Simultaneous Hydrogen Production with the Degradation of Naphthalene in Seawater Using Solar Light-Responsive Carbon-Modified (CM)-n-TiO₂ Photocatalyst

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ABSTRACT

The simultaneous photocatalytic production of hydrogen and degradation of naphthalene in seawater was successfully achieved using carbon modified titanium oxide (CM-n-TiO₂) nanoparticles under natural sunlight illumination. Compared to unmodified titanium oxide (n-TiO₂), CM-n-TiO₂ nanoparticles exhibited significantly higher photocatalytic efficiency. It is considered that carbon modification is responsible for the significant enhancement in the observed photoactivity. The experimental results indicated that the simultaneous production of hydrogen and degradation of naphthalene was favorable at pH 8 and optimal catalyst dose of 1.0 g·L⁻¹. The solar photocatalytic degradation of naphthalene in seawater using CM-n-TiO₂ successfully fitted using Langmuir-Hinshelwood model, and can be described by pseudo-first order kinetic model.

Keywords: Photocatalysis; Titanium Oxide; Carbon Modification; Hydrogen Production; Naphthalene

1. Introduction

Photocatalysis on semiconductor surfaces has attracted considerable attention in recent years as a potential means for water splitting to produce hydrogen [1-8], and mineralization of organic pollutants present in water and wastewater [9-18]. Among many semiconductor oxides, titanium dioxide (n-TiO₂) has been proven to be the most promising semiconductor due to its optical and electronic properties, low cost, high level of photocatalytic activity, chemical stability and non-toxicity. However, its utilization in the solar light is hampered by the fact that it is a UV absorber. Its wide band gap (3.0 - 3.2 eV) limits its photosresponse in the ultraviolet region which is only a small fraction (~5%). Therefore, several attempts were made to extend its optical response to the visible spectral range by doping with transition metal [19,20], nitrogen [21,22], and sulfur [23]. Recently, it has been reported that carbon modification of n-TiO₂ lowered its bandgap energy to 2.32 eV, and thereby exhibited higher photoreponse [3].

The principle of photocatalysis on titanium dioxide semiconductor is based on the conversion of photon energy to chemical energy. The elementary mechanism of this process includes a number of steps, which have been exhaustively described in the literature [24,25]. Illumination of TiO₂ by light with energy (hν) greater than or equal to the bandgap energy (Eg) of TiO₂ elevates electron in the valence band (VB) to the conduction band (CB), and a positive hole is formed in the valence band (Equation (1)). The conduction band electron (e⁻cb) is strongly reducing, and the valence band hole (h⁺vb) is strongly oxidizing. At the external TiO₂ surface, the positive hole and the excited electron can take part in redox reactions with adsorbed groups.

\[ \text{TiO}_2 + h \nu \rightarrow e^{-}_{\text{cb}} + h^{+}_{\text{vb}} \]  

(1)

The photoinduced production of hydrogen from water is attained by photogenerated electrons (e⁻cb), provided that their energy is sufficient to reduce protons toward hydrogen molecules (Equation (3)). To achieve this process, the CB level should be more negative than hydrogen production level (E_{H_2/H_2O}) while the VB should be more positive than water oxidation level (E_{O_2/H_2O}) for efficient oxygen production from water by photocatalysis.

\[ 2h^{+}_{\text{vb}} + H_2O(1) \rightarrow 1/2O_2 + 2H^+ \]  

(2)
One of the major disadvantages of semiconductor photocatalytic system is that, the photo-generated electrons and holes can recombine in bulk or on surface of the semiconductor within a very short time, resulting in reduction in the photocatalytic efficiency. To resolve this problem, electron donors (sacrificial reagents or hole scavengers) were added to react irreversibly with the photogenerated VB holes (\(h^*_b\)), thereby suppressing the electron-hole recombination [26,27]. If this sacrificial agent is a pollutant present in water or wastewater, the positive hole recombination [26,27]. Consequently, enhancement of the \(H_2\) production rate with simultaneous degradation of the organic substrate can be obtained. A simplified diagram illustrating the simultaneous photocatalytic production of hydrogen and degradation of organic compound using TiO\(_2\) under illumination of light is presented in Figure 1.

\[
2H^+ + 2e^- \rightarrow H_2 (g) \quad (3)
\]

\[
h^*_b + \text{Organic pollutants} \rightarrow CO_2 (g) \quad (4)
\]

\[
h^*_b + H_2O (1) \rightarrow \text{OH} + H^+ \quad (5)
\]

\[
\text{OH} + \text{Organic pollutant} \rightarrow CO_2 (g) \quad (6)
\]

The vast majority of researches on TiO\(_2\) photocatalysis have focused on a single process; either the photodegradation of pollutants or hydrogen generation under illumination of artificial UV light or simulated sunlight. Despite the importance of seawater as it has been considered to supplement the limited sources of water available for drinking, as well as for the production of hydrogen energy [28], most of the studies on photocatalytic hydrogen production and degradation of pollutants have been performed using pure water. Based on the previous considerations, the present study focused on the synthesis of visible light active carbon-modified (CM)-n-TiO\(_2\) nanoparticles that is capable of harvesting the maximum solar light in the visible region. The simultaneous production of hydrogen and degradation of naphthalene, as a sacrificial agent, in natural seawater was investigated using the synthesized photocatalyst under illumination of real sunlight. The effects of photocatalyst loading, naphthalene concentration, and pH on the photocatalytic performance were also studied.

