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γ -CD-Functionalized TiO₂ Nanoparticles For the Photocatalytic Degradation of Organic Dyes

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ABSTRACT

n this work, an efficient photocatalyst based on gamma-cyclodextrinmodified titanium dioxide nanoparticles (TiO_2/γ -CD NPs) was synthesized and used for photocatalytic degradation of rhodamine B (RhB), methyl orange (MO) and methylene blue (MB). The results of FESEM, EDX, TEM, FT-IR, XRD and BET surface area measurement showed that the TiO_2 NPs were effectively modified with y-CD. The photocatalytic properties of the TiO_{y} -CD NPs were evaluated by the degradation of some organic dyes in aqueous solution under ultraviolet (UV) light illumination. The experimental results confirmed that the TiO₃/y-CD had exhibited efficient photocatalytic activities higher than that of the pure TiO_2 in the degradation of investigated dyes. The y-CD could increase the lifetime of the excited states of the unreactive guests and facilitate electron transfer from the excited dye to TiO_2 conduction band. The results indicated that the first-order kinetic model well describes the degradation of the dyes by TiO_2/γ -CD NPs. The photocatalytic reaction rate constants for RhB, MO and MB dyes in the presence of TiO_2/γ -CD NPs were 4, 5.6 and 4.2 times higher than that of pure TiO₂, respectively. In addition, the TiO₂/ γ -CD NPs can be used for several times in real application as an effective photocatalyst. Prog. Color Colorants Coat. 13 (2020), 23-39© Institute for Color Science and Technology.

1. Introduction

Nowadays, water pollution has become an increasingly serious problem with organic dyes as common contaminants [1]. Dyes are among the hazardous chemical compounds which are found in industrial effluents. Therefore, it is essential to find adequate treatments to eliminate them because their presence in water at first place decreases light diffusion, preventing the photosynthesis of aqueous plants [2-4]. Also, dyes can cause dermatitis, allergy, skin irritation and also a mutation in humans and provoke cancer [5-7]. Thus, the efficient treatment of colored wastewaters is very important to reduce emissions of toxic dyes and protect the aquatic environment [8-10].

In recent years, many efforts have been dedicated to decompose the hazardous organic dyes [11]. Advanced oxidation processes (AOPs) act based on the formation of unstable and powerful species with high reactivity tendency (e.g. O_2^{-} , •OH, H_2O_2). These species mineralize the resistant organic materials to harmless materials such as carbon dioxide and water [12, 13]. Semiconductor photocatalysis is an attractive AOP because of many advantages, such as applying solar or UV light, complete mineralization of the pollutants,

and low to moderate cost [14, 15].

Among them, photocatalysis utilizing titanium dioxide (TiO₂) seems to be the most attractive method for water decontamination [16]. TiO₂ has three different crystalline phases (anatase, rutile, and brookite) among which anatase TiO_2 is the best photocatalyst because of the low recombination rate of its photo-generated electrons and holes [17]. Another reason for the increased interest in TiO₂ is that the process can be carried out under ambient conditions. Also, TiO₂ has the advantages of high chemical stability, availability, relatively low price and nontoxicity [18]. However, TiO₂ can only use less than 5% of the available due to its large band gap (anatase = $\frac{1}{2}$ 3.2 eV). Many techniques have been examined not only to extend the spectral response of TiO₂ into the visible region but also to reduce the recombination of photo-generated electrons and holes, thus enhancing its photocatalytic activity. Since the photocatalytic reactions predominantly occur on the surface, the interaction affinity between TiO₂ and pollutants is the key factor that can influence the photocatalytic efficiency. The most commonly used method for enhancing the surface coverage of organic pollutants on the catalyst is the surface modification of TiO₂ particles [19, 20].

