Preparation and characterization of SnO2 doped TiO2 nanoparticles: Effect of phase changes on the photocatalytic and catalytic activity

Shawky M. Hassan a,*, Awad I. Ahmed a, Mohammed A. Mannaab, **

a Chemistry Department, Faculty of Science, Mansoura University, Mansoura, Egypt
b Chemistry Department, Faculty of Science, Amran University, Sa’adah, Yemen

A B S T R A C T

The effects of phase changes on the photocatalytic and catalytic activities of SnO2/TiO2 nanoparticles prepared via surfactant-assisted sol-gel method were investigated. The as-prepared SnO2/TiO2 was calcined at 400°C, 500°C, 600°C, and 700°C. The prepared samples were studied by XRD, TEM, SEM, FTIR, BET, UV-vis diffuse reflection spectroscopy (DRS) and Photoluminescence (PL) spectra. The results showed that the crystallite size and anatase-to-rutile phase transformation increase greatly with increasing the calcination temperature. The transformation of anatase to rutile phase was found to be between 400°C and 600°C, and then the anatase completely transformed to rutile phase at 700°C. Also, the specific surface area and pore volume decrease, whereas the mean pore size increases with increasing the calcination temperature. The effect of calcination temperature on the catalytic activity of the samples was tested by different applications: photodegradation of Methylene Blue (MB), Rhodamine B (RhB) dyes and phenol and synthesis of xanthene (14-phenyl-14H-dibenzo[a,j]xanthene). The mineralization of MB and RhB has been confirmed by chemical oxygen demand (COD) measurements. The results showed that the SnO2/TiO2 nanoparticles calcined at 500°C exhibit the highest photocatalytic and catalytic activities.

1. Introduction

Metal oxides play an important role in heterogeneous catalysis as solid catalysts in the industry and many synthetic conversions [1,2]. In recent years, metal oxide semiconductors were used as photocatalysts for environmental protection from pollutants that resulted from industrial waste products such as dyes, organic and inorganic pollutants which caused considerable problems to microorganisms, aquatic environments, and human beings [3–11]. Photodegradation method is one of the most popular methods in wastewater treatment due to its effectiveness, operational simplicity, and low cost [12–18]. Among various oxides semiconductors photocatalysts, TiO2 has considerable attention due to its special optoelectronic properties, physicochemical stability and nontoxicity [19–23]. TiO2 has a wide bandgap (3.2 eV) and the fast recombination of the photogenerated charge carriers (electron/hole, e/h, pairs) still hinders the application of this technique [24,25]. The photocatalytic activity of TiO2 can be improved by morphological modifications [26] and chemical modifications [27], or a combination of morphological and chemical modifications [28]. Different methods have been developed for enhancing the efficiency of the TiO2 powders. The most popular method depends on doping TiO2 with metal and nonmetal elements [29,30], semiconductor coupling [31], dye sensitization [32]… etc. Coupling TiO2 with other semiconductors can enhance the photoactivity of TiO2 due to the reducing of the recombination rate of e/h pairs [31,33–35]. Coupling SnO2 and TiO2 is one of the effective methods to lower e/h pair’s recombination [3], which increases the quantum efficiency and enhances the photocatalytic activity. Hence, coupling TiO2 with SnO2 can reduce e/h pairs recombination rate which increases the photocatalytic activity of TiO2 [36].

In addition, the calcination temperature can affect the structure, morphology, crystal phase, the crystal size of the TiO2 doped SnO2 which in turn affects the photoactivity, and catalytic activity of the SnO2/TiO2 nanoparticle [37–39]. However, few studies have been carried out on the effects of calcination temperatures on structural, photocatalytic, biological and catalytic properties of SnO2/TiO2.
nanoparticles. Sato et al. and Zhang et al. showed that calcination of samples leads to release of lattice oxygen from TiO₂ which enhances the photocatalytic activity [40,41].

The present study aims to study the effect of phase changes on the photocatalytic and catalytic properties of the SnO₂/TiO₂ nanoparticles. The catalytic activity of SnO₂/TiO₂ nanoparticles was investigated by photodegradation of MB, RhB and phenol as well as the synthesis of 14-phenyl-14H-dibenzo [a,j] xanthene.

