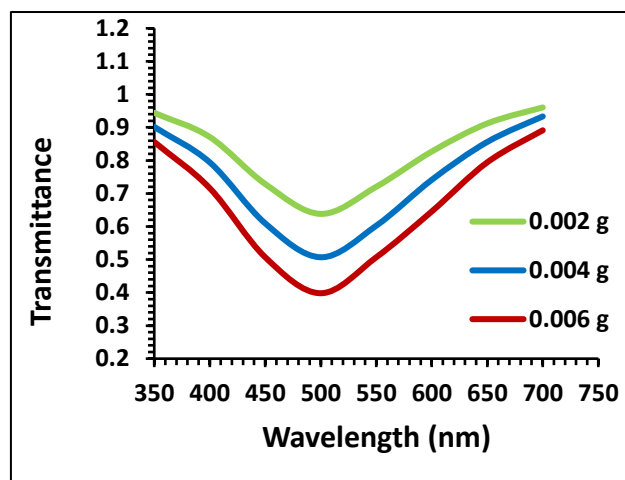


Figure 6. Emission spectrum of PVA/Congo red dye films with added SiO₂ at different weights.

The results showed an increase in absorbance A , absorption coefficient α , and extinction coefficient K , as well as a clear decrease in energy gap values and a clear decrease in transmittance with increasing weights and concentrations of Congo red dye doped with silicon dioxide nanoparticles SiO₂.

Table 2. optical properties of (PVA) films prepared with different weights of Congo red dye and with the addition of (SiO₂) nanoparticles.

Weight (g) (CR)	A	T	R	$\alpha(\text{cm}^{-1})$	K (1×10^{-4})	n	E_g (ev)
0.002	0.196	0.638	0.166	50.1	2.20	2.38	2.21
0.004	0.293	0.509	0.198	75.0	3.28	2.60	2.10
0.006	0.402	0.398	0.201	102.6	4.49	2.62	1.95

A fixed weight percentage of silicon dioxide nanoparticles (MgO) was added to those nanofilms prepared with different weight percentages of dye (0.002, 0.004, and 0.006 g). The absorption spectrum was studied using ultraviolet spectroscopy (Figure 7), and the emission spectrum was studied using a fluorescent device (Figure 8).

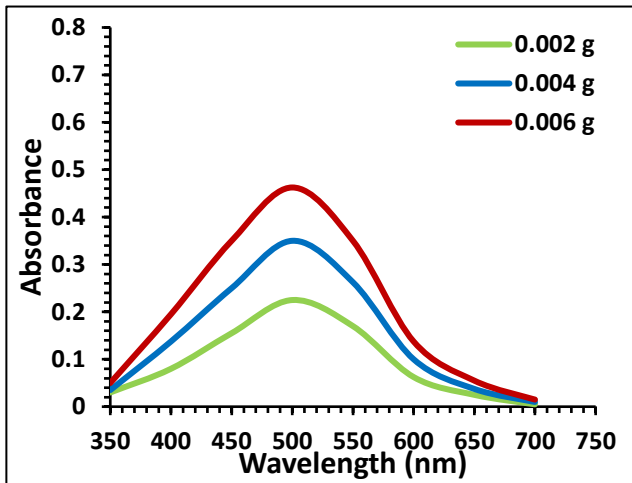


Figure 7. Absorption spectrum of (PVA/Congo red dye) films with added (MgO) at different weights.

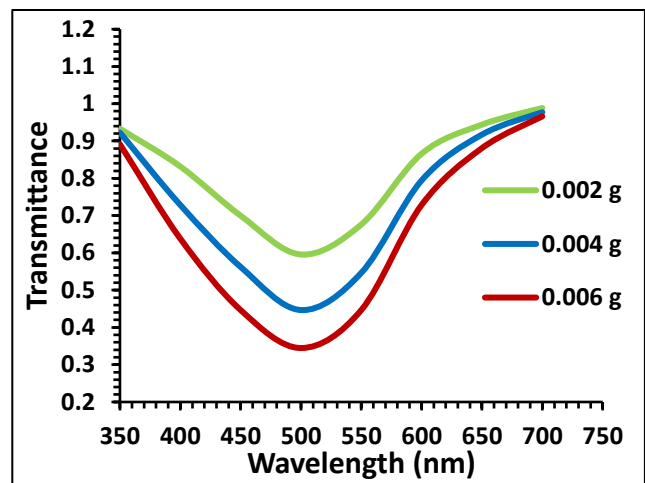


Figure 8. Emission spectrum of (PVA/Congo red dye) films with added (MgO) at different weights.

The results showed an increase in absorbance, absorption coefficient, and extinction coefficient, as well as a clear decrease in energy gap values and a clear decrease in transmittance with increasing weights and concentrations of Congo red dye doped with magnesium oxide nanoparticles MgO. Table (3).

