Using one-step facile and solvent-free mechanochemical process to synthesize photoactive Fe_2O_3-TiO_2 in treatment of industrial wastewater

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ABSTRACT

In this present study, Fe_2O_3-TiO_2 photocatalyst was synthesized and used to degrade real industrial wastewater, namely pulp and paper mill effluent (PPME). Fe_2O_3-TiO_2 was synthesized via ball milling at ambient conditions without incorporating any solvent. Comprehensive characterization studies and photocatalytic evaluations of the synthesized Fe_2O_3-TiO_2 were conducted in this study. It was verified that Fe_2O_3-TiO_2 possessed crystalline structures of γ-Fe_2O_3, anatase and rutile TiO_2. Also, a good dispersion of Fe and O elements within the TiO_2 framework could be attained. A detection of Fe-O-Ti bond elucidated a substitution of Ti^{4+} by Fe^{3+} in the TiO_2 lattice sites through mechanical milling, which ultimately enhanced the

photocatalytic activities of Fe_2O_3-TiO_2. Moreover, Fe_2O_3-TiO_2 exhibited enhanced catalytic properties in terms of specific surface area (58.40 m^2/g), porosity (0.29 cm^3/g), band gap (2.95 eV), and charge separation in comparison with commercial P25. The present work also proved that both characteristics and photoactivity of Fe_2O_3-TiO_2 were significantly affected by its synthesis conditions (milling time, milling speed, and Fe_2O_3 loading). The highest treatment efficiency of PPME (62.3% of chemical oxygen demand or COD removal) was achieved using Fe_2O_3-TiO_2, which was synthesized at 20 min, 250 rpm and 1 mol% of milling time, milling speed and Fe_2O_3 loading, respectively. Noticeably, the photoactivity of the Fe_2O_3-TiO_2 was more superior than the P25 (40.6% of COD removal). This study proved that mechanochemical process enabled the green synthesis of Fe_2O_3-TiO_2 that could be used in treatment of real industrial wastewater.

Keywords: Ball milling; Iron (III) oxide; Titanium (IV) oxide; Photocatalysis; Pulp and paper mill effluent; Wastewater treatment

1. Introduction

Pulp and paper mills are one of the major sources of industrial pollution worldwide, in which pulp and paper effluent (PPME) contains high amount of total suspended solids, chemical oxygen demand (COD), and other toxic contaminants [1]. However, most PPME treatment plants apply biological treatment systems, which result in ineffective removal of colour and toxicity from the effluent [2]. As an alternative, advanced oxidation processes (AOPs) have been proposed in wastewater treatment systems to effectively oxidize recalcitrant pollutants into biodegradable intermediates and innocuous compounds (i.e. carbon dioxide and water) due to the generation of highly potent oxidant, hydroxyl radicals (·OH) [3,4]. Other advantages of AOPs include colour removal from the wastewater, lower sludge production, and simplicity in operation [5]. Among several AOPs, powerful oxidants such as ozone, hydrogen peroxide, and potassium permanganate have been studied in photocatalysis of wastewater. Typically, these oxidants were used in homogenous photocatalysis processes, which incurred instability and difficulty in catalyst separation process [6]. Conversely, heterogeneous photocatalysis is deemed as the most economically profitable and environmentally safe technology among other AOPs in the removal of organic pollutants from water systems [7]. Hence, heterogeneous photocatalysis was employed as a promising treatment route to degrade highly contaminated PPME in this current study.

Numerous studies have established that TiO_2 as one of the most promising photocatalysts to initiate photocatalytic reactions, owing to its optical and electronic properties, strong oxidizing power, chemical inertness, high stability, non-toxicity, corrosion resistant, inexpensiveness, and environmentally benign nature as compared to other photocatalysts [8-10]. However, TiO_2 has a

wide band gap (anatase phase: 3.2 eV and rutile phase: 3.0 eV) and presents a high recombination rate of photogenerated electron-hole pairs [11,12]. In view of this, coupling of TiO_2 with other metal oxides (e.g. Fe_2O_3 [13], WO_3 [14], ZnO [15], SnO_2 [16], and CeO_2 [17]) was investigated extensively for its potential application in degradation of organic pollutants. Generally, the synthesis of these hybrid metal oxides photocatalysts employed conventional methods (such as sol-gel, hydrothermal, solvothermal, precipitation, and chemical/physical vapour deposition) that posed several drawbacks. These conventional methods were predominantly multi-step procedures, necessitated the utilization of toxic metal-organic precursors, and required expensive equipment [18,19]. Also, longer duration was needed, which was undesirable for industrial fabrication purposes [18]. Therefore, development of a greener and facile fabrication method using non-solvent synthesis under ambient temperature and atmospheric pressure was pursued in the current work.

Green chemistry was an initiative driven by the U.S. Environmental Protection Agency in the early 1990. It involved the design of chemical products and processes that reduced or eliminated the need and generation of hazardous substances [20]. Growing emphasis on green chemistry led to the use of mechanochemical process as a prospective method to activate and fabricate a photocatalyst under a solvent-free condition [21]. Previously, mechanochemical reaction was applied widely in areas including material synthesis, coal industry, extractive metallurgy, powder surface modification, pharmacy, and waste management [22]. During the course of mechanochemical process via ball milling (mechanical milling), accumulated potential energy with shear and friction forces were transferred from milling balls to the materials. This energy induced severe plastic deformation as well as created new interfaces and defects on the materials, which potentially led to substantial improvement in material properties of the final

product [23-25]. Mechanochemical process has gained importance over conventional synthesis methods because of its greener and facile technique [8,18]. In comparison with conventional synthesis methods, mechanochemical process did not require solvents and thus, no wastes were generated from catalyst washing. It also eliminated the need of multi-step procedures, high temperature and pressure conditions, plus no additions of hazardous and expensive chemicals were required [25,26]. Moreover, mechanochemical process yielded large quantities of desired product at ambient conditions within a very short processing time [8,18]. The advantages from this process serve as a very lucrative aspect from an economical viewpoint, thus, making mechanochemical synthesis very attractive for large-scale industrial production [18].

Herein, the current study demonstrated a facile and solvent-free mechanochemical process via mechanical milling to synthesize Fe_2O_3-TiO_2 photocatalyst as an approach towards a greener process. The synthesized Fe_2O_3-TiO_2 was used in degrading real PPME. To the best of our knowledge, there has been no report concerning the use of mechanochemically fabricated Fe_2O_3-TiO_2 photocatalyst in treating real industrial effluent, such as PPME. Thus, a detailed characterization study was performed to closely examine the structural and textural properties of the fabricated Fe_2O_3-TiO_2 via mechanochemical process. To further understand mechanochemical process, effects of fundamental synthesis conditions (i.e. milling time, milling speed, and Fe_2O_3 loading) on the properties and photoactivity of Fe_2O_3-TiO_2 were studied.

2. Experimental details

2.1. Materials

Iron (III) oxide, tungsten (VI) oxide, zinc oxide, cerium (IV) oxide, anatase titanium (IV) oxide, rutile titanium (IV) oxide, and Aeroxide® P25 were purchased from Sigma-Aldrich. All chemicals were used as received without further modification. Raw PPME was collected from Muda Paper Mills Sdn. Bhd., Kajang, Selangor. According to Subramonian et al. [27], raw PPME should be pre-treated using coagulation process to reduce the amount of total suspended solids from the effluent. In this study, PPME was pre-treated to the methods proposed by Subramonian et al. [28] and the pre-treated PPME with lesser suspended solids was used to evaluate the photocatalytic performance of the synthesized Fe_2O_3-TiO_2.

2.2. Mechanochemical synthesis of Fe_2O_3-TiO_2

Fe_2O_3-TiO_2 photocatalyst was fabricated in the absence of solvent via mechanochemical process using a planetary ball mill (Fritsch Pulverisette 5). Two zirconia vials with 500 cm^3 capacity were filled with a stoichiometric amount of Fe_2O_3 and P25 powder. 10 mm diameter balls were used as milling medium. Ball to powder mass ratio was kept constant at 10:1. Effect of mechanochemical synthesis conditions on the fabricated photocatalyst was studied by varying the milling time (10-30 min), milling speed (150-350 rpm), and Fe_2O_3 molar content (0.4-1.2 mol%). The synthesized Fe_2O_3-TiO_2 was then characterized and its catalytic performance was evaluated based on COD removal of PPME.

130 **2.3. Characterization study**

131 Crystallinity and phase identification of samples were determined from powder X-ray
132 diffraction (XRD) patterns. XRD data was recorded on a X-ray diffractometer (Bruker D8
133 Discovery) using Ni filtered Cu-Kα radiation (λ = 0.154056 nm) at a scan rate of 0.02° s^{-1}. The
134 accelerating voltage and current were 40 kV and 40 mA, respectively. Crystallite sizes of the
135 samples were calculated based on Scherrer formula. Surface morphology and elemental
136 compositions of the samples were obtained using field electron scanning electron spectroscopy
137 (FESEM) (Hitachi SU8010) equipped with energy-dispersive X-ray (EDX). X-ray photoelectron
138 spectroscopy (XPS) analysis was conducted on a Kratos Axis-Ultra DLD instrument with a
139 monochromatized Al Kα X-ray source (15 kV, 200 W) at a pressure of 7.6×10^{-9} Torr and 20 eV
140 pass energy. All binding energies were referenced to C 1s peak at 284.6 eV of the adventitious
141 carbon. Transmission electron microscopy (TEM) images were taken with a JEOL JEM-2100F
142 microscope operated at 200 kV. Meanwhile, textural properties of the samples were analyzed
143 based on nitrogen adsorption/desorption isotherms using Micromeritics, ASAP 2020. Specific
144 surface areas and pore distributions were determined from Brunauer-Emmett-Teller (BET) and
145 Barrett-Joyner-Halenda (BJH) methods, respectively. Raman spectra were acquired using
146 HORIBA Scientific, LabRAM HR Evolution with an excitation wavelength of 514 nm under
147 room temperature whereas Fourier transform infrared (FTIR) spectra were recorded over a range
148 of 4000-400 cm^{-1} at room temperature using a FTIR spectrophotometer (Thermo Scientific
149 Nicolet iS10). Additionally, ultraviolet-visible (UV-vis) diffused reflectance spectra (DRS) were
150 recorded on a UV-vis spectroscopy (Cary 100, Agilent) with $BaSO_4$ as reference. Band gap
151 energies of the samples were estimated from plot of transformed Kubelka-Munk function $[F(R) \cdot h\nu]^{1/2}$ against abscissa of photon energy ($h\nu$). Photoluminescence (PL) emission spectra was

analyzed using a fluorescence spectrometer (LS55, Perkin Elmer) at an excitation wavelength of 315 nm with 500 nm min^{-1} scanning speed. The widths of the excitation and emission slits were fixed at 10 nm.