2. Experimental

2.1. Preparation of SnO₂/TiO₂ nanoparticles

A conventional sol-gel method was employed to prepare SnO₂/TiO₂ nanoparticles from titanium (IV) isopropoxide (Aldrich, 97%) as a Ti-precursor and SnCl₄·xH₂O as a Sn-precursor. CTAB was used as template and ethanol as solvent. The synthetic procedure was carried out as follows [19,42]: 2 g of CTAB was dissolved in 50 ml of ethanol and stirred for 30 min; then 11.7 ml of titanium (IV) isopropoxide was added under continuously stirred conditions. 0.70 g of SnCl₄·xH₂O was dissolved in ethanol and added to the mixture under vigorous stirring for 3 h with 1:9 mol% ratio of SnO₂:TiO₂. Then, 5 ml of ammonia (32%) was added dropwise to the mixture. The mixture was left in air for 24 h to complete the reaction. After that, the gel was filtrated and washed with de-ionized water several times until the ammonia and all chloride ions were removed (chloride ions tested by silver nitrate solution) and then dried in an oven at 100°C for 24 h. Finally, the powder was calcined at 400°C, 500°C, 600°C and 700°C for 3 h.

2.2. Characterization

XRD patterns were conducted on a Philips PW 1830 diffractometer with Cu Kα radiation operated at 40 kV (2θ range of 10–80°) and the crystallite size (D) was calculated from the Scherrer equation [36]. Transmission electron microscopy (TEM) was performed using a JEOL 2000FX operated at 120 kV. The SEM micrographs were obtained using SEM: JEOL JSM-5800LV. Surface area measurements were conducted on a Quantachrome Autosorb 3B using nitrogen as the adsorbent. The surface area was calculated using the Brunauer–Emmett–Teller (BET) equation from the adsorption branch. The pore size distribution was calculated by analyzing the adsorption branch of the nitrogen sorption isotherm using Barret–Joyner–Halenda (BJH) method. Fourier transform infrared (FTIR) spectra were performed using Shimadzu FTIR. The spectra were recorded in the range of 400–4000 cm⁻¹ using the KBr disk technique. The UV-vis diffuse reflectance spectra (DRS) of the samples were examined by a PerkinElmer Lambda 950 instrument to estimate the bandgap energy of the prepared photocatalysts. Photoluminescence (PL) spectra were measured on a PerkinElmer FP-6500 fluorescence spectrophotometer with the excitation wavelength of 315 nm.

2.3. Catalytic activity measurements

2.3.1. Photocatalytic activity evaluation

The photocatalytic activity of the SnO₂/TiO₂ nanoparticles was measured by the photodegradation of MB, RhB and phenol solutions under UV-vis irradiation. The examination of the photocatalytic reactions was occurred using a cooling-water-cycle system keeping the reaction temperature constant. The source of light was Halogen lamp (400 W) which fixed at a distance of 30 cm from the reactor. The mixture of 0.05 g of the catalyst was dispersed in 50 ml of dye (10 mg. L⁻¹). The reaction was initially stirred for 30 min in the dark to achieve the adsorption-desorption equilibrium of dye on the surface of the catalyst. After that, 2 ml of the solution was taken at fixed intervals; centrifuged and 1 ml of the supernatant was diluted in a 10 ml flask for analysis on a Shimadzu, MPC-2200 UV-vis spectrophotometer at λmax 666 nm for MB and 554 nm for RhB and 276 nm for phenol. The photocatalytic degradation rate (D %) has been calculated according to the following formula [43]:

\[ D\% = \left( \frac{C_0 - C_t}{C_0} \right) \times 100 \]
where $C_0$ and $C_t$ are the concentration of dye solution at initial and after irradiation time ($t$). Also, for exploring the reactive species might produce in the photocatalytic reaction, we used different scavengers including Na$_2$EDTA, isopropanol (IPA), carbon tetrachloride (CCl$_4$), and benzoquinone (BQ) as scavengers of $H^+$, $\cdot$OH, $e^-$ and $\cdot$O$_2^-$, respectively, at concentration of 1 mM [44]. The COD was determined using HACH DR2800 photometer. The mineralization ($\%$COD) of MB and RhB solutions after photodegradation were calculated from the equation:

$$\%\text{COD} = \left( \frac{\text{COD}_{\text{Initial}} - \text{COD}_{\text{Final}}}{\text{COD}_{\text{Initial}}} \right) \times 100$$