Table 3. optical properties of (PVA) films prepared with different weights of Congo Red dye and with the addition of (MgO) nanoparticles.

Weight (g) (CR)	A	T	R	$\alpha(\text{cm}^{-1})$	K ($\times 10^{-4}$)	n	Eg (ev)
0.002	0.226	0.595	0.179	54.8	2.40	2.47	2.12
0.004	0.355	0.446	0.199	86.1	3.77	2.61	1.99
0.006	0.445	0.344	0.211	107.9	4.72	2.70	1.86

A fixed weight percentage of silicon dioxide nanoparticles (TiO_2) was added to those nanofilms prepared with different weight percentages of dye (0.002, 0.004, and 0.006 g). The absorption spectrum was studied using ultraviolet spectroscopy (Figure 9), and the emission spectrum was studied using a fluorescent device (Figure 10).

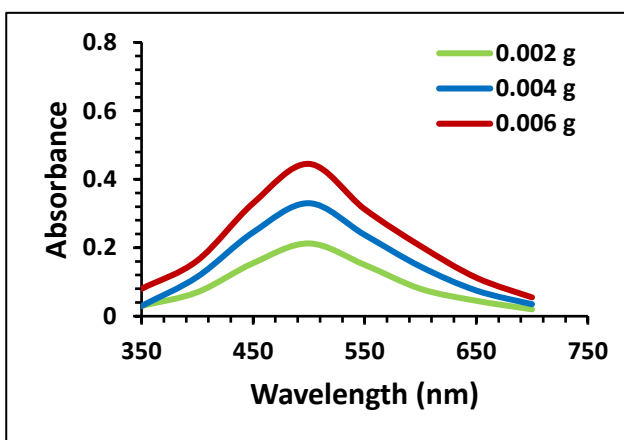


Figure 9. Absorption spectrum of (PVA/Congo red dye) films with added (TiO₂) at different weights.

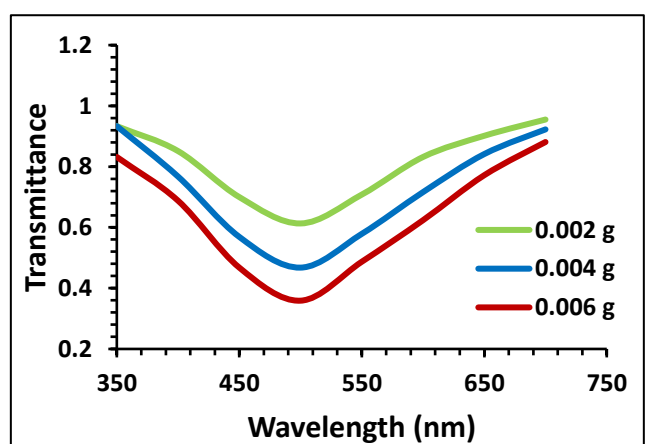


Figure 10. Emission spectrum of (PVA/Congo red dye) films with added (TiO₂) at different weights.

The results showed an increase in absorbance, absorption coefficient, and extinction coefficient, as well as a clear decrease in energy gap values and a clear decrease in transmittance with increasing weights and concentrations of Congo Red dye doped with titanium dioxide nanoparticles TiO₂. Table (4). This behavior aligns with the findings reported in research [21].

Table 4. optical properties of (PVA) films prepared with different weights of Congo red dye and with the addition of (TiO₂) nanoparticles.

Weight (g) (CR)	A	T	R	$\alpha(\text{cm}^{-1})$	K (1×10^{-4})	n	Eg (ev)
0.002	0.205	0.62	0.175	47.2	2.06	2.43	2.18
0.004	0.315	0.48	0.205	72.5	3.17	2.65	2.05
0.006	0.430	0.36	0.210	99	4.33	2.69	1.92

The fluorescence curve results showed a clear increase in light emission intensity with increasing weights of the Congo red dye, with the peak remaining stable at approximately (625)nm. This enhances the efficiency of the films in converting the focus of incident light, a promising indicator for improving the efficiency of photoconcentrators, Figure (11).

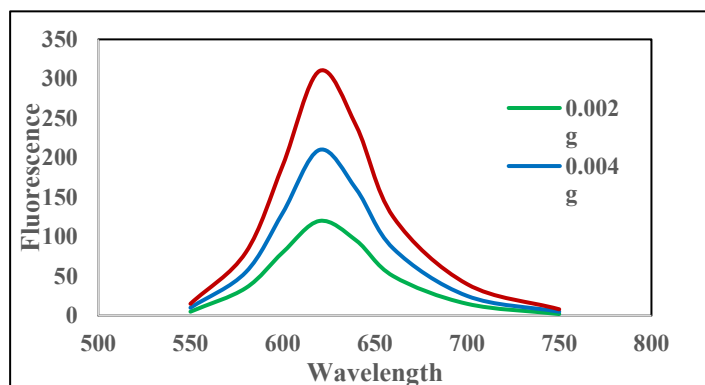


Figure 11. Fluorescence spectra of Congo red dye at different weights

The results of the fluorescence curves showed an increase in the intensity of light emission with increasing weights of the Congo Red dye with added (SiO₂) Nanoparticles, where the peak of the spectrum proved stable at a wavelength of (625) nm, which proves the efficiency of the films in converting the concentration of incident light, and this is a good indicator in raising the efficiency of the photoconcentrator Figure (12).