2.4. Photocatalytic evaluation of Fe_2O_3-TiO_2

Photoactivity of the prepared Fe_2O_3-TiO_2 was evaluated in terms of photodegradation of PPME. In a typical procedure, 1.0 g/L of Fe_2O_3-TiO_2 was dispersed in 50 mL of PPME at pH 4. The suspension was magnetically stirred in the dark at 800 rpm for 30 min to achieve adsorption-desorption equilibrium. Then, the suspension was exposed to UV irradiation (400 W of UV lamp) for 3 h under continuous stirring and aeration (air flow rate = 4.0 L/min). The initial and final samples were withdrawn from the suspension before and after irradiation to determine a change in COD (Equation (1)). Photocatalyst was removed from the samples by centrifugation (13500 rpm for 15 min).

$$COD\ removal, \% = \frac{COD_{initial} - COD_{final}}{COD_{initial}} \times 100 \qquad (1)$$

3. Results and discussion

3.1. Effect of mechanical milling on characteristics and photoactivity of Fe_2O_3-TiO_2

In mechanochemical synthesis, metal oxide powders (Fe_2O_3 and TiO_2) were plastically deformed due to high-energy impact between milling balls and wall of the vial, producing the final composite Fe_2O_3-TiO_2 [8]. Fundamental mechanochemical synthesis conditions played a crucial role in manipulating photocatalytic properties of Fe_2O_3-TiO_2 [7]. Therefore, the present

176 study investigated the effect of mechanochemical process conditions (milling time, milling
177 speed, and loading of Fe_2O_3) on the intrinsic properties and photoactivity of Fe_2O_3-TiO_2.
178
179 **3.1.1. Effect of milling time**
180 Change in Fe_2O_3-TiO_2 morphology as a function of milling time was observed from FESEM
181 images. Mechanically milled Fe_2O_3-TiO_2 samples were gradually ground to finer particles from
182 10 to 20 min (Fig. 1a-c) due to longer duration of impact and shear forces incurred from the
183 milling balls. However, prolonging the milling time above 20 min resulted in highly
184 agglomerated particles with rough surfaces (Fig. 1d and e). Similar findings were observed by
185 House et al. [29]. Powder that was milled at 25 and 30 min had a high surface energy, which
186 facilitated the powder to reunite and reagglomerate in order to reduce surface energy and re-
187 stabilize the system [30]. In short, fracture of solids only occurred at shorter milling time
188 whereas reagglomeration appeared at longer milling time [31]. Surface morphology of Fe_2O_3-
189 TiO_2, P25 and Fe_2O_3 powder were also compared. From the FESEM images, P25 powder (Fig.
190 1f) consisted of uniform spherical particles whereas Fe_2O_3 (Fig. 1g) particles were large and
191 irregular-sized. The fabricated Fe_2O_3-TiO_2 (Fig. 1a-c) photocatalyst was finer than Fe_2O_3 (Fig.
192 1g). In addition, Fe_2O_3-TiO_2 (Fig. 1a-c) was irregular in shape, randomly organized, and slightly
193 agglomerated as compared to P25 (Fig. 1f). Carneiro et al. [8] also reported very similar catalyst
194 morphology that was induced by the effect of ball milling.
195 An employment of mechanochemical synthesis was reported to promote mesoporosity and
196 change in specific surface area of the materials [32]. Hence, surface properties of the synthesized
197 Fe_2O_3-TiO_2 were evaluated at different milling time and were compared with Fe_2O_3 and pristine
198 P25. According to IUPAC classification, nitrogen adsorption/desorption isotherm of Fe_2O_3-TiO_2

showed a typical type IV pattern with a hysteresis loop beginning around relative pressure of 0.7 (Fig. 2). The pattern suggested the occurrence of mesoporous structure with a broad pore size distribution [32,33]. Pore size distribution curve (inset in Fig. 2) depicts a wide range of pore diameter from 4 to 35 nm with the pore size mainly distributed at 17 nm, implying that an incorporation of Fe_2O_3 into TiO_2 lattice through mechanochemical synthesis did not defect the surface mesoporous structure of the TiO_2 [34]. Specific surface area, pore volume, and pore size of Fe_2O_3-TiO_2 were found to be higher than P25 (Table 1). Higher textural properties provided better surface adsorption and mass transfer between organic pollutants and Fe_2O_3-TiO_2 in the catalyst pore, suggesting a potential enhancement in photocatalytic activity [34].

The specific surface areas, pore volumes, and pore sizes of the milled samples were also clearly affected by the milling time (Table 2). Overall, the aforementioned textural properties improved from milling time 10 to 20 min because of repeated fracturing of solids induced by the milling balls, which consequently led to a reduction in particle size, and an increase in both surface area and porosity [31]. However, a deterioration of textural properties occurred from 25 to 30 min due to reagglomeration of solids as evidenced in Fig. 1d and e. Similarly, the photocatalytic trend also displayed a gradual increase in COD removal (52.7 to 62.3%) from 10 to 20 min, followed by a decrease (57.4 to 52.8%) from 25 to 30 min of milling time (Fig. 3). One-way analysis of variance (ANOVA) revealed that the recommended milling time was 20 min. Thus, subsequent synthesis of Fe_2O_3-TiO_2 photocatalyst was carried out based on this milling time.

3.1.2. Effect of milling speed

Change in milling speed stimulated modifications to the crystallite structure of Fe_2O_3-TiO_2. It was proven in this study that by increasing the milling speed (150 to 350 rpm), XRD diffraction peaks (Fig. 4) became broader with diminishing intensities. The result denoted the presence of smaller-sized particles formed at elevated milling speed [8]. Besides, crystallite sizes of Fe_2O_3-TiO_2 also decreased with increasing milling speed (150 to 350 rpm) as shown in Table 3. Mechanical impact from the milling balls at rising milling speed deformed the powders and introduced lattice defects, leading to a reduction in crystallite size [8]. Fig. 5 shows an improvement in catalytic activity from 150 to 250 rpm (52.2 to 62.3% of COD removal, respectively) followed by a drop from 300 to 350 rpm (53.2 to 50.2% of COD removal, respectively). Decline in photoactivity at elevated milling speed was attributed to higher rutile content in Fe_2O_3-TiO_2 at 300 to 350 rpm (Table 3). The rutile phase fraction for each sample (Table 3) was determined from the XRD patterns (Fig. 4) using Spurr equation. At higher milling speed, more collisions occurred between the milling balls and powders. Following that, an increase of local temperature and pressure at the collision sites induced an anatase-to-rutile phase transformation of the fabricated Fe_2O_3-TiO_2 [8]. One-way ANOVA suggested that 250 rpm was the recommended milling speed to prepare Fe_2O_3-TiO_2 and subsequent milling was carried out using this speed.

In addition, XRD patterns of the synthesized Fe_2O_3-TiO_2 (Fig. 4) exhibited characteristic peaks of Fe_2O_3, anatase, and rutile TiO_2. Peaks at 25.3, 37.8, 48.1, 54.4, 55.1, 62.7, 69.0, and 75.1°corresponded to (101), (004), (200), (105), (211), (204), (116), and (215) planes, respectively of anatase TiO_2 (JCPDS card file: 21-1272). Trace amounts of rutile TiO_2 present in Fe_2O_3-TiO_2 were represented at 27.4 , 36.0 , 39.2 , 54.2 , 56.7 , 69.9°, which were assigned to (110), (101), (200), (211), (220), and (112) planes, respectively (JCPDS card file: 21-1276). The

presence of both anatase and rutile phases was due to the mix phases of P25 (anatase: ~80% and rutile: ~20%) used as a material to fabricate Fe_2O_3-TiO_2. Meanwhile, traces of Fe_2O_3 present in Fe_2O_3-TiO_2 showed lower peak intensities at 30.2, 35.5, 57.0, and 62.9°, which were indexed to (220), (311), (511), and (440) planes, respectively (JCPDS card file: 39-1346). The low peak intensities were due to low concentration of Fe_2O_3 (1 mol%) added during the fabrication of Fe_2O_3-TiO_2 [12]. Upon closer observation, angular positions of certain XRD peaks of the synthesized Fe_2O_3-TiO_2 were slightly shifted as compared to the peaks of P25. This implied a small distortion in TiO_2 crystal lattice due to presence of Fe. The TiO_2 lattice distortion was a result from Ti^{4+} replaced by Fe^{3+} because of their comparable radii (0.068 and 0.064 nm, respectively) [8,35]. A substitution of Ti^{4+} by Fe^{3+}increased the number of oxygen vacancies, which promoted photoactivity of Fe_2O_3-TiO_2 [35]. Overall, the XRD patterns of Fe_2O_3-TiO_2 established the coexistence of Fe_2O_3, anatase and rutile TiO_2 crystalline structures. Additionally, average crystallite sizes of Fe_2O_3-TiO_2, P25, and Fe_2O_3 were 22.99, 24.29, and 17.45 nm, respectively (Table 1).

3.1.3. Effect of Fe_2O_3 loading

PL measurement was conducted to evaluate the correlation between photoactivity of Fe_2O_3-TiO_2 and Fe_2O_3 loading. Peak intensity of PL spectra correlated to the recombination rate of electron-hole pairs whereby weaker peak intensity represented lower recombination rate [36]. According to the PL signals (Fig. 6), an addition of Fe_2O_3 from 0.4 to 1.2 mol% reduced the PL peak intensities, signifying better charge separation at higher Fe_2O_3 molar content. Due to the close radii of Fe^{3+} (0.064 nm) and Ti^{4+} (0.068 nm), an increase of Fe_2O_3 loading led to more substitution of Ti^{4+} by Fe^{3+}, consequently, generating more oxygen vacancies [35]. An increase

267 in oxygen vacancies, which acted as electron donors in TiO_2 lattice, promoted better charge
268 separation. On the other hand, excessive addition of Fe_2O_3 could cause an undesirable energy
269 transfer between nearby ions due to shorter distance of Fe-Fe ions, leading to a deterioration in
270 charge separation and reduction in photoactivity [35]. As a comparison, the synthesized Fe_2O_3-
271 TiO_2 exhibited a significant 84% reduction in PL emission intensity as compared to P25 (Fig. 6).
272 The reduction of emission intensity signified a high efficiency of charge separation and transfer
273 between the two Fe_2O_3 and TiO_2 metal oxides in the synthesized Fe_2O_3-TiO_2 [37]. Theoretically,
274 an incorporation of Fe_2O_3 into TiO_2 lattice resulted in the substitution of Ti^{4+} by Fe^{3+} species,
275 creating oxygen vacancies, which in turn supported charge separation [35].