### 2.3.2. Synthesis of 14-phenyl-14H-dibenzo [a,j] xanthene

The reaction was carried out using a mixture of the benzaldehyde (1 mmol) and β-naphthol (2 mmol) with 0.10 g of the activated catalyst (at 120 °C for 2 h) in an oil bath at 125 °C under stirring for the appropriate time. The reaction completion was examined by TLC. The catalyst was separated from the product by simple filtration where the solid product was dissolved in chloroform. Chloroform was evaporated and the product was recrystallized using aqueous ethanol (15%) for two times [45,46]. The product was identified by m.p. and FTIR spectra. The %yield of xanthene was calculated as follows:

$$\text{Yield (wt\%)} = \frac{\text{Obtained weight of product}}{\text{Theoretical weight of product}} \times 100$$

### Table 1

| Temperature (°C) | $D$ (nm) | $E_g$ (eV) | $S_{BET} (m^2/g)$ | $V_p (cm^3/g)$ | $D_p$ (nm) | %Xanthene |
|-----------------|----------|-----------|------------------|----------------|------------|-----------|
| 400°            | 6.9      | 3.07      | 32.5             | 0.13           | 9.3        | 89.12     |
| 500°            | 9.2      | 2.95      | 29.6             | 0.11           | 10.6       | 93.50     |
| 600°            | 18.4     | 2.94      | 25.7             | 0.09           | 16.2       | 78.58     |
| 700°            | 23.5     | 2.91      | 19.7             | 0.07           | 25.3       | 68.62     |

![Fig. 2. TEM and HRTEM images of SnO$_2$/TiO$_2$ nanoparticles calcined at (a, b) 500 °C (c, d) 700 °C.](image-url)
3. Results and discussion

3.1. XRD analysis

XRD patterns of the SnO$_2$/TiO$_2$ nanoparticles calcined at different temperature are shown in Fig. 1. It can be seen that all the samples were composed of anatase ($2\theta = 25.28^\circ$) and rutile ($2\theta = 27.5^\circ$) phases [47,48]. The intensity of the peaks that attributed to the anatase phase decreased with increasing the calcination temperature, while the rutile phase increased and became more preferential, indicating the improvement of rutile phase crystallization. At 400 °C, the transformation of anatase to rutile phase is small and increased with increasing the temperature to 600 °C and at 700 °C the anatase peak disappeared. These results indicate that the rutile phase is more stable at high calcination temperatures. The peaks associated with the corresponding SnO$_2$ are not detected in the XRD patterns for samples calcined at 400°C and 500°C, which indicate that SnO$_2$ is well dispersed on the TiO$_2$ surface. At 700°C, new peaks appeared at $2\theta = 26.7^\circ$, 32.32° and 33.9° which indicating the aggregation of SnO$_2$ crystals on TiO$_2$ surface [49]. The crystallite size of SnO$_2$/TiO$_2$ nanoparticles was calculated and listed in Table 1. It is clearly shown, with increasing the calcination temperature, the crystallite size increased gradually. This because of increasing the particles aggregation accelerate the growth of crystallite sizes [43]. According to the kinetics studies, the transformation from anatase-to-rutile phase needs high activation energy to overcome both strain energy for the oxygen ions and break the Ti–O bonds as the titanium ions redistribute [50].

3.2. TEM analysis

The morphology and particles size of SnO$_2$/TiO$_2$ calcined at different temperatures were analyzed by TEM and HRTEM. Fig. 2 shows that the average particle size increased with increasing the calcination temperature. This resulted due to fuse the particles together and forming larger agglomerates [51]. Both samples showed an almost spherical shape with different average particle sizes. HRTEM images exhibit lattice fringes with interplanar spacing 0.34 nm and 0.32 nm which corresponding to (101) anatase and (110) rutile planes, respectively [43]. With increasing the calcination temperature to 700 °C, only 0.32 interplanar spaces appeared. This confirms the transformation of anatase to rutile with increasing calcination temperature. These results showed that the rutile phase is more stable at high calcination temperatures compared with the anatase phase.