Among the various surface modifiers, cyclodextrins (CDs) could be specified. Gamma-cyclodextrin (γ-CD) is considered to be important owing to its special features such as torus-shaped ring structure, suitably sized hydrophobic cavity, hydrophilic exterior and ecofriendly nature [19, 20]. As one of the most common host molecules, y-CD not only modifies the external morphology of the photocatalyst, but also enhances the intrinsic properties including photoelectric activity, photo-activity and energy transfers [21-24]. y-CD could stabilize TiO₂ colloids and facilitate interfacial electron transfer processes [25-27]. y-CD can capture photo-generated holes when attached to the TiO₂ surface, which leads to the enhanced photocatalytic degradation of TiO_2 [28]. γ -CD-modified TiO_2 particles could concentrate and adsorb the organic pollutants from its aqueous solution and transfer it to the photocatalyst surface. The interaction between the surface of y-CD-modified TiO₂ and pollutants was also enhanced to further promote the degradation of the pollutants. In addition, surface modification of nanocrystalline TiO₂ particles with γ -CD may alter the optical properties of nanoparticles compared to

unmodified nanocrystallites [29]. More importantly, TiO_2 can be donated with the recognition ability for certain guest molecules after modification with γ -CD. This can lead to more guest-targeting and efficient functions of TiO_2 which plays an important role as a "channel or bridge" between the guest molecules and the surface of the photocatalysts [25, 28, 30].

In this work, TiO_2/γ -CD NPs as an efficient photocatalyst was prepared and employed for the photocatalytic degradation of some commercial organic dyes in aqueous solutions. The structure and morphology of the prepared photocatalysts were characterized by FESEM, EDX, TEM, FT-IR, XRD and BET techniques. The experimental parameters were studied to find out the factors influencing the photocatalytic degradation efficiency. These factors were the initial concentration of the dye solution, pH, illumination time and catalyst concentration. The rate of dye degradation was considerably enhanced using TiO_2/γ -CD NPs in comparison with pure TiO₂.

2. Experimental

2.1. Materials and equipment

(*γ*-CD), Gamma-cyclodextrin titanium (IV)isopropoxide (TTIP), p-toluenesulfonyl chloride (p-TsCl), ethylenediamine (EDA), epichlorohydrin (EP), glacial acetic acid, ethanol, acetone, acetonitrile, methanol, sodium hydroxide, hydrochloric acid, rhodamine B (RhB), methyl orange (MO) and methylene blue (MB) were purchased from Sigma-Aldrich and Merck Chemical companies and used purification. The without any photocatalytic degradation of the dyes was studied with a nanoparticle UV-exciter (high-pressure mercury lamp, 500 W, 220 V). The UV-Visible absorption spectra were recorded using a Pharmacia Biotech spectrophoto-meter. Fourier transform infrared (FT-IR) spectra were recorded on a Shimadzu 8400 FT-IR spectrophotometer. The morphologies and phases of samples were investigated using field emission scanning electron microscopy (FESEM, MIRA 3TESCAN-XMU), transmission electron microscopy (TEM, Zeiss- EM10C-80 KV), energy dispersive X-Ray (EDX, Hitachi Su 3500) and powder X-ray diffraction (XRD, Philips, PW 1800). The nitrogen adsorption-desorption isotherms were obtained at -196 °C using a conventional volumetric apparatus (Bel Japan, BELSORP. Mini II). Scheme 1 shows the structure of the investigated organic dyes.



Scheme 1: The structure of the investigated organic dyes.

2.2. Synthesis of γ -CD-modified TiO₂ nanoparticles

Sol-gel method was used for the preparation of titanium dioxide nanoparticles (TiO₂ NPs) [19]. TiO_2/γ -CD NPs as efficient photocatalyst were prepared according to our recent work [20]. In the final step of TiO₂/ γ -CD NPs preparation, EP was used as the cross-linker for linking γ -CD-NH₂ to TiO₂ NPs. TiO₂ NPs (0.5 g) were dissolved in 5 mL deionized water followed by addition of γ -CD-NH₂ (0.5 g) and then homogenizing with a magnetic stirrer. Pure γ -CD-NH₂ was attached to the surface of TiO₂ NPs by adding 20 µL of EP to the sample. The mixture was mixed at room temperature for 12 h. The precipitate collected by suction filtration was washed successively with deionized water. Then, the obtained yellow powder was dried in vacuum at 60 °C. Scheme 2 shows the synthetic route for the synthesis of TiO_2/γ -CD NPs.

2.3. Photocatalytic activity tests

The photocatalytic activity of TiO₂/γ-CD NPs was evaluated using the photodegradation of aqueous solutions of RhB, MO and MB dyes under UV light source. A total of 0.1 g of TiO₂/ γ -CD NPs, as a photocatalyst, was added to 100 mL of aqueous dye solutions (100 ppm) and then the suspension was stirred in the dark for 20 min in order to reach adsorption-desorption equilibrium. Then, the system was irradiated with a high-pressure mercury lamp (500 W, 220 V). At regular irradiation time intervals of 10 min, 10 mL sample was withdrawn and centrifuged to remove the catalyst and the concentration of RhB, MO and MB dyes were analyzed by UV-Vis spectrophotometer. The maximum wavelength (λ_{max}) used for determination of a residual concentration of RhB, MO and MB dyes in supernatant solution was 545, 460 and 660 nm, respectively. The ratio of dye concentration at time t to the initial concentration, C_t/C_0 , was recorded to measure the change of dyes with photocatalytic time.