276 Band gap measurements from diffuse reflectance study pave way to a better understanding
277 of the optical response of fabricated Fe_2O_3-TiO_2 [38]. Band gaps of Fe_2O_3-TiO_2 samples at
278 different Fe_2O_3 loading are displayed in the transformed Kulbeka-Munk function plot (Fig. 7a).
279 Although the band gap values were in close range (2.85-2.95 eV) despite a change in Fe_2O_3
280 molar content, the photodegradation efficiency (Fig. 8) improved significantly from 40.6 to
281 62.5% with increasing Fe_2O_3 loading (0.4 to 1.2 mol%, respectively). Upon light absorption,
282 excited electrons from TiO_2 conduction band were transferred to the interface of Fe_2O_3 and
283 converted Fe^{3+} into Fe^{2+} [37,39]. Since the unstable Fe^{2+} was rapidly oxidized by dissolved
284 oxygen to Fe^{3+}, Fe^{3+} once again behaved as a shallow trapping site for photoexcited electrons
285 from TiO_2, hindering electron-hole pair recombination [36,39]. So, at higher Fe_2O_3 molar
286 content, more Fe^{3+} was incorporated into TiO_2 lattice [40]. Thus, electron-hole recombination
287 was suppressed more effectively and enhanced the photoactivity of Fe_2O_3-TiO_2 [40]. However,
288 further addition of Fe_2O_3 beyond 1.0 mol% did not help to improve photoactivity of the catalyst
289 due to high percentage of free Fe_2O_3 (Fe^{3+}), which was not incorporated into TiO_2 lattice [40].

290 On the other hand, band gap values of Fe_2O_3-TiO_2 were enhanced considerably as compared to
291 P25 (Table 1 and Fig. 7a). An improvement in band gap values indicated a successful
292 incorporation of Fe^{3+} into the TiO_2 framework [40]. Notably, coupling of Fe_2O_3 with TiO_2
293 stimulated better light harvesting ability and further extended the light absorption range as shown
294 in Fig. 7b. In addition, plot of transformed Kulbeka-Munk function (Fig. 7a) reveals that band
295 gap energy of Fe_2O_3-TiO_2 was lower (2.95 eV) than P25 (3.35 eV). This observation was
296 probably due to electronic coupling between the wide band gap of TiO_2 with the narrow band
297 gap of Fe_2O_3 [41].

298 Based on one-way ANOVA, maximum photodegradation efficiency of PPME (62.3% COD
299 removal) was observed at 20 min of milling time, 250 rpm of milling speed, and 1 mol% of
300 Fe_2O_3 loading. The synthesized Fe_2O_3-TiO_2 photocatalyst was 1.5-times more superior to the
301 commercial P25 (40.6% COD removal).

302

303 **3.2. Comparison of other metal oxide-TiO_2 photocatalysts with Fe_2O_3-TiO_2**

304

305 Other metal oxide candidates (WO_3, ZnO, and CeO_2) were introduced into the TiO_2 lattice
306 under recommended milling conditions and their photocatalytic activity was compared with
307 Fe_2O_3-TiO_2. Based on the photodegradation of PPME (Fig. 9 and Table 4), it was apparent that
308 Fe_2O_3-TiO_2 attained the highest COD removal (62.3%) as compared to other metal oxide-TiO_2
309 photocatalysts (35.4-45.5%), P25 (40.6%), anatase TiO_2 (24.9%), rutile TiO_2 (2.9%), and Fe_2O_3
310 (1.1%). Therefore, Fe_2O_3-TiO_2 was established as a desired and promising photocatalyst to
311 degrade PPME in this work.

312

3.3. Detailed characterizations of Fe_2O_3-TiO_2

The fabricated Fe_2O_3-TiO_2 under recommended milling conditions (20 min of milling time, 250 rpm of milling speed, and 1 mol% of Fe_2O_3 loading) was subjected to additional characterization studies to further investigate its catalytic properties.

3.3.1. Elemental compositions and distribution

EDX spectrum (Fig. 10a) shows simultaneous presence of Fe, Ti and O elements in Fe_2O_3-TiO_2, which was produced through mechanochemical process. In addition, EDX mapping (Fig. 10b-d) shows extensive dispersion of Fe and O elements within the TiO_2 framework. This result indicated that Fe_2O_3 was well distributed throughout the fabricated Fe_2O_3-TiO_2 using mechanochemical process. Elemental compositions of Fe_2O_3-TiO_2 sample was further verified using XPS analysis.

In order to ascertain the chemical states of Fe, Ti and O existing in Fe_2O_3-TiO_2, XPS analysis was conducted. As displayed in Fig. 11a, XPS survey spectrum detected the presence of Fe (Fe 2p), Ti (Ti 2p), and O (O 1s) in Fe_2O_3-TiO_2. Carbon peak (C 1s) was attributed to the carbon tape used as a support during XPS analysis. High resolution XPS spectra reveal chemical species within the prepared Fe_2O_3-TiO_2 (Fig. 11b-d). Binding energies of Fe $2p_{3/2}$ and Fe $2p_{1/2}$ were 710.7 and 724.5 eV respectively, verifying the presence of Fe^{3+}. An absence of peaks around 707 and 719 eV ruled out the presence of Fe^{2+}, firmly supporting the addition of γ-Fe_2O_3 phase into TiO_2 [42]. Peaks corresponding to Ti^{4+} were centered at 458.6 and 464.4 eV, which were analogous to Ti $2p_{3/2}$ and Ti $2p_{1/2}$, respectively. From O 1s spectra, binding energy at 529.8

335 eV was assigned to lattice oxygen, O^{2-} species from Fe_2O_3 and Ti-O-Ti [34,43]. The attained XPS
336 findings (Fig. 11a-d) were in conformity with the obtained EDX analysis data (Fig. 10a).
337
338 **3.3.2. Surface morphology**
339 TEM image (Fig. 12a) shows that Fe_2O_3-TiO_2 nanoparticles had an average particle size of
340 30 nm. Darker regions corresponded to Fe_2O_3 particles whereas lighter regions were ascribed to
341 TiO_2 nanoparticles. Noticeably, an intimate contact between Fe_2O_3 and TiO_2 particles was
342 formed from mechanochemical process. The contact was advantageous for charge transfer
343 between the two metal oxides due to a shorter carrier diffusion length that would suppress
344 recombination of electron-hole pairs [37]. Furthermore, Fe_2O_3 particles appeared to be well-
345 dispersed throughout the Fe_2O_3-TiO_2 sample. High resolution TEM (HRTEM) image (Fig. 12b)
346 revealed clear lattice fringes of Fe_2O_3 and TiO_2. Lattice fringe of 0.29 nm was equivalent to
347 (220) plane of γ-Fe_2O_3, whereas lattice fringes of 0.35 and 0.32 nm corresponded to (101)
348 anatase plane and (110) rutile plane of TiO_2, respectively [43,44].
349
350 **3.3.3. Raman analysis**
351 Based on Raman spectrum of the Fe_2O_3-TiO_2 sample (Fig. 13), major Raman peaks at 155,
352 394, 514, and 633 cm^{-1} were indexed to the typical structure of TiO_2 whereas peak at 205 cm^{-1}
353 indicated the presence of γ-Fe_2O_3 [35,45]. A formation of Fe-O-Ti bond in the fabricated Fe_2O_3-
354 TiO_2 was evidenced by a peak at 279 cm^{-1}. This denoted that Fe^{3+} replaced some Ti^{4+} species in
355 lattice sites of the crystalline structure, indicating a successful synthesis of Fe_2O_3-TiO_2
356 photocatalyst [35]. Peak intensity analogous to the presence of Fe_2O_3 was low due to low
357 concentration of Fe_2O_3 (1 mol%). An incorporation of Fe atoms into Ti lattice sites also caused a

358 shift of peaks to slightly greater frequencies as a result from force constant and vibrational
359 amplitudes of neighbouring bonds [34,35].
360
361 **3.3.4. FTIR analysis**
362 FTIR analysis was employed to determine the functional groups present in Fe_2O_3-TiO_2 [21].
363 Based on Fig. 14, FTIR spectrum of Fe_2O_3-TiO_2 was similar to P25, signifying that Fe_2O_3 was
364 well-infused into the TiO_2 lattice [39]. Two bands observed at 3400 and 1634 cm^{-1} were
365 characteristics of O-H stretching vibrations and H-OH bending of hydroxyl groups present [46].
366 These bands played a significant role in photocatalytic reactions to react with photogenerated
367 holes on the Fe_2O_3-TiO_2 surface upon light irradiation. Broad peak at 3250 cm^{-1} was due to O-H
368 stretching vibration of water whereas bands at 2924 and 2840 cm^{-1} were attributed to C-H
369 stretching vibrations of alkyl chain [40,42].
370
371
372 **4. Conclusions**
373
374 In this study, a photoactive Fe_2O_3-TiO_2 catalyst was successfully synthesized using a one-
375 step facile and solvent-free mechanochemical process under ambient temperature and
376 atmospheric pressure. Characterization studies showed that the synthesized Fe_2O_3-TiO_2
377 possessed crystalline structures of γ-Fe_2O_3, anatase, and rutile phases of TiO_2. It was further
378 confirmed that Fe, Ti and O elements were present and were well-dispersed within the Fe_2O_3-
379 TiO_2 framework. Enhanced photoactivity of Fe_2O_3-TiO_2 was attributed to the following
380 distinctive traits: (i) formation of Fe-O-Ti bond due to substitution of Ti^{4+} by Fe^{3+} in TiO_2 lattice;

(ii) higher specific surface area (58.40 m^2/g) and porosity (0.29 cm^3/g) than commercial P25; (iii) lower band gap (2.95 eV) than P25 due to electronic coupling of TiO_2 and Fe_2O_3; (iv) and suppressed electron-hole recombination rate, which was ascribed to the incorporation of Fe^{3+} that acted as a charge-transfer mediator. In addition, the highest treatment efficiency of PPME (62.3% of COD removal) was achieved by using Fe_2O_3-TiO_2, which was synthesized at 20 min of milling time, 250 rpm of milling speed, and 1 mol% of Fe_2O_3 loading. Markedly, the photoactivity of Fe_2O_3-TiO_2 was 53.4% higher than the commercial P25. In conclusion, this study provided a better insight into the potential use of mechanochemical process as a greener, simpler and low-cost approach in synthesizing high efficiency photocatalysts to degrade complex industrial effluent.