3.3. SEM analysis

Fig. 3 illustrates the surface morphology of SnO$_2$/TiO$_2$ nanoparticles calcined at different temperatures. The images show that the increasing in the calcination temperature was accompanied by increases in the protrusion and aggregation of SnO$_2$ on the surface of TiO$_2$ due to the densification of the TiO$_2$ morphology [52]. Also, the average size of aggregated particles increased with increasing the calcination temperature. The increase in the particle size resulted due to the primary crystallite size of anatase and rutile increases during the heat treatment and another reason is due to the increasing aggregation of particles at high calcination temperature [6].

---

Fig. 3. SEM images of SnO$_2$/TiO$_2$ nanoparticles calcined at (a) 400°C (b) 500°C and (c) 700°C.
3.4. Surface areas and pore size distribution

Fig. 4a shows nitrogen adsorption-desorption isotherms of SnO$_2$/TiO$_2$ calcined at 400$^\circ$C, 500$^\circ$C, 600$^\circ$C, and 700$^\circ$C. The samples exhibited typical type IV adsorption isotherms, indicating the characteristics of mesoporous materials [39]. With increasing the calcination temperature from 400$^\circ$C to 700$^\circ$C, the specific surface area and pore volume decrease, whereas the mean pore size increases (Table 1). Moreover, with increasing the calcination temperature, the hysteresis loops shift to higher relative pressure range and the areas of the hysteresis loops decrease indicating that some pores collapse during the calcination [41]. This indicated that the average pore size increased and the volume of pore decreased with increasing calcination temperature.

The pore size distribution was calculated from the desorption branch of the isotherm and presented in Fig. 4b. It can be seen that the calcination temperature influenced the pore size distribution of the SnO$_2$/TiO$_2$ nanoparticles. With increasing the calcination temperature, the BJH pore size distribution of samples exhibited a systematic shift toward larger mesopores which can be associated with the severe collapse of the initial porous structure occurred for the calcination temperature increases.

![Fig. 4. N$_2$ adsorption-desorption isotherms (a) and pore size distribution curves (b) of SnO$_2$/TiO$_2$ calcined at different temperatures.](image)
3.5. FTIR measurements

Fig. 5 illustrates the FTIR spectra of SnO2/TiO2 nanoparticles calcined at 400˚C, 500˚C, 600˚C, and 700˚C. The spectra display broadband centered at 3410 cm⁻¹ which assigned to the stretching vibration of –OH and/or physically adsorbed water on the SnO2/TiO2 surface [22,53]. Another band appeared at 1625 cm⁻¹ is related to the bending vibration of hydroxyl groups on the surface of the oxides [22,54]. No bands correspond to the organic template, CTAB, indicating that the calcination treatment at 400 ˚C is sufficient to remove the template. The broadband in the region below 800 cm⁻¹ is associated with the stretching mode of vibrations of bridged Sn–O–Sn, Ti–O–Ti, and Ti–O–Sn bonds of titanium and tin oxides [3,53]. The small bands that notice at 1350 and 1030 cm⁻¹ assigned to the hetero Ti–O–Sn bond [42]. At 700 ˚C, the intensity of the bands at 1625 cm⁻¹ decreased. This is due to the release of hydroxyl groups on the surface of SnO2/TiO2 nanoparticles when calcined at 700˚C [55].

Fig. 5. FTIR spectra of the SnO2/TiO2 nanoparticles calcined at (a) 400˚C (b) 500˚C (c) 600˚C (d) 700˚C.

Fig. 6. UV–vis spectra of the SnO2/TiO2 nanoparticles calcined at different temperatures.
3.6. UV–vis diffuse reflectance

UV–vis spectra of the SnO$_2$/TiO$_2$ nanoparticles calcined at 400°, 500°, 600°, and 700 °C are shown in Fig. 6. All samples show a strong absorption below 450 nm due to the interband electronic transitions [6,43]. It’s reported that the coupling of TiO$_2$ with SnO$_2$ can improve the photocatalytic activity. This may be due to created additional energy levels by Sn ions in the bandgap of TiO$_2$ [56,57], which facilitates the transition of electrons from VB to the CB. The small absorption edges in the visible region are mainly caused by...
oxygen vacancies [58,59]. The bandgap energy (E_g) can be estimated according to the relation [60,61]:

\[ a h v = A (h v - E_g)^n \]

where \( a \) is the absorbance coefficient, \( h \) is the Planck constant, \( v \) is the wavenumber, \( A \) is a constant and \( E_g \) is the bandgap energy in which \( n = 1/2 \) for direct bandgap materials and \( n = 2 \) for indirect bandgap [62].