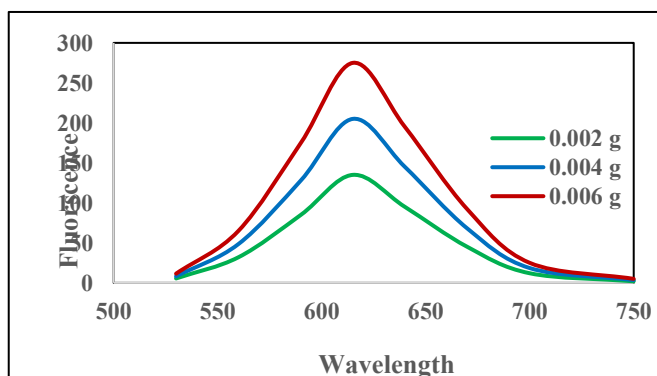


Figure 12. Fluorescence spectra of Congo Red dye with added SiO₂ Nanoparticles at different weights

The results of the fluorescence curves showed an increase in the intensity of light emission with increasing weights of the Congo Red dye with added (MgO) Nanoparticles, where the peak of the spectrum proved stable at a wavelength of (625) nm, which proves the efficiency of the films in converting the concentration of incident light, and this is a good indicator in raising the efficiency of the photoconcentrator, Figure (13).

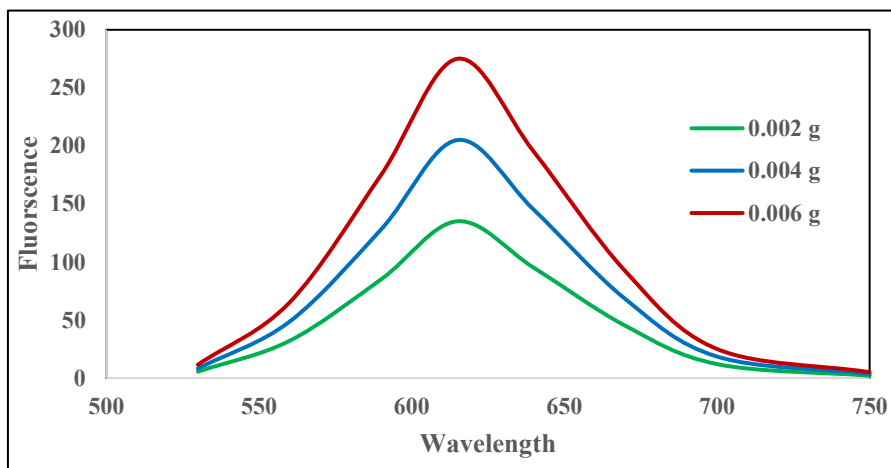


Figure 13. Fluorescence spectra of Congo Red dye with added (MgO) Nanoparticles at different weights Nanoparticles at different weights

The results of the fluorescence curves showed an increase in the intensity of light emission with increasing weights of the Congo Red dye with added (TiO₂) Nanoparticles, where the peak of the spectrum proved stable at a wavelength of 625 nm, which proves the efficiency of the films in converting the concentration of incident light, and this is a good indicator in raising the efficiency of the photoconcentrator, Figure (14).

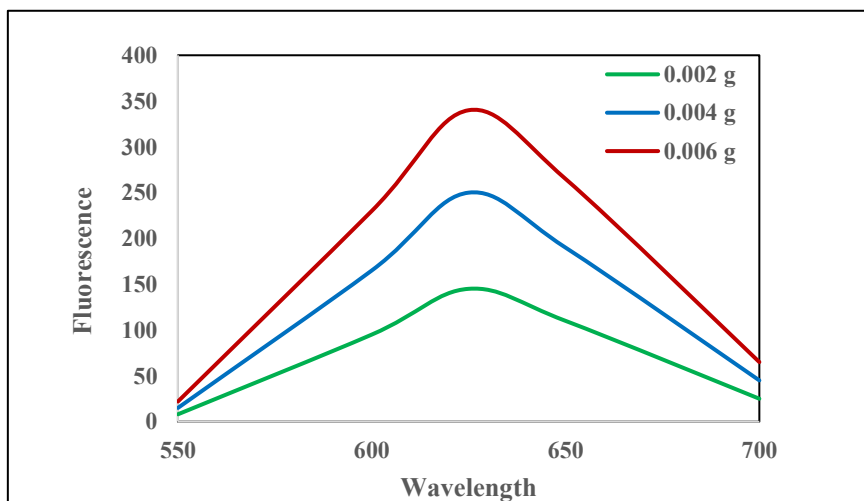


Figure 14. Fluorescence spectra of Congo Red dye with added (TiO₂) Nanoparticles at different weights Nanoparticles at different weights