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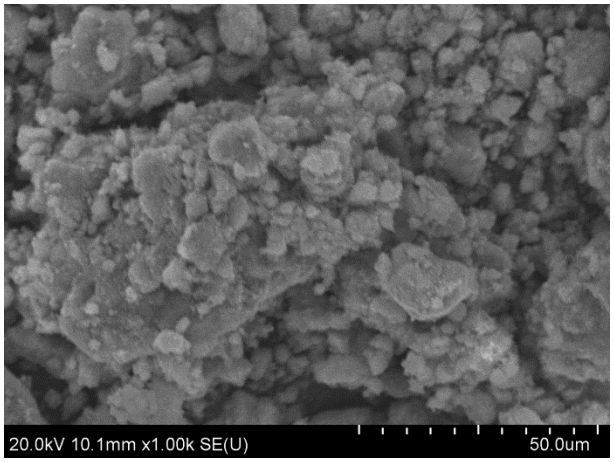
List of Figures



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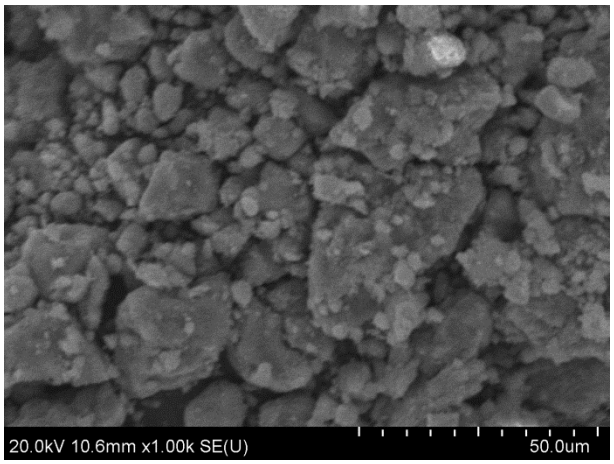

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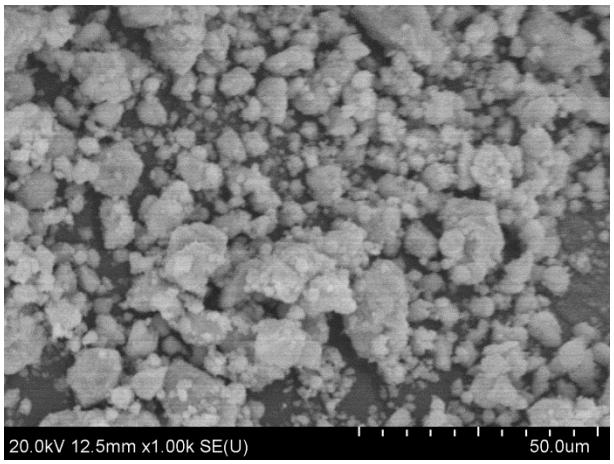

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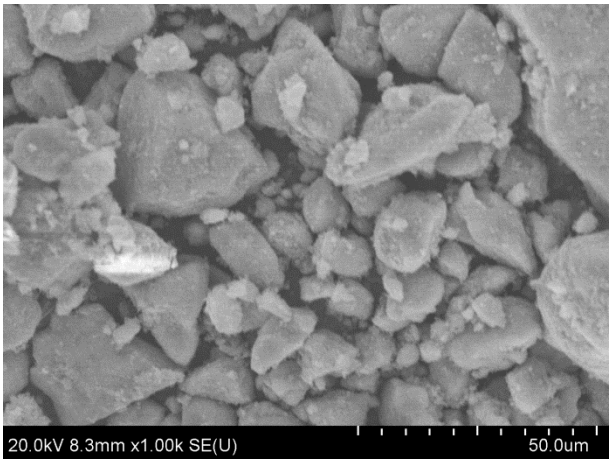

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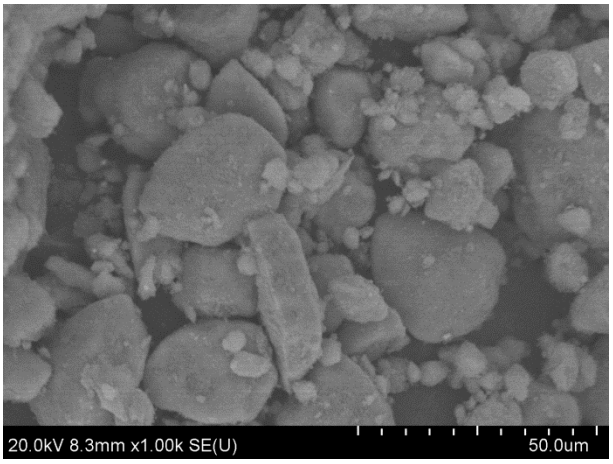

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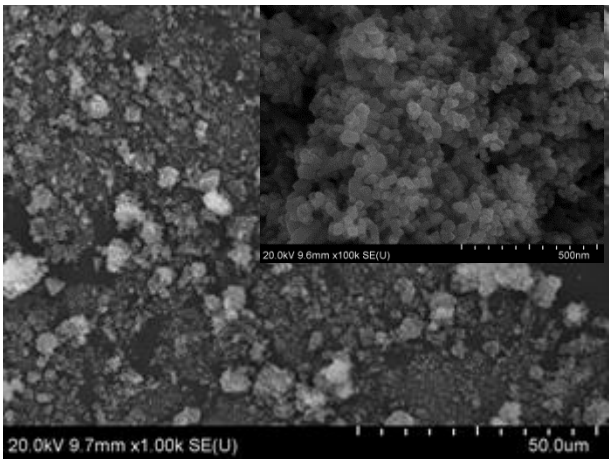

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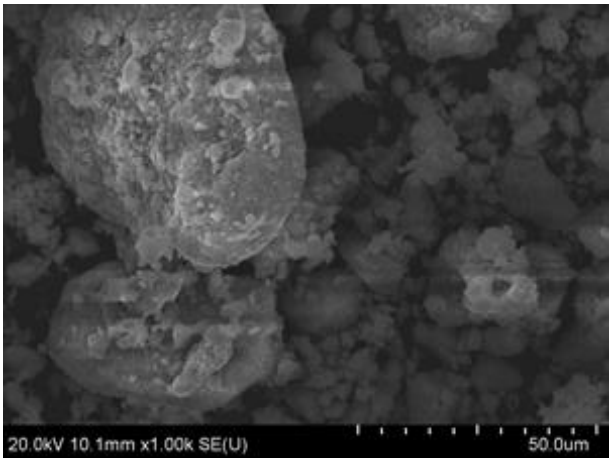


Fig. 1. (g)

Fig. 1. FESEM images of (a) Fe_2O_3-TiO_2 milled at 10 min, (b) 15 min, (c) 20 min, (d) 25 min and (e) 30 min, (f) P25 and (g) Fe_2O_3.

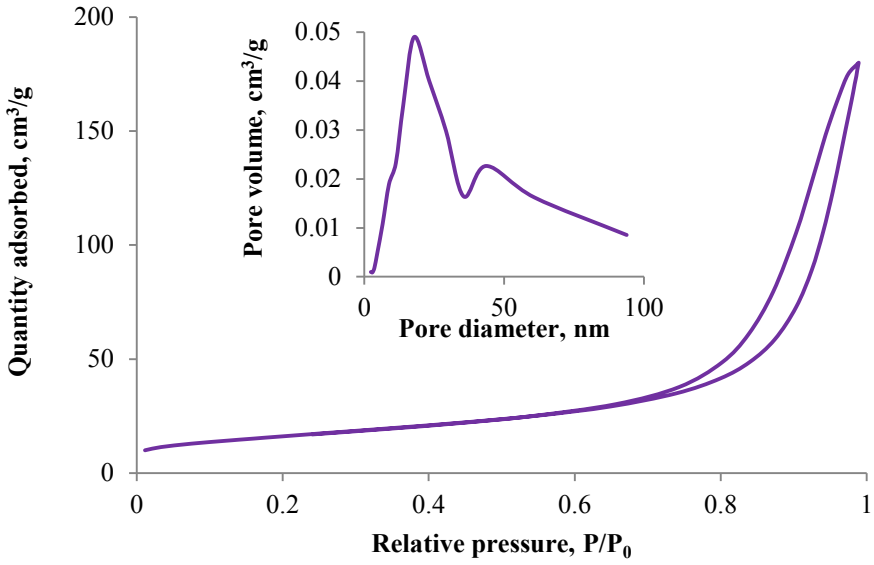


Fig. 2. Nitrogen adsorption/desorption isotherm. Inset shows the BJH pore size distribution of Fe_2O_3-TiO_2.