Scheme 2: Synthetic route for the synthesis of TiO₂/γ-CD photocatalyst.

3. Results and Discussion

3.1. Characterization

The structure of the prepared photocatalysts was characterized by FT-IR, XRD and EDX techniques. All the functional groups of γ -CD are correctly assigned in FT-IR spectra. A new peak at 3282 cm⁻¹ in FT-IR spectrum of y-CD-NH₂ was attributed to N-H stretching vibrations. Appearance of this characteristic peak with absorption bands of γ -CD shows that the γ -CD was successfully modified with EDA [31, 32]. O-H stretching and bending vibrations in the FT-IR spectra of the pure TiO₂ were recognized by the absorption bands at 3415 cm⁻¹ and 1629 cm⁻¹. In addition, a broad absorption peak at 657-789 cm⁻¹ is attributed to the Ti-O-Ti stretching band in the synthesized TiO₂ NPs [19]. In addition, the broad absorption band at about 3388 cm⁻¹ in FT-IR spectrum of the TiO₂/ γ -CD NPs is assigned to the O-H groups of y-CD. The C-H stretching vibration peak in γ -CD appears at 2927 cm⁻¹; it reveals that the structure of γ -CD linked to the TiO₂ NPs has not damaged [19, 33]. In addition, the strong peaks at 1029 and 1157 cm⁻¹ for TiO₂/ γ -CD NPs are resulted from the anti-symmetric glycosidic (C-O-C) vibrations and coupled (C-C/C-O) stretch vibration in γ-CD, respectively [19].

The synthesized TiO₂ NPs show diffraction peaks at 2θ values of 25.3, 37.8, 48.1, 53.7 and 55.1° which correspond to anatase (101), (004), (200), (105), and (211) crystal planes, respectively. All diffraction peaks in the XRD pattern of pure TiO₂ are in good agreement with standard data (JCPDS Card No.: 21-1272) [34, 35]. The intensity of the characteristic TiO₂ peaks decreased after chemical modification of pure TiO₂ by γ -CD. This may indicate that the surface of TiO₂ NPs is modified with γ -CD molecules. In addition, the peak at 22.8° in the TiO₂/ γ -CD XRD pattern confirmed that γ -CD molecules are successfully attached onto the TiO₂ surface [36]. Furthermore, the broad diffraction peaks in the TiO₂/ γ -CD NPs are due to the presence of abundant oxygen-containing functional groups on TiO₂

NPs. These results clearly exhibited that $\gamma\text{-CD}$ molecules are successfully cross-linked to the TiO_2 NPs.

The chemical elements Ti, O and C in the TiO₂ NPs, and Ti, O, C, N, S and Cl in the TiO₂/ γ -CD NPs with acceptable percentages are observed. This analysis also indicated that the γ -CD molecules are cross-linked to the TiO₂ NPs.

Furthermore, the surface morphology of pure TiO₂ NPs and TiO₂/ γ -CD NPs were evaluated by FESEM images (Figure 1). As can be seen from Figure 1, the spherical morphology of pure TiO₂ NPs with nano dimensions observed clearly. In the case of TiO_2/γ -CD NPs, the spherical shape of TiO₂ NPs has disappeared and nanomaterials with new structure and morphology were formed. As shown in Figure 1, the obtained TiO_2/γ -CD NPs had cavity structures, which indicate that the TiO_2 NPs surface is modified by γ -CD molecules. In addition, the particle size of the TiO_2/γ -CD NPs was in the range of 10-22 nm. TEM images of the TiO₂/ γ -CD NPs are shown in Figure 2. These images demonstrate that the developed TiO_2/γ -CD photocatalyst was in the nano dimensions and was modified with a large number of γ -CDs.