The bandgap energy values of SnO_2/TiO_2 nanoparticles calcined at 400, 500, 600, and 700 °C were estimated from the plot of \((a h v)^2 \) versus photon energy in electron volts (Fig. 6 inset). The obtained \( E_g \) are shown in Table 1. The results show the \( E_g \) became narrower with increasing the calcination temperature. This may due to two reasons: the first, as the calcination temperature increased, the crystallite size increased and led to a decrease in the bandgap energy, and the second reason, due to the phase transformation increased with increasing the calcination temperature where the bandgap of the rutile phase is smaller than that of anatase phase [6,37,41,43].

3.7. Photoluminescence spectra

Photoluminescence spectra of the SnO_2/TiO_2 calcined at different temperature were conducted in the wavelength range of 350–600 nm. As presented in Fig. 7, the shape of the PL spectra for all samples were similar. The PL signals at about 385 and 405 nm were ascribed to the band-band PL emission which was generated by the incident light with energy approximately equal to that of the band gaps of the anatase and the rutile phases of TiO_2, respectively [6,37]. The PL emission peaks at about 470 nm are possibly
attributed to defect states in the band gaps resulting from oxygen vacancies at different depths [20].

Moreover, the PL intensity decreased with the increasing calcination temperature from 400 to 500 °C and then enhanced sharply at 600 and 700 °C. The weak PL intensity of SnO₂/TiO₂ calcined at 500 °C suggested a low recombination efficiency of the photoinduced e/h pairs and consequently a longer lifetime of the photoinduced electrons [37]. Increasing PL intensity of the SnO₂/TiO₂ with increasing the calcination temperature could be ascribed to the excessive rutile phase and the destruction of the surface microstructure [63].

3.8. Catalytic activity measurements

3.8.1. Photocatalytic measurements

Fig. 8 shows the photodegradation of aqueous solutions of MB, RhB and phenol over SnO₂/TiO₂ nanoparticles calcined at 400°, 500°, 600°, and 700 °C. The photocatalytic activity of the SnO₂/TiO₂ increases with increasing the calcination temperature to reach a maximum at 500 °C and then decreases with the further increase in the calcination temperature. These results indicate that at 500 °C the interaction between mixed phases is the strongest which makes the sample more active than that calcined at 400 °C and above 500 °C. Also at 500 °C, the samples show good crystallization.

Table 2

| Calcination temperature | MB   | RhB   |
|-------------------------|------|-------|
| 400°                    | 0.02863 | 0.02529 |
| 500°                    | 0.03871 | 0.03033 |
| 600°                    | 0.02347 | 0.01837 |
| 700°                    | 0.01951 | 0.01392 |

Fig. 10. % COD removal and photodegradation of MB and RhB dyes vs. time.

Fig. 11. The pseudo-first-order kinetics of degradation of (a) MB (b) RhB over SnO₂/TiO₂ nanoparticles at different calcination temperature.
and low surface defects, which in turn enhanced the photocatalytic activity \[6,64\]. Also, the samples that calcined blew 500 °C show weak photocatalytic activity than that calcined at 500 °C due to low crystallization of anatase phase \[31\]. As the temperature increases above 500 °C, the photoactivity decreases due to the increases in phase transformation \[65\]. Increasing the amount of rutile phase compared to that of the anatase phase led to decrease the photodegradation of MB, RhB, and phenol because the photocatalytic activity of rutile phase is lower than that of the anatase phase \[36,66\].

Fig. 9 shows the effects of the addition of radicals scavengers on the photodegradation of MB and RhB over SnO2/TiO2 calcined at 500 °C. The results showed slightly retardation of MB and RhB degradation after additions of Na2EDTA and BQ indicating small effects of H+ and ·O2- species in the photodegrading of MB and RhB, while the additions of CCl4 and IPA were accompanied with remarkably decrease in the photodegradation of MB and RhB indicating that e− and ·OH played the main role in the degradation process. Scheme 1 illustrates the suggested photodegradation mechanism of MB, RhB and phenol over SnO2/TiO2.