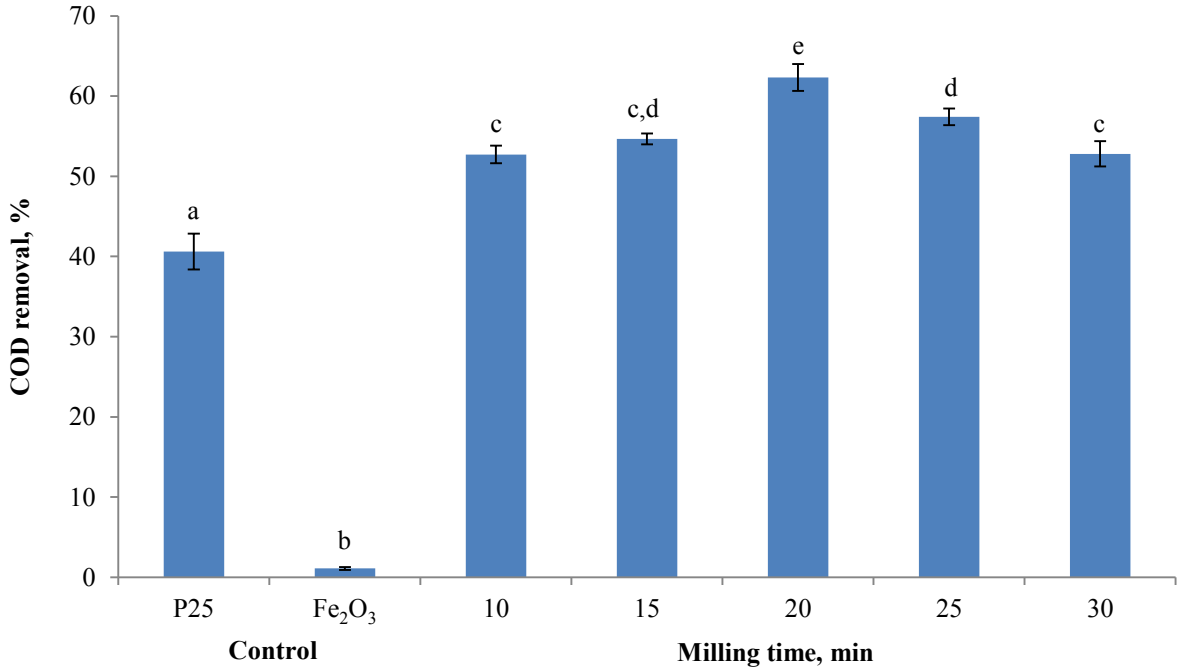


Fig. 3. Effect of milling time on photodegradation of PPME (milling speed = 250 rpm; [Fe_2O_3] = 1 mol%; ball:powder mass ratio = 10:1; irradiation time = 3 h; initial effluent pH = 4; [Fe_2O_3-TiO_2] = 1.0 g/L; air

flow rate = 4.0 L/min; n = 3). Values annotated with different letters represent significant differences (one-way ANOVA, Tukey's test; P <0.05).

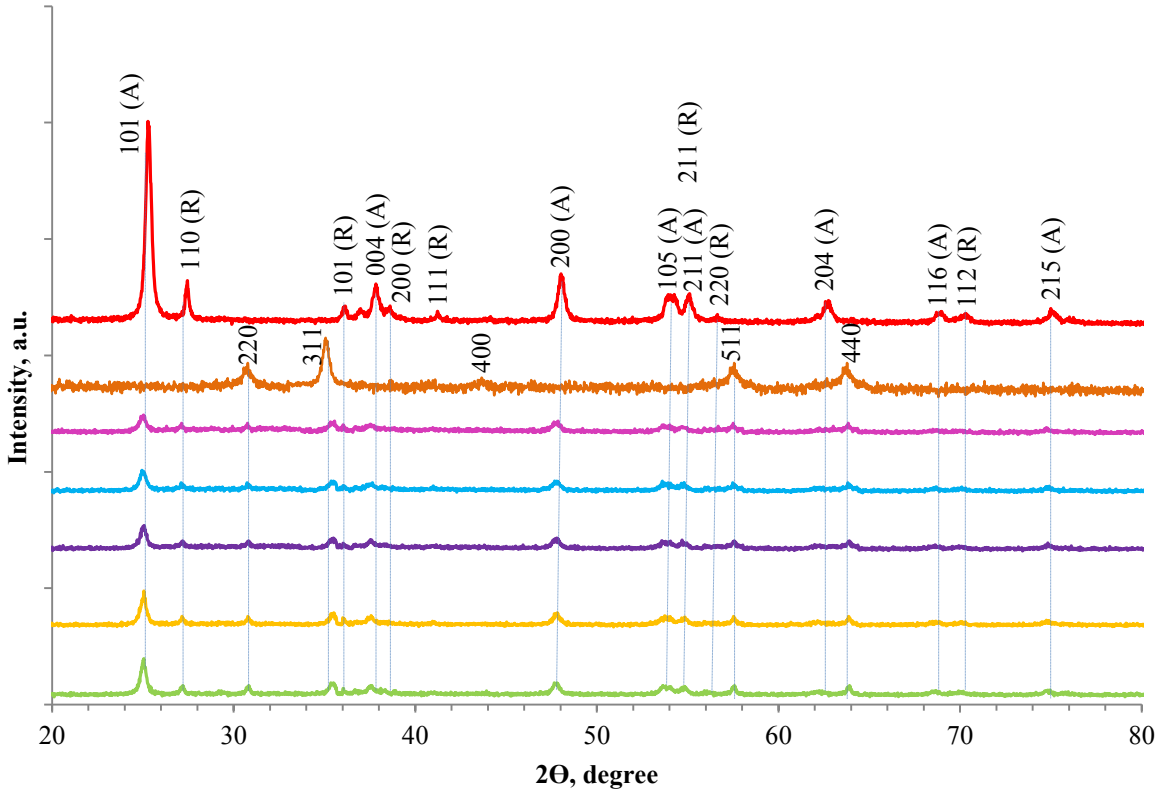


Fig. 4. XRD patterns of P25 (red), Fe_2O_3 (brown), and Fe_2O_3-TiO_2 milled at 150 rpm (green), 200 rpm (yellow), 250 rpm (purple), 300 rpm (blue) and 350 rpm (pink) (A: anatase phase; R: rutile phase).

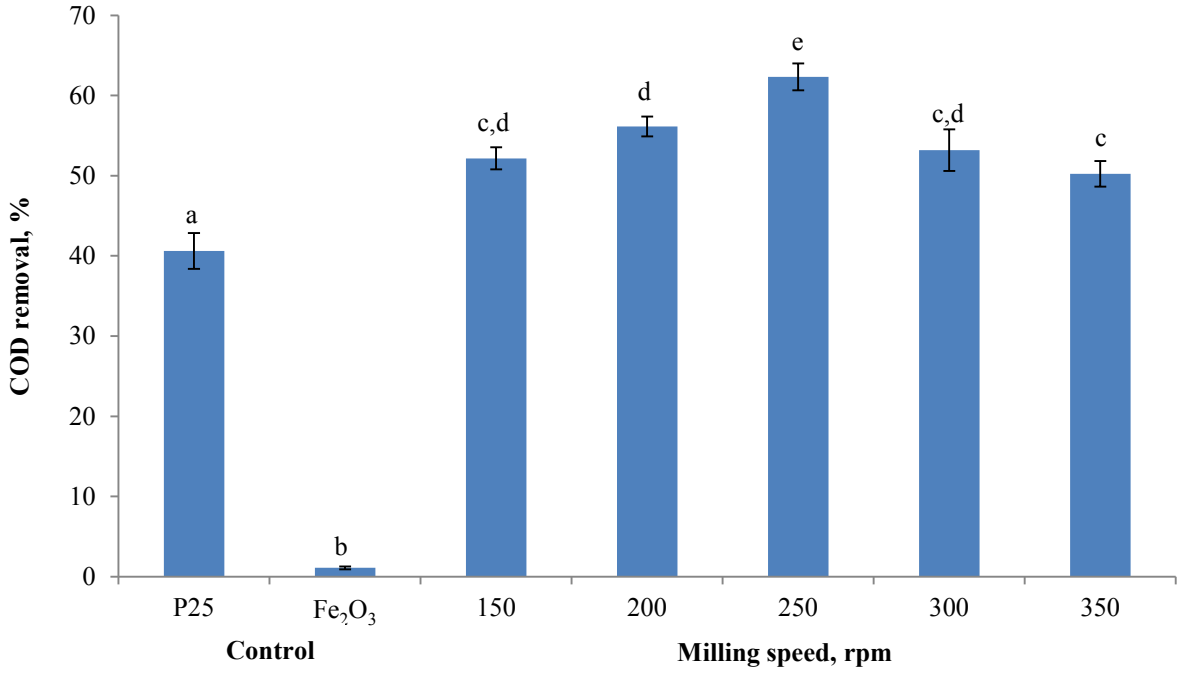


Fig. 5. Effect of milling speed on photodegradation of PPME (milling time = 20 min; [Fe_2O_3] = 1 mol%; ball:powder mass ratio = 10:1; irradiation time = 3 h; initial effluent pH = 4; [Fe_2O_3-TiO_2] = 1.0 g/L; air flow rate = 4.0 L/min; n = 3). Values annotated with different letters represent significant differences (one-way ANOVA, Tukey's test; $P < 0.05$).

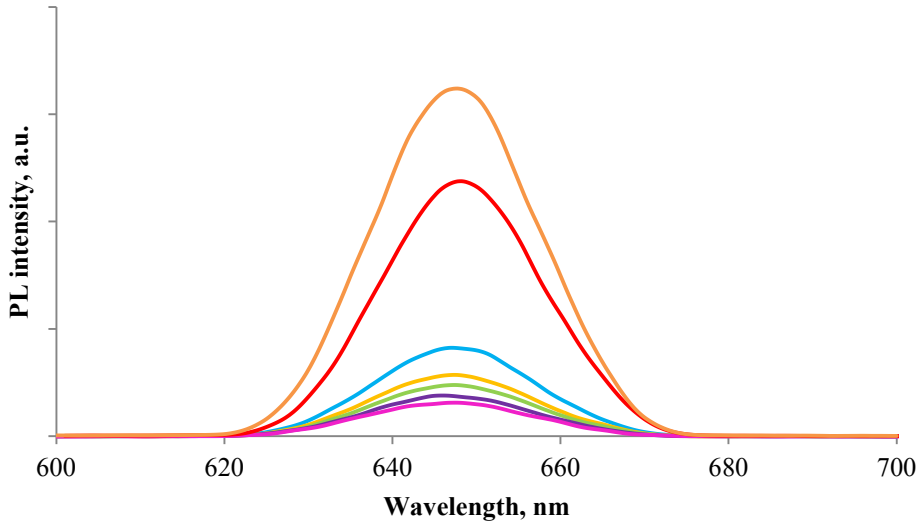


Fig. 6. PL spectra of P25 (red), Fe_2O_3 (brown), and Fe_2O_3-TiO_2 with Fe_2O_3 loading of 0.4 mol% (blue), 0.6 mol% (yellow), 0.8 mol% (green), 1.0 mol% (purple) and 1.2 mol% (pink).