The results showed a significant improvement in the efficiency of the solar cell ($\eta\%$) as a result of the clear increase in short-circuit current (I_{sc}), open-circuit voltage (V_{oc}), and fill factor (FF) with increasing the weight loading ratio of the Congo red pigment, as shown in Table (5).

Table 5. Performance parameters of solar cells made from (PVA) films doped with Congo red dye at different weights.

Weight (g) (CR)	I _{sc} (A)	V _{oc} (V)	FF	η%
0.002	2.2	0.55	0.5	0.8
0.004	5.0	0.62	0.57	1.9
0.006	8.5	0.66	0.6	3.5

The results showed a significant improvement in the efficiency of the solar cell (η%) as a result of the clear increase in short-circuit current (I_{sc}), open-circuit voltage (V_{oc}), and fill factor (FF) with increasing the weight loading ratio of (SiO₂) nanoparticles added to the Congo red dye, as shown in Table (6). It also aligns with research [22].

Table 6. Performance parameters of the solar cell made from PVA films doped with Congo red dye at different weights, with the addition of (SiO₂) nanoparticles.

Weight (g) (CR)	I _{sc} (A)	V _{oc} (V)	FF	η%
0.002	2.5	0.57	0.55	0.9
0.004	5.5	0.61	0.59	2.19
0.006	9.8	0.67	0.61	3.8

The results showed a significant improvement in the efficiency of the solar cell (η%) as a result of the clear increase in short-circuit current (I_{sc}), open-circuit voltage (V_{oc}), and fill factor (FF) with increasing the weight loading ratio of (MgO) nanoparticles added to the Congo red dye, as shown in Table (7).

Table 7. Performance parameters of the solar cell made from PVA films doped with Congo red dye at different weights, with the addition of (MgO) nanoparticles.

Weight (g) (CR)	I _{sc} (A)	V _{oc} (V)	FF	η%
0.002	3.23	0.59	0.57	1.18
0.004	6.21	0.63	0.60	2.2
0.006	10.13	0.7	0.62	4.5

The results showed a significant improvement in the efficiency of the solar cell (η%) as a result of the clear increase in short-circuit current (I_{sc}), open-circuit voltage (V_{oc}), and fill factor (FF) with increasing the weight loading ratio of (TiO₂) nanoparticles added to the Congo red dye, as shown in Table (8).

Table 8. performance parameters of the solar cell made from PVA films doped with Congo red dye at different weights, with the addition of (TiO₂) nanoparticles.

Weight (g) (CR)	I _{sc} (A)	V _{oc} (V)	FF	η%
0.002	3.5	0.60	0.60	1.2
0.004	6.5	0.65	0.62	2.6
0.006	10.5	0.72	0.65	4.8

2. Conclusion

1. Efficiency of Polymer Films: The use of polyvinyl alcohol (PVA) polymer as a matrix for the Congo Red dye demonstrated high efficiency in forming homogeneous thin films that function as effective light-concentrating solar cells (LSCs).

2. Optical Properties: Increasing the weight concentration of the Congo Red dye and the added nanomaterials resulted in a significant improvement in absorbance and absorption coefficient (α), with a decrease in transmittance, thus enhancing the film's ability to trap photons.

3. Stability of the Emission Spectrum: Fluorescence curves showed that the photoemission peak remained stable at a wavelength of 625 nm for all prepared samples, indicating that the Stokes shift was sufficient to prevent reabsorption and increase light flux towards the cell edges.

4. Effect of Nano-Enhancing Agents: The addition of nano-oxides contributed to varying degrees of energy conversion efficiency ($\eta\%$). Titanium dioxide particles (TiO_2) achieved the highest efficiency at 4.8%, followed by magnesium oxide (MgO) at 4.5%, and then silicon dioxide (SiO_2) at 3.8%, compared to the pure pigment, which recorded 3.5%.

5. Electrical Characteristics: The study recorded a direct increase in short-circuit current (J_{sc}) and open-circuit voltage (V_{oc}) with increasing nano-load ratios, confirming the success of the concentrators in focusing incident solar radiation and converting it into additional electrical energy.

6. Sustainability: This study provides an economical and environmentally friendly solution using renewable organic pigments and nanomaterials to enhance the performance of conventional solar cells and reduce the cost of energy production.

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