Fig. 10 shows the %COD removal of MB and RhB solutions after photodegradation for 180 min of irradiation. The results illustrate that the SnO2/TiO2 that calcined at 500 °C showed the highest photodegradation and %COD removal values of MB and RhB, indicating that the calcination at 500 °C is the appropriate temperature. The difference in the values of both photodegradation of MB and RhB and %COD refers to the presence of small amounts of colorless intermediates that not degraded. The significant COD removal values confirm the mineralization of MB and RhB.

The kinetic study of the photocatalytic degradation of MB and RhB was investigated for SnO2/TiO2 nanoparticles calcined at 400°, 500°, 600°, and 700 °C by Langmuir—Hinshelwood kinetic model. This model belongs to the first-order kinetics according to the following formula \[67\]:

\[
\ln \left( \frac{C_0}{C_t} \right) = kt
\]

where \(C_0\) and \(C_t\) are concentrations of dye at initial and after irradiation time \(t\) (min) and \(k\) is the rate constant of dyes photodegradation. Fig. 11a, b show the kinetic curves of photodegradation of MB and RhB over SnO2/TiO2 nanoparticles, respectively. The rate constants \(k\) and the correlation coefficients \(R^2\) were calculated and listed in Table 2. The linear relationship between \(\ln \left( \frac{C_0}{C_t} \right)\) and \(t\) indicates that the degradation of MB and RhB obey the pseudo-first-order reaction. The value of \(k\) increases with increasing the calcination temperature to reach a maximum at 500 °C and then decreases as the calcination temperature increases.

3.8.2. Synthesis of 14-phenyl-14H-dibenzo [α,j] xanthene

![Scheme 1: Suggested mechanism for the photodegradation of MB, RhB, and phenol over SnO2/TiO2 nanoparticles.](image)

Fig. 12. Effect of calcination temperature on the %xathene for SnO2/TiO2 nanoparticles.
Effect of calcination temperature of SnO$_2$/TiO$_2$ nanoparticles on the formation of xanthene is shown in Fig. 12 and Table 1. The results illustrate that the % yield increased with increasing the calcination temperature to 500 °C and then decreased as the calcination temperature increased. The calcination at 500 °C is the optimum temperature of SnO$_2$/TiO$_2$ nanoparticles where the catalyst showed the highest catalytic activity. Compared with other results obtained over other catalysts as sulfamic acid/Cr-ML-101 [68], modified SBA-15, MCM-41 [69], ZnO [70] and NbCl$_4$ [71] indicate that the SnO$_2$/TiO$_2$ acted as an efficacious catalyst.

The reusability of SnO$_2$/TiO$_2$ nanoparticles calcined at 500 °C was checked using the recovered catalyst. The catalyst was recovered by dissolving the product in chloroform and separated by simple filtration, washed with chloroform and dried at 100 °C for 1 h. The results showed that no significant loss in the catalytic activity of the SnO$_2$/TiO$_2$ nanoparticles with increasing the number of reuse times of the catalyst as shown in Fig. 13.

4. Conclusion

SnO$_2$/TiO$_2$ nanoparticles have been successfully synthesized via surfactant-assisted sol-gel method. The results showed that the anatase to rutile phase transformation and the crystallite size increased with increasing the calcination temperature. The anatase to rutile phase transformation increased with increasing the calcination temperature and the anatase phase disappeared at 700 °C. The optimum calcination temperature of the SnO$_2$/TiO$_2$ catalyst is 500 °C. At this temperature, the % yield of xanthene was 93.5% whereas the photodegradation percentage of MB and RhB dyes was 100% and 90% for phenol after 2 h. Increasing the calcination temperature over 500 °C led to a sharp decrease in the catalytic activity. The presence of anatase and rutile phases together showed higher activity compared with anatase or rutile alone. These results show that the catalytic activities and physicochemical properties of the SnO$_2$/TiO$_2$ nanoparticles strongly depend on the calcination temperature.

References

[1] S.M. Hassan, M.A. Mannaa, A.A. Ibrahim, Nano-sized mesoporous phosphated tin oxide as an efficient solid acid catalyst, RSC Adv. 9 (2019) 810–818.

[2] M.B. Gawande, R.K. Pandey, R.V. Jayaram, Role of mixed metal oxides in catalysis science—versatile applications in organic synthesis, Catal. Sci. Technol. 2 (2012) 1113.