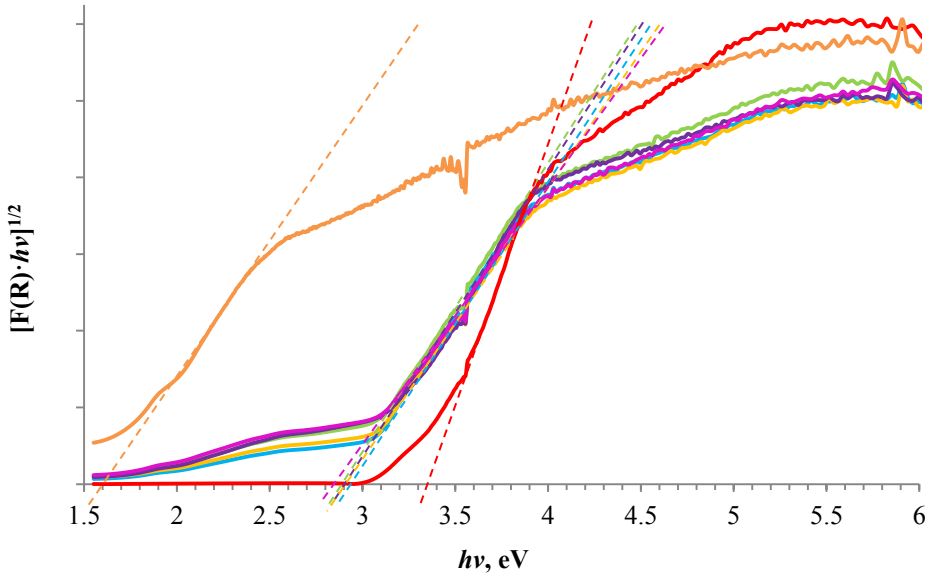


Fig. 7. (a)

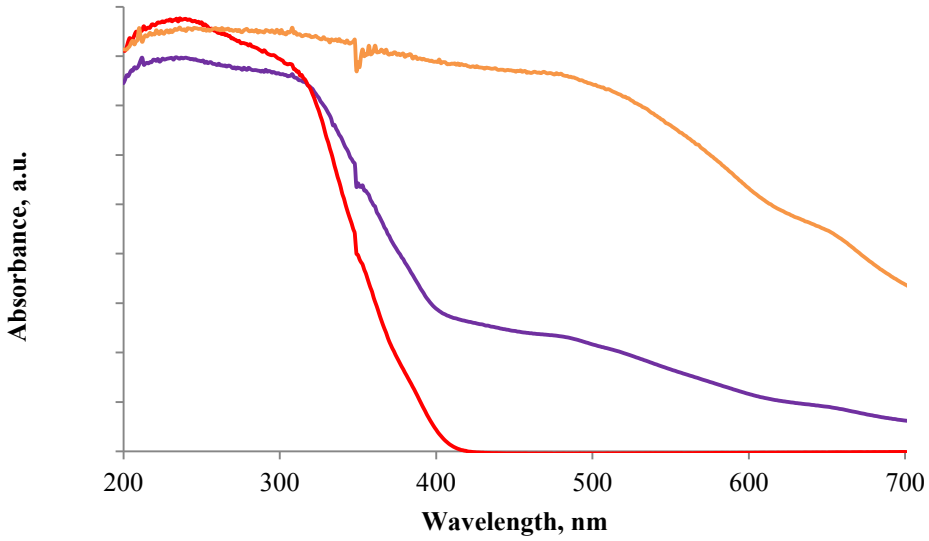


Fig. 7. (b)

Fig. 7. (a) Plot of transformed Kulbeka-Munk function $[F(R)\cdot h\nu]^{1/2}$ versus $h\nu$ of P25 (red), Fe_2O_3 (brown), and Fe_2O_3-TiO_2 with Fe_2O_3 loading of 0.4 mol% (blue), 0.6 mol% (yellow), 0.8 mol% (green), 1.0 mol% (purple) and 1.2 mol% (pink). (b) DRS spectra of P25 (red), Fe_2O_3 (brown), and Fe_2O_3-TiO_2 with Fe_2O_3 loading 1.0 mol% (purple).

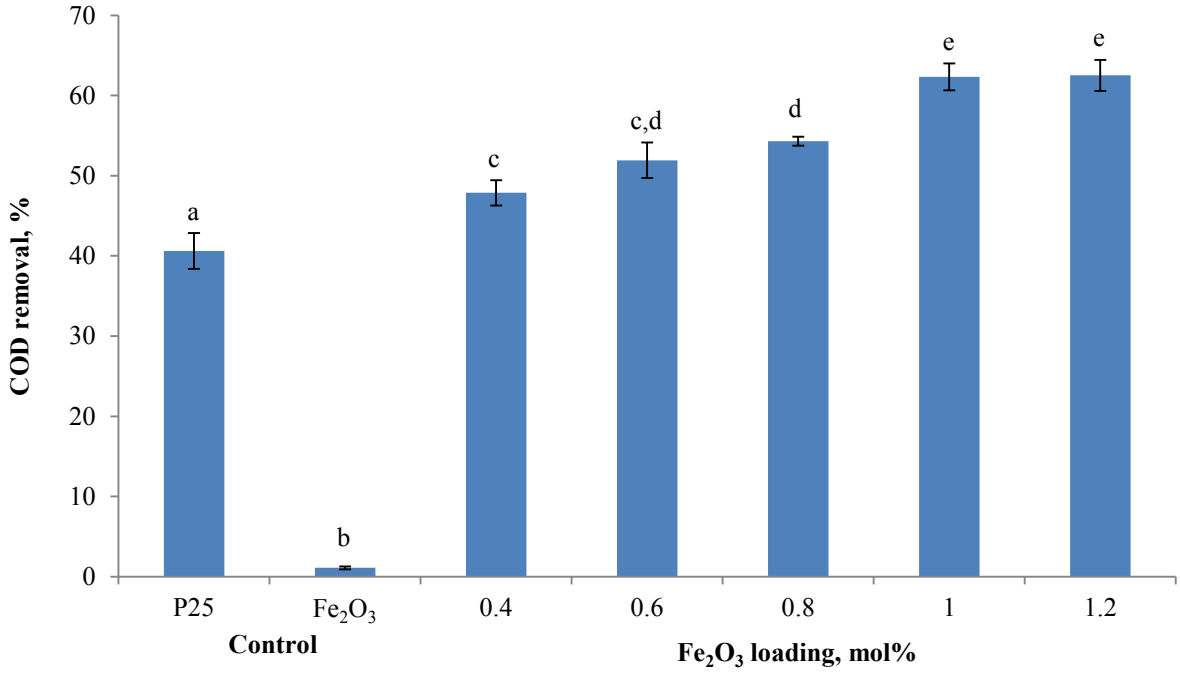


Fig. 8. Effect of Fe_2O_3 loading on photodegradation of PPME (milling time = 20 min; milling speed = 250 rpm; ball:powder mass ratio = 10:1; irradiation time = 3 h; initial effluent pH = 4; [Fe_2O_3-TiO_2] = 1.0 g/L; air flow rate = 4.0 L/min; *n* = 3). Values annotated with different letters represent significant differences (one-way ANOVA, Tukey's test; P <0.05).

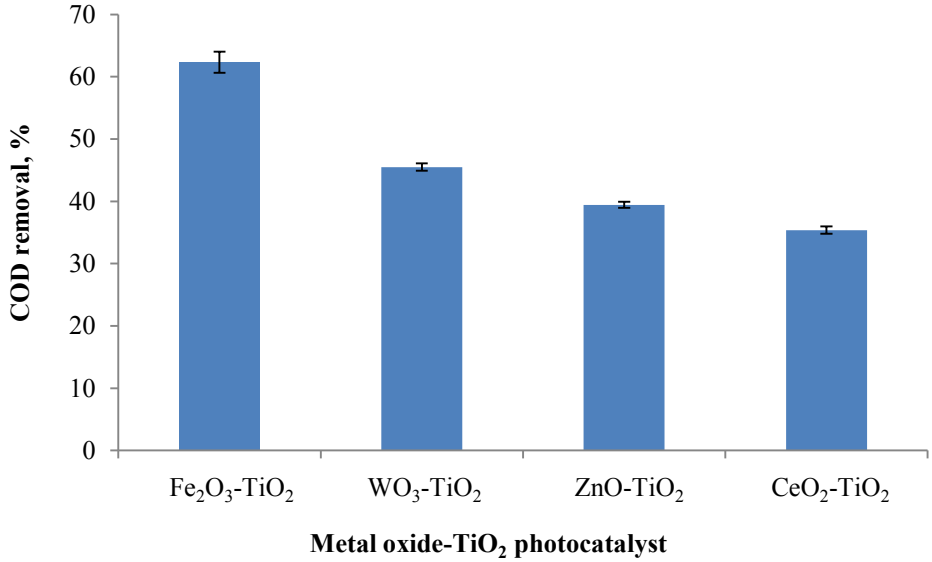


Fig. 9. Comparison of other metal oxide-TiO_2 photocatalysts with Fe_2O_3-TiO_2.