According to the Brunauer-Emmett-Teller (BET) method (Figure 3a), the specific surface area measured for TiO₂/ γ -CD NPs is 383.131 m²/g. The obtained isotherm for TiO2/y-CD NPs can be considered as a type-IV isotherm (mesoporous structure) with high specific surface area. In addition, the pore size distribution for TiO₂/ γ -CD NPs is presented in Figure 3b. The total pore volume (V_t) and the average pore diameter (D_{BJH}) are 0.543 cm³/g and 0.692 nm, respectively. Compared with commercial P25 TiO₂, functionalization of TiO_2 NPs with γ -CD led to the increase of specific surface area from 48 to $383.131 \text{ m}^2/\text{g}$. Consequently, this nanophotocatalyst with a high specific surface area could be applied for the treatment of synthetic and industrial wastewater samples.



Figure 1: FESEM images of pure TiO₂ (a, b) and TiO₂/γ-CD (c, d) nanoparticles at different magnifications.



Figure 2: TEM image of TiO₂/ γ -CD NPs at different magnifications.



Figure 3: (a) Nitrogen adsorption-desorption isotherm and (b) pore size distribution curve for TiO₂/γ-CD NPs.

3.2. Effect of pH on the photocatalytic ability

pH is one of the important factors in the elimination of dyes from water in the adsorption, photocatalytic degradation, and other water treatment processes. The effects of pH on the photocatalytic degradation of the investigated dyes were studied over the range from 3.0 to 12.0, and the results are shown in Figure 4. the case of cationic RhB and MB dyes, In the degradation efficiency was increased with increasing pH value from 3.0 to 12.0. Optimum pH values for RhB and MB were observed at pH 9.0. In the case of anionic MO dye, the highest degradation was observed at pH 5.0 and the degradation efficiency was decreased in the pH range from 6.0 to 12.0, as shown in Figure 4. Illumination time plays a vital role in the photocatalytic degradation process of the dyes. The results show that the photocatalytic degradation of dyes continuously increased with increasing the time after adsorption-desorption equilibrium. According to the presence of hydroxyl groups on the surface of the TiO_2/γ -CD NPs, it can be used for various dyes in different pH condition of solutions. Meanwhile, these groups can produce electrostatic interactions with cationic RhB and MB dyes in basic solution and electrostatic interactions with anionic MO dye in the acidic solution.

3.3. Effect of catalyst dosage on the photocatalytic degradation of dyes

Catalyst dosage is an important quantitative variable in water purification process using photocatalytic degradation method. The effect of TiO_2/γ -CD NPs dosage on the photocatalytic degradation of RhB, MO,

and MB dyes are shown in Figure 5. The results show that by increasing the amount of catalyst from 0.002 to 0.020 g, the degradation of dye has increased continuously for constant solute concentration. At lower concentrations of TiO₂/ γ -CD NPs, the catalyst surface and the absorption of light by the surface are limiting factors. Thus, an increase in catalyst loading greatly enhances the process efficiency [16]. The increase of efficiency may be due to the fact that more surface area is available for photocatalytic degradation reaction by increasing the amount of TiO₂/ γ -CD NPs [37]. The γ -CD-modified TiO₂ particles could concentrate and adsorb the organic dyes from its aqueous solution and transfer it to the photocatalyst surface.

3.4. Effect of initial dye concentration

The influence of initial dye concentration on the photocatalytic degradation of RhB, MO and MB dyes was studied. As can be seen from Figure 6, as the initial dye concentration increases, the degradation efficiency decreases because the photo-generation of holes or hydroxyl radicals on the catalyst surface is reduced [16]. Under these circumstances, the active sites of the catalyst are covered by dye molecules and degradation products, which compete with H₂O and OH for adsorption on the same sites, resulting in the lower formation of OH⁻ radicals which is the most important oxidant essential for high degradation efficiency [38-40]. In addition, the significant quantity of light radiation that may be screened by dye molecules should be taken into account, since less photon reaches the photocatalyst surface for further generation of OH⁻ [41].







Figure 5: Effect of catalyst dosage on the photocatalytic degradation of dyes (Optimum pH values, C₀ = 100 ppm).



Figure 6: Effect of initial dye concentration on the photocatalytic degradation of dyes (Optimum pH values, Catalyst dosage = 0.01 g).