[3] S.E. Hosseini Yeganeh, M. Kazzaz, B. Kouzegar Kaleji, S.H. Kazemi, B. Hosseinzadeh, Electrohydrostatic deposition of Sn-doped TiO$_2$ nanoparticles and its optical and photocatalytic properties, J. Mater. Sci. Mater. Electron. 29 (2018) 10841–10852.

[4] S.M. El-Dafrawy, M. Farag, S.M. Hassan, Photodegradation of organic compounds using chromium oxide-doped nano-sulfated zirconia, Res. Chem. Intermed. 43 (2017) 6343–6365.

[5] M.A. Mannaa, S.M. Hassan, A.I. Ahmed, Synthesis and bioactivities of H$_3$PW$_{12}$O$_{40}$/SnO$_2$–TiO$_2$ nanocomposite, Int. J. Mod. Chem. 10 (2018) 69–79.

[6] L. Zhang, Y. Li, Q. Zhang, H. Wang, Well-dispersed Pt nanocrystals on the heterostructured TiO$_2$/SnO$_2$ nanofibers and the enhanced photocatalytic properties, Appl. Surf. Sci. 319 (2014) 21–28.

[7] S. Asuha, X.G. Zhou, S. Zhao, Adsorption of methyl orange and Cr(VI) on mesoporous TiO$_2$ prepared by hydrothermal method, J. Hazard Mater. 181 (2010) 204–210.

[8] P. Kongnong, L. Sikong, S. Niyomwas, V. Rachpech, Photocatalytic antibacterial performance of glass fibers thin film coated with N-doped SnO$_2$/TiO$_2$, Sci. World J. 2014 (2014).

[9] Z. Pei, Z. Kaiqiang, D. Yu, B. Bo, G. Weisheng, S. Yourui, Adsorption of organic dyes by TiO$_2$ @Yeast-carbon composite microspheres and their in situ regeneration evaluation, J. Nanomater. 2015 (2015).

[10] S.M. Hassan, A.A. Ibrahim, S.A. El-Hakam, M.A. Mannaa, Surface acidity and catalytic activity of phosphomolybdic acid/SnO$_2$ catalysts, Int. J. Mod. Chem. 4 (2013) 104–116.

[11] L. Aulellos, M. Franzen, M. Ostwald, G. Berndes, G. Lakshmi, N.H. Ravindranath, Perspective: jatropha cultivation in southern India: assessing farmers’ experiences, Biofuels Bioprod. Biorefining. 6 (2012) 246–256.

[12] S. Sikong, J. Damchan, K. Kootarnond, S. Niyomwas, Effect of doped SiO$_2$ and calcinations temperature on phase transformation of TiO$_2$ photocatalyst prepared by sol-gel method, Songklanakarin J. Sci. Technol. 30 (2008) 385–391.

[13] K.H. Bourne, F.R. Cannings, R.C. Pitkethly, The structure and properties of acid sites in a mixed-oxide system. I. Synthesis and infrared characterization, J. Phys. Chem. 74 (1970) 2197.