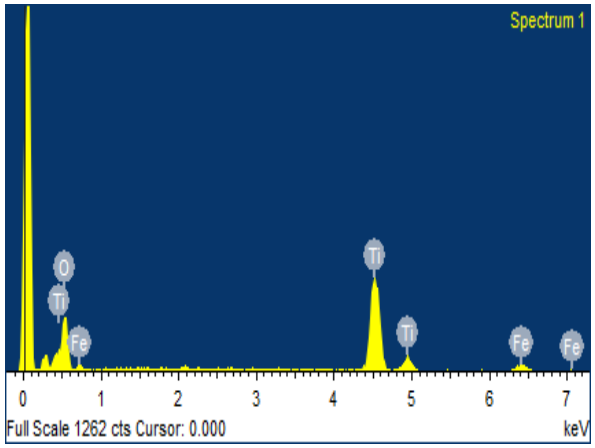
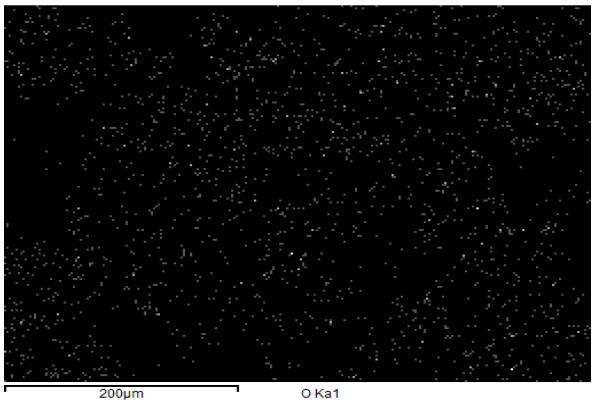


Fig. 10. (a)



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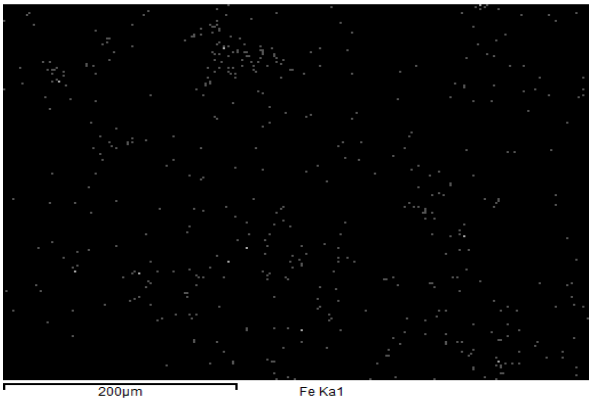

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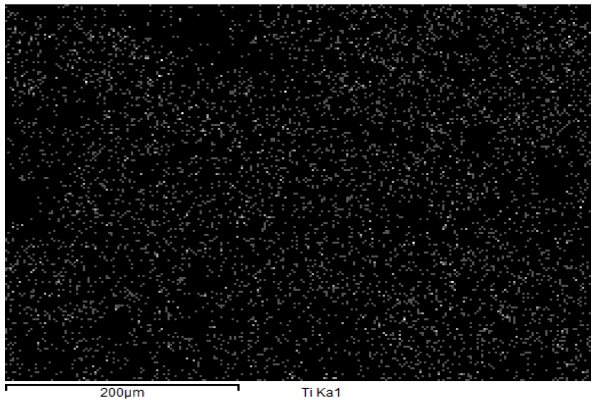
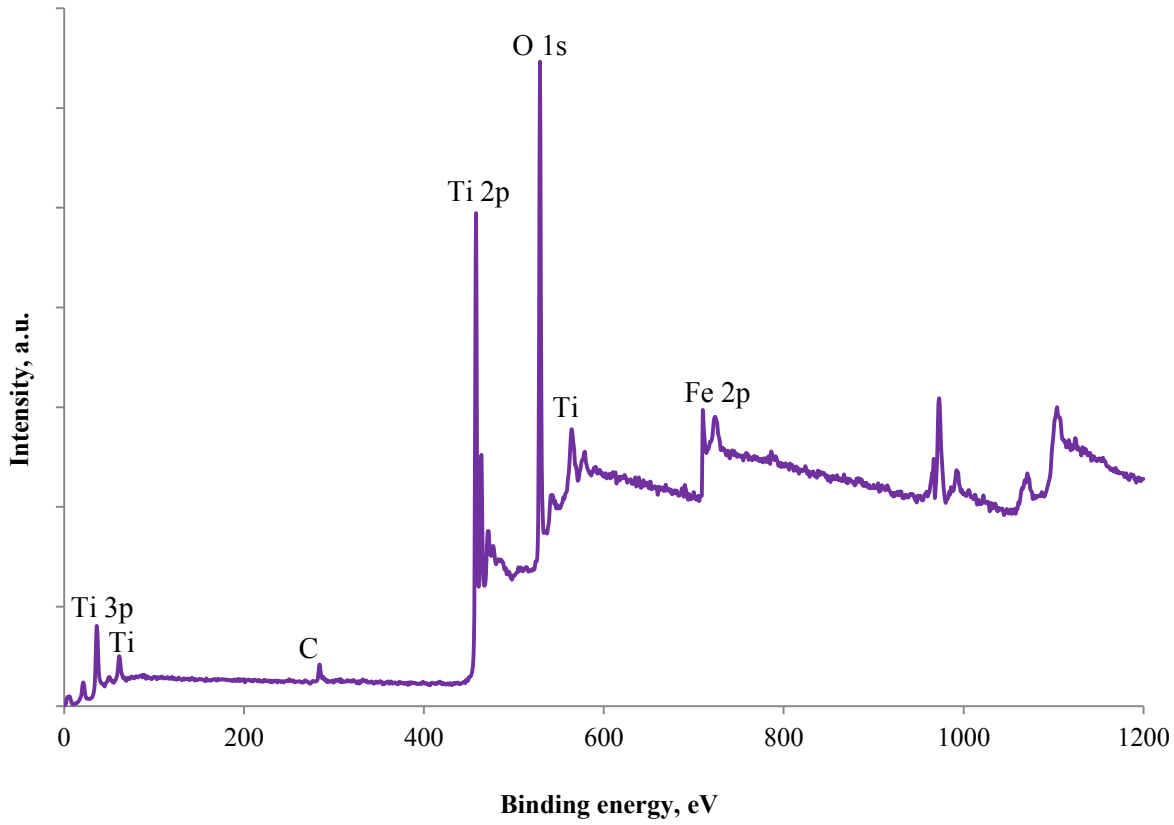


Fig. 10. (d)

Fig. 10. (a) EDX spectrum of Fe_2O_3-TiO_2. EDX mapping of (b) O, (c) Fe, and (d) Ti elements in Fe_2O_3-TiO_2.



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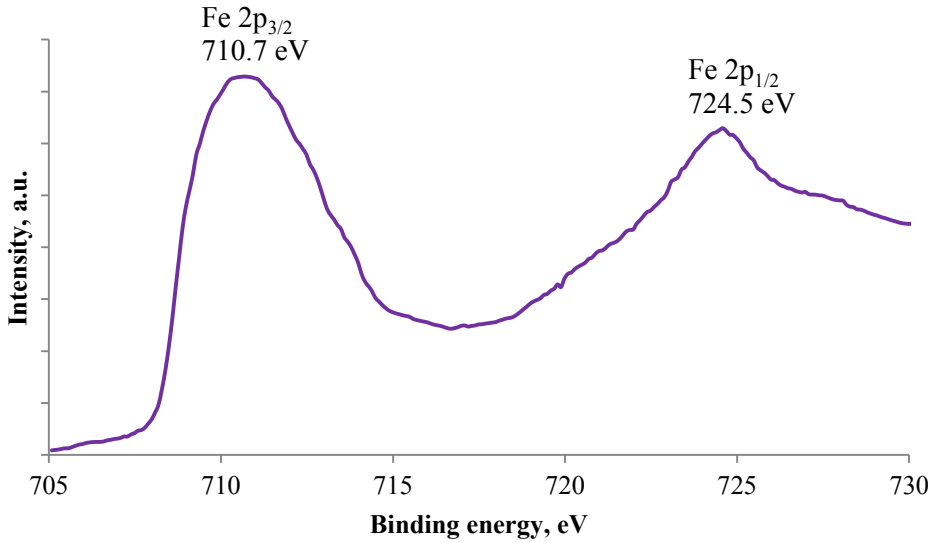

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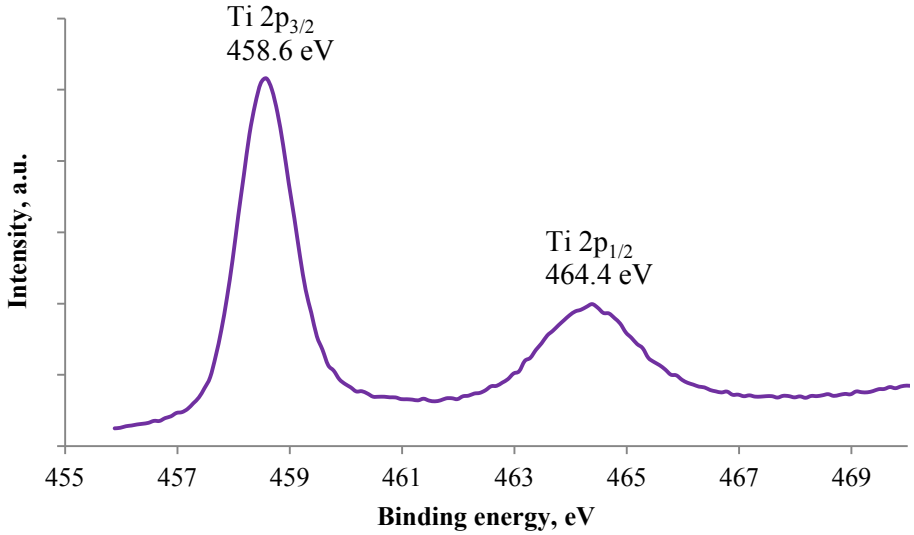

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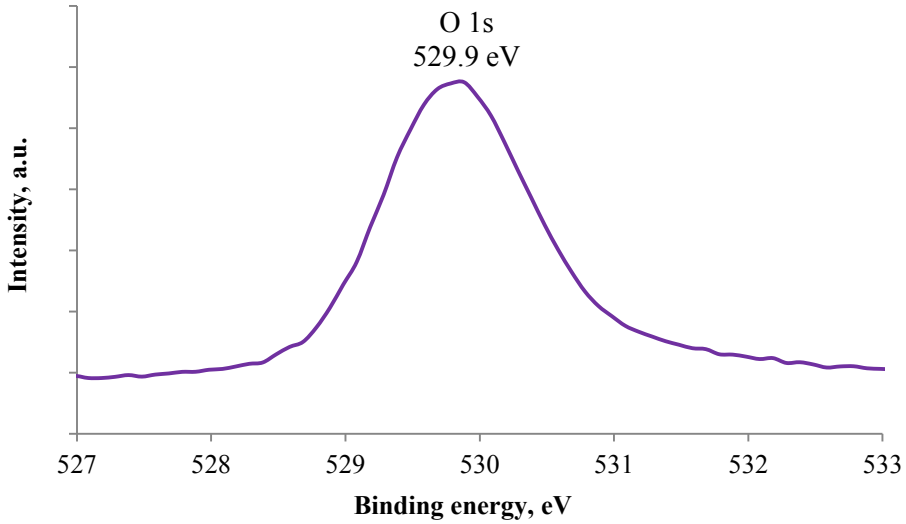

Fig. 11. (d)

Fig. 11. XPS (a) survey spectrum and narrow spectra of (b) Fe 2p, (c) Ti 2p, and (d) O 1s of Fe_2O_3-TiO_2.