3.5. Comparing photocatalytic degradation of dyes using pure TiO₂ and TiO₂/ γ CDNPs

The degradation of the investigated dyes in UV-TiO₂ and UV-TiO₂/ γ -CD systems are compared in Figure 7. The increase in degradation efficiency in UV-TiO₂/ γ -CD system in comparison to TiO₂ could be related to: (1) γ -CD stabilizes TiO₂ colloids and facilitate interfacial electron transfer processes, and (2) γ -CD can capture photo-generated holes when attached to the TiO₂ surface, which leads to the enhanced photocatalytic degradation of TiO₂ [27, 28]. In addition, TiO₂/ γ CD NPs showed excellent photocatalytic performance toward RhB, MO and MB dyes in comparison to other photocatalysts (Table 1).

3.6. Recyclability and stability

To evaluate the recyclability and stability of the TiO₂/ γ -CD NPs for the photocatalytic dye degradation, the photocatalyst powders were reused for six times under the same reaction conditions and the results are presented in Figure 8. After six cycles, the TiO₂/ γ -CD NPs still provided excellent photocatalytic degradation of RhB, MO and MB dyes and the decreasing trend in the final degradation efficiency was about 17% after 6 consecutive experiments. The results show that TiO₂/ γ -CD NPs as an effective photocatalyst can be used several times in real applications.

3.7. Kinetics of photocatalytic degradation

Figure 9 shows the kinetics of dye degradation for an initial concentration of 100 ppm under optimized conditions. The photocatalytic dye degradation can be described by the first-order kinetic model (Eq. 1) [46, 47]:

$$\ln(C_o/C_t) = K_1 t \tag{1}$$

where K_1 (min⁻¹) is the first-order rate constant for photocatalysis, C_o (mg/L) is the initial concentration of dye in aqueous solution at time t = 0; and C_t (mg/L) is the residual concentration of dye at time t (min). The linear relationship of $\ln(C_0/C_t)$ versus *t* has been plotted using the data in Figure 7.

The degradation of dyes in the presence of TiO₂ and TiO_2/γ -CD NPs followed a first-order kinetic model. The results show that K₁ for the degradation of RhB, MO and MB dyes in the presence of TiO_2 were 0.0045, 0.0157 and 0.0102 min⁻¹, respectively, while K₁ for the degradation of RhB, MO and MB dyes in the presence of TiO₂/γ-CD NPs were 0.0180, 0.0883 and 0.0429 min⁻¹, respectively. It is well known that the photocatalytic degradation reaction rate of dyes in aqueous solutions with TiO_2/γ -CD NPs was obviously higher than that with TiO₂ [16]. When γ -CD was introduced to the TiO₂ structure, the photocatalytic reaction rate constants for RhB, MO and MB dyes were 4, 5.6 and 4.2 times higher, respectively. Thus, the rate of degradation of the dyes under UV irradiation was considerably enhanced using TiO₂/y-CD NPs compared to those degraded by the pure TiO₂.

Photocatalyst/dosage (mg)	Dye/mg L ⁻¹	Light	Time (min)	Efficiency (%)	Ref.
CoFe ₂ O ₄ -graphene/25	RhB/20	Vis	240	94	[42]
ZnGa ₂ O ₄ /60	RhB/10	UV	24	99.8	[43]
TiO_2 - γ - $CD/10$	RhB/100	UV	180	100	This work
CoFe ₂ O ₄ -graphene/25	MO/2O	Vis	240	71	[42]
ZnGa ₂ O ₄ /60	MO/10	UV	32	99	[43]
TiO ₂ -γ-CD/10	MO/100	UV	60	100	This work
CoFe ₂ O ₄ -graphene/25	MB/20	Vis	240	100	[42]
Ag/ZnO/24	MB/80	UV	60	55	[44]
ZIF-8/25	MB/50	UV	120	82	[45]
TiO ₂ -γ-CD/10	MB/100	UV	70	100	This work

 Table 1: Photocatalytic degradation efficiencies of RhB, MO and MB dyes with different catalysts.



Figure 7: Efficiency of photocatalytic dye degradation in UV-TiO₂ and US-TiO₂/γ-CD systems, (Optimum illumination time, Optimum pH values, Catalyst dosage = 0.01, C₀ = 100 ppm).



Figure 8: Cyclic photocatalytic dye degradation experiments by TiO_2/γ -CD NPs (Optimum illumination time, Optimum pH values, Catalyst dosage = 0.01, C_0 = 100 ppm).



Figure 9: Kinetics of photocatalytic degradation of RhB, MO and MB dyes using TiO₂ and TiO₂/ γ -CD NPs.