[14] S.-T. Ong, P.-S. Keng, W.-N. Lee, S.-T. Ha, Y.-T. Hung, Dye waste treatment, Water 3 (2011) 157–176.
M. Zhang, Q. Wang, C. Chen, L. Zang, W. Ma, J. Zhao, Oxygen atom transfer in
H. Shi, M. Zhou, D. Song, X. Pan, J. Fu, J. Zhou, S. Ma, T. Wang, Highly porous
D. Li, X. Cheng, X. Yu, Z. Xing, Preparation and characterization of TiO2 based
M. Huang, S. Yu, B. Li, D. Lihui, F. Zhang, M. Fan, L. Wang, J. Yu, C. Deng, In-
S.M. Hassan, A.I. Ahmed, M.A. Mannaa, Structural, photocatalytic, biological
V. Vimonses, S. Lei, J. Jin, C.W.K. Chow, C. Saint, Kinetic study and equilibrium
W. Roh, I. Eum, D. Jeong, B.E. Yi, J. Na, C.H. Ko, The effect of calcination tem-
N. Wetchakun, B. Incessungvorn, K. Wetchakun, S. Phanichphant, In
M.M. Mohamed, W.A. Bayoumy, N.Y. Hebalkar, Highly stabilized and
S. Bagwasi, B. Tian, J. Zhang, M. Nasir, Synthesis, characterization and ap-
M. Li, S. Zhang, L. Li, M. Wang, W. Zhang, B. Pan, A thermally stable meso-
V. Rodríguez-González, S.O. Alfaro, L.M. Torres-Martín, S.H. Cho, S.W. Lee, Silver-TiO2 nanocomposites: synthesis and harmful algae bloom UV-photo-
L. Kongkaew, C. Duan, B. Kang, W. Lai, P.X. Cai, Zinc oxide AuTiO2 hollow mi-
S. Wang, L. Zhao, J. Ran, Z. Shu, G. Dai, P. Zhai, Effects of calcination temper-
eral photocatalytic activity of ordered titanate nanoribbon SnO2 films fabricated during an EPD process, Int. J. Photoenergy 2012 1 7 1 2.
Y. Gai, J. Li, S.S. Li, J.B. Xia, S.H. Wei, Design of narrow-gap TiO2: a passivated
codoping approach for enhanced photoelectrochemical activity, Phys. Rev.
G. Colón, M.C. Hidalgo, J.A. Navio, Photocatalytic behaviour of sulfated TiO2 for
H. Kim, J. Kim, W. Kim, W. Choi, Enhanced Photocatalytic and Photo-
electrochemical performance of the Temescal Group-TiO2 doped SnO2 nano-
D.R. Baker, P.V. Kamat, Photocatalysis of TiO2 nanotubes with CdS quantum dots: particulate versus tubular support architectures, Adv. Funct.
M. Huang, S. Yu, B. Li, D. Lihui, F. Zhang, M. Fan, L. Wang, J. Yu, C. Deng, In-
D. Li, X. Cheng, X. Yu, Z. Xing, Preparation and characterization of TiO2 based
A. Simpraditpan, T. Wirunmongkol, S. Pavasupree, W. Pecharap. Effect of calcination temperature on structural and photocatalyst properties of nano-
fibers prepared from low-cost natural limonite iron mineral by simple hydro-
thermal method, Mater. Res. Bull. 48 (2013) 3211–3217.
Y. Zhang, H.Y. Zhu, X. Jiao, Y.Q. Fu, Y.M. Xu. Effect of calcination temperature on physical parameters and photocatalytic activity of mesoporous titanias spheres using citosan/poly(vinyl alcohol) hydrogel beads as a template, Appl. Surf. Sci. 319 (2014) 189–196.
M. Chen, Q. Wang, C. Chen, L. Zang, W. Zhu, J. Zhao. Oxygen atom transfer in the photocatalytic oxidation of alcohol by Ti2O2: oxygen isotope stud-
es, Angew. Chem. Int. Ed. 48 (2009) 6081–6084.
G. Wang, L. Xu, J. Zhang, T. Yin, D. Han, Enhanced photocatalytic activity of
J. Cao, X. Liu, Q. Wang, C. Chen, L. Zang, W. Zhu, J. Zhao. Oxygen atom transfer in the photocatalytic oxidation of alcohol by Ti2O2: oxygen isotope stud-
es, Angew. Chem. Int. Ed. 48 (2009) 6081–6084.
S.M. Hassan et al. / Journal of Science: Advanced Materials and Devices xxx (xxxx) xxx
Please cite this article as: S.M. Hassan et al., Preparation and characterization of SnO2 doped TiO2 nanoparticles: Effect of phase changes on the photocatalytic and catalytic activity. Journal of Science: Advanced Materials and Devices, https://doi.org/10.1016/j.jsamd.2019.06.004

ARTICLE IN PRESS
[70] G.B. Dharma Rao, M.P. Kaushik, A.K. Halve, An efficient synthesis of naphtha [1,2-ε]oxazinone and 14-substituted-14H-dibenzo[a,j]xanthene derivatives promoted by zinc oxide nanoparticle under thermal and solvent-free conditions, Tetrahedron Lett. 53 (2012) 2741–2744.

[71] A. De Andrade Bartolomeu, M.L. De Menezes, L.C. Da Silva Filho, Efficient one-pot synthesis of 14-aryl-14H-dibenzo[a,j]xanthene derivatives promoted by niobium pentachloride, Chem. Pap. 68 (2014) 1593–1600.