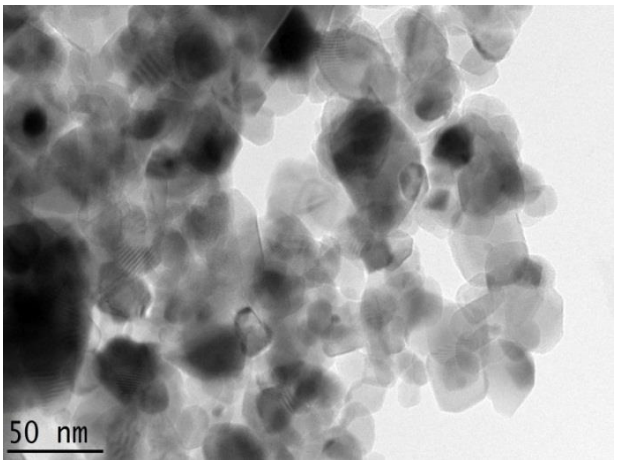

Fig. 12. (a)

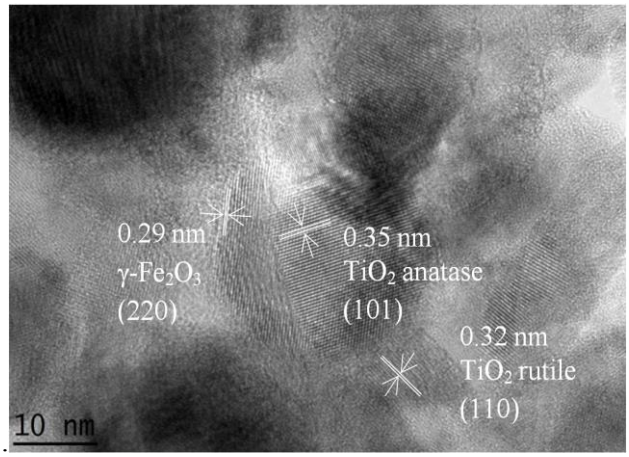

Fig. 12. (b)

Fig. 12. (a) TEM image of Fe_2O_3-TiO_2. (b) HRTEM image of Fe_2O_3-TiO_2.

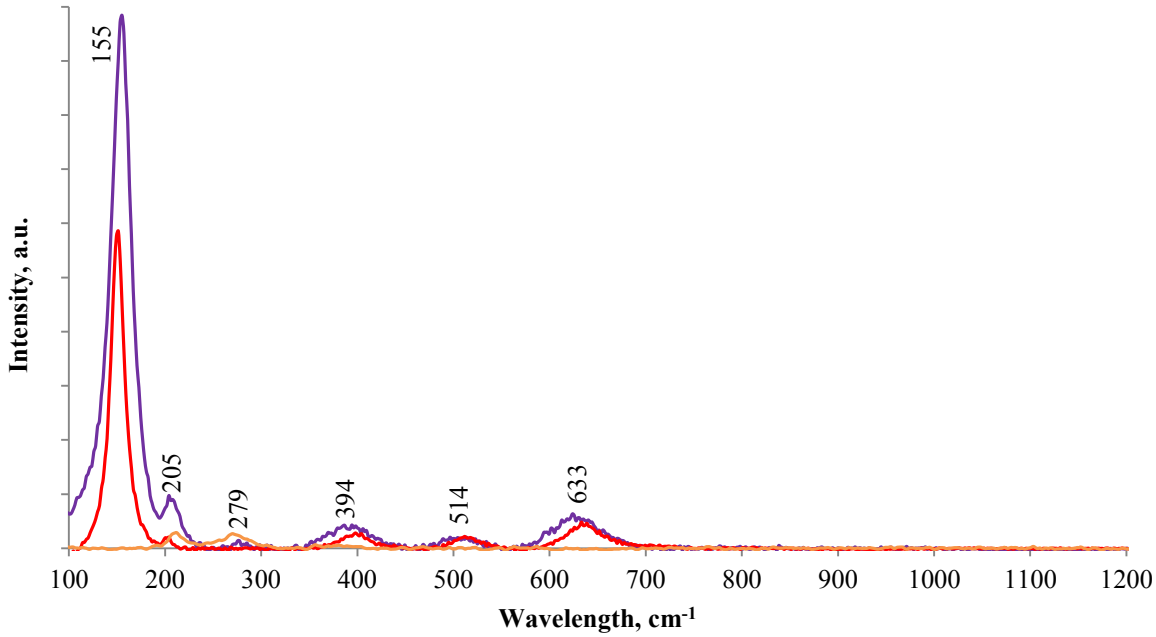

Fig. 13. Raman spectra of Fe_2O_3-TiO_2 (purple), P25 (red), and Fe_2O_3 (brown).

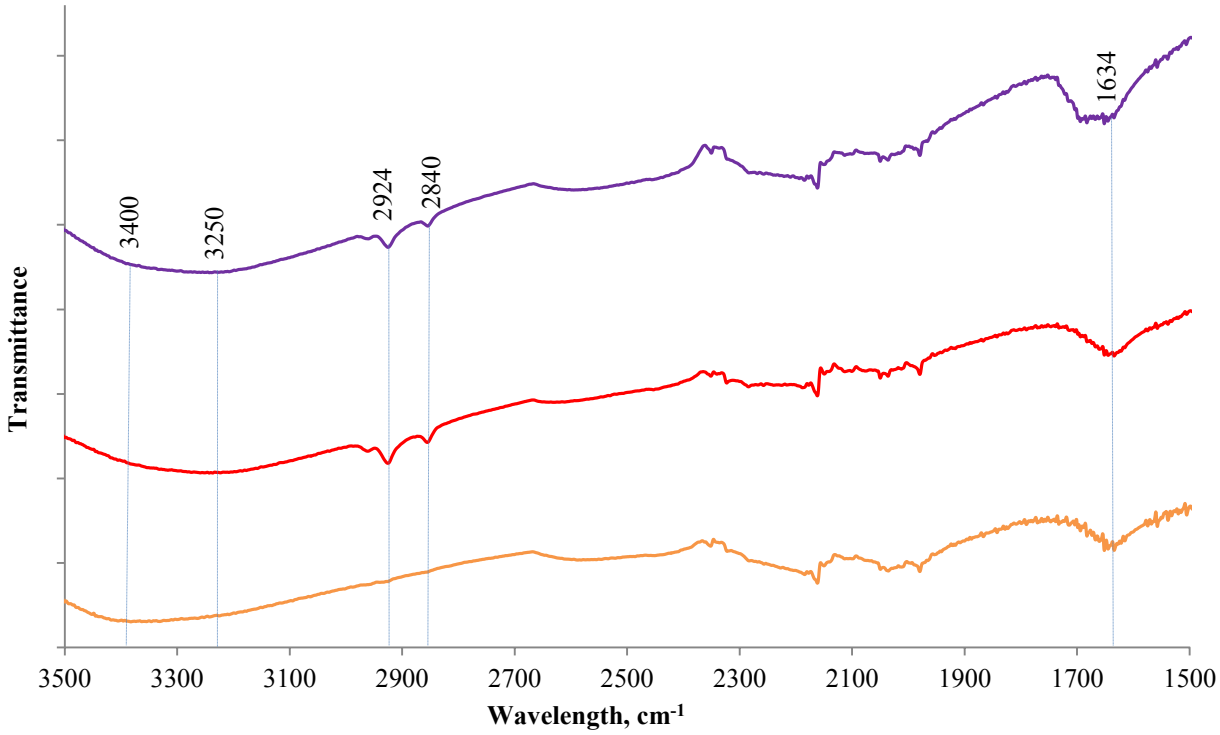

Fig. 14. FTIR spectra of Fe_2O_3-TiO_2 (purple), P25 (red), and Fe_2O_3 (brown).

List of Tables

Table 1

Comparison of catalyst characteristics among Fe_2O_3-TiO_2, P25 and Fe_2O_3.

Sample	XRD	Surface analysis			Band gap energy, eV
	Crystallite size, nm	Specific surface area, m^2/g	Pore volume, cm^3/g	Pore size, nm	
Fe_2O_3-TiO_2*	22.99	58.40	0.29	18.52	2.95
P25	24.29	52.32	0.17	15.62	3.35
Fe_2O_3	17.45	7.70	0.03	13.14	1.60

*Mechanochemical synthesis conditions: milling speed =250 rpm; [Fe_2O_3] =1 mol%; ball:powder mass ratio =10:1

Table 2

Textural properties of Fe_2O_3-TiO_2 at different milling time.

Milling time, min	Surface analysis		
	Specific surface area, m^2/g	Pore volume, cm^3/g	Pore size, nm
10	55.57	0.26	16.16
15	56.99	0.28	17.22
20	58.40	0.29	18.52
25	55.18	0.24	15.29
30	52.41	0.22	15.00

Mechanochemical synthesis conditions: milling speed =250 rpm; [Fe_2O_3] =1 mol%; ball:powder mass ratio =10:1

Table 3

Crystallite properties of Fe_2O_3-TiO_2 at different milling speed.

Milling speed, rpm	XRD analysis	
	Crystallite size, nm	Rutile phase fraction, %
150	25.72	0.29
200	24.05	0.29
250	22.99	0.36
300	22.00	0.38
350	21.42	0.44

Mechanochemical synthesis conditions: milling time =20 min; [Fe_2O_3] =1 mol%; ball:powder mass ratio =10:1

Table 4

Control photocatalytic experiments.

Control	COD removal, %
Photolysis	0.1
Catalysis (in the dark using Fe_2O_3-TiO_2)	0.4
P25	40.6
Anatase TiO_2	24.9
Rutile TiO_2	2.9
Fe_2O_3	1.1