3.8. Mechanism of photocatalytic degradation

Based on the experimental results, it could be concluded that TiO_2/γ -CD NPs exhibit better photocatalytic activity than pure TiO_2 in the degradation of dyes under UV irradiation. This can be attributed to the electron transfer between γ -CD and TiO_2 , which can enhance the photocatalytic activity of TiO_2/γ -CD NPs effectively. In other words, the attached γ -CD played a role as a "bridge" or "channel" between TiO_2 powders and dyes, which facilitated the electron injection from excited dyes to the conduction band of TiO_2 and finally led to faster degradation of dye pollutants.

The possible reaction mechanism for degradation of RhB, MO and MB dyes by using TiO₂/ γ -CD NPs as catalyst under UV irradiation is demonstrated in Figure 10 which shows the possible pathways of dye degradation on TiO₂/ γ -CD NPs. Dye molecules enter into the cavity of γ -CD, which is linked to the TiO₂ surface in the equilibrium stage. An electron is rapidly injected from the excited dye to the conduction band [48-50]. The dye and dye cation radical then undergo degradation (Eq. 2-9).

 $Dye + TiO_2/\gamma - CD \rightarrow TiO_2/\gamma - CD \cdot Dye$ (2)

$$TiO_2/\gamma$$
-CD•Dye + hv \rightarrow TiO_2/γ -CD•¹Dye*
+ TiO_2/γ -CD•³Dye*

$$\text{TiO}_2/\gamma\text{-CD} \bullet \text{Dye}^* \rightarrow (e)\text{TiO}_2/\gamma\text{-CD} + \text{Dye}^+$$
 (4)

$$\text{TiO}_2/\gamma\text{-CD}\bullet\text{Dye}^* + \text{O}_2 \rightarrow \text{TiO}_2/\gamma\text{-CD}\bullet\text{Dye} + {}^{1}\text{O}_2$$
 (5)

$$(e)TiO_2/\gamma-CD + O_2 \rightarrow TiO_2/\gamma-CD + O_2^{-}$$
(6)

$$Dye^{\bullet^+} \rightarrow Products$$
 (7)

$$Dye + {}^{1}O_{2} \rightarrow Products$$
 (8)

$$Dye + \bullet O_2^- \to Products \tag{9}$$

Photo-generated radicals have significant effect on the stability of the surface linked γ -CD. The reaction constant between γ -CD and •OH is 4.2×10^9 L/mols However, the lifetime of •OH is quite short (20 ns), and •OH is not the predominant radical under UV irradiation [51]. Therefore, only those radicals generated in close proximity could react with γ -CD. Since the TiO₂ surface is not fully covered with γ -CD, it is quite reasonable to assume that the reaction between γ -CD and •OH is limited. Another important radical in illumination of TiO_2/γ -CD NPs is the superoxide anion radical $(\bullet O_2)$. Actually, cyclodextrin derivates are used to improve the efficiency of $\cdot O_2^{-1}$ trapping using various nitrones as scavengers [52]. Therefore, the reaction between γ -CD and diffusion mediated $\cdot O_2^-$ can be neglected. In general, the lifetime of the excited states of unreactive guests increases when incorporated into cyclodextrins. Therefore, γ -CD facilitates the electron injection from the excited dyes to the TiO₂ conduction band and thereby enhances the degradation.



(3)

Figure 10: Mechanism of photocatalytic degradation of dyes using TiO₂/γ-CDNPs.

4. Conclusion

In this work, TiO₂/ γ -CD NPs as an environmentally friendly catalyst were successfully synthesized and tested for photocatalytic degradation of cationic and anionic dyes from synthetic wastewater. The structure and the surface morphology of the prepared photocatalysts were characterized by FESEM, EDX, TEM, FT-IR, XRD and BET techniques and results showed that TiO₂ NPs were effectively modified with γ -CD. The surface characterization of the photocatalyst TiO₂/ γ -CD showed high BET specific surface area of 383.131m²/g. The study of dye photocatalytic degradation kinetics demonstrated that the first-order

5. References

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kinetic model describes well the photodegradation of dyes on TiO_2/γ -CD. Furthermore, the experimental results revealed that the rate of dye degradation under UV irradiation was considerably enhanced using TiO_2/γ -CD NPs instead of pure TiO_2 . The results of cyclic degradation showed that the developed photocatalyst can be used several times in real applications.

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