2. Experimental


Regular (unmodified) titanium dioxide (n-TiO\(_2\)) nanoparticles were synthesized by hydrolysis and oxidation of titanium trichloride (TiCl\(_3\) 12% in hydrochloric acid (5% - 12%), Sigma-Aldrich) in an aqueous medium. Visible light active carbon modified titanium dioxide (CM-n-TiO\(_2\)) nanoparticles were synthesized by a sol-gel method using titanium butoxide (Ti[O(CH\(_2\)]\(_3\)CH\(_3\)]\(_4\), Fluka, 97%), a carbon-containing precursor, as a molecular precursor of TiO\(_2\) as well as a carbon source. Details on the procedures used for catalysts preparation and characterization can be found elsewhere [18].

2.2. Photocatalytic Experiments

All solar photocatalytic experiments were carried out at the Faculty of Marine sciences, Obhur, Jeddah, KSA, in the daytime between 11:00 am to 15:00 pm, during May-June, 2013. Natural seawater samples were collected from Sharm Obhur, Jeddah, KSA. Before spiking with different concentrations of naphthalene, seawater samples were passed through Whatman GFC to remove any solid particles. Experimental set up consisted of a magnetically stirred 500 mL top-covered Pyrex glass photoreactor loaded with the seawater solution containing different concentrations of naphthalene, samples were passed through Whatman GFC to remove any solid particles. Experimental set up consisted of a magnetically stirred 500 mL top-covered Pyrex glass photoreactor loaded with the seawater solution containing different concentrations of naphthalene, seawater samples were passed through Whatman GFC to remove any solid particles. Experimental set up consisted of a magnetically stirred 500 mL top-covered Pyrex glass photoreactor loaded with the seawater solution containing different concentrations of naphthalene, seawater samples were passed through Whatman GFC to remove any solid particles. Experimental set up consisted of a magnetically stirred 500 mL top-covered Pyrex glass photoreactor loaded with the seawater solution containing different concentrations of naphthalene, seawater samples were passed through Whatman GFC to remove any solid particles.
thalene at its maximum absorption wavelength (275 nm) as follows:

\[ \eta = \left[ \frac{(C_o - C_t)}{C_o} \right] \times 100 \]  

(7)

where \( C_o \) represents the initial concentration of the naphthalene and \( C_t \) represents the concentration of naphthalene at solar light irradiation time (t).

3. Results and Discussion

3.1. Photocatalytic Activity of n-TiO\(_2\) and CM-n-TiO\(_2\)

In order to examine the photocatalytic efficiency of CM-n-TiO\(_2\) comparison with unmodified n-TiO\(_2\) was performed under the same experimental conditions. It is clearly observed that the photocatalytic efficiency of CM-n-TiO\(_2\) towards the simultaneous photocatalytic production of hydrogen and degradation of naphthalene (10 ppm) in seawater under illumination of natural sunlight is much higher than that of n-TiO\(_2\) (Figure 2). The enhanced photocatalytic activity of carbon modified CM-n-TiO\(_2\) nanoparticles can be attributed to carbon modification of TiO\(_2\) [3,5-8,17,18].

3.2. Effect of Solution pH

It is known that the pH of the solution is a key parameter in the photocatalytic reactions, it can directly influence the surface charge of the semiconductor, thereby affecting the interfacial electron transfer and the photoredox process [29]. The possible functional groups on TiO\(_2\) surface in water are TiOH\(^+\), TiOH, and TiO\(^-\). The point of zero charge (pH\(_{pzc}\)) of TiO\(_2\) is an important factor determining the distribution of the surface groups.

When pH > pH\(_{pzc}\), the surface of TiO\(_2\) is negatively charged with the species TiO\(^-\) (Equation (8)), and positively charged with the species TiOH\(^+\) at pH < pH\(_{pzc}\) (Equation (9)).

\[ \text{TiOH} + \text{OH}^- \rightarrow \text{TiO}^- + \text{H}_2\text{O} \]  

(8)

\[ \text{TiOH} + \text{H}^+ \rightarrow \text{TiOH}_2^+ \]  

(9)

The role of pH in the photocatalytic production of H\(_2\) and degradation of naphthalene in seawater under illumination of natural sunlight using CM-n-TiO\(_2\) was studied by keeping all other experimental conditions constant and varying the initial pH of the solution from 3 to 9. As can be seen in Figure 3, both the production of H\(_2\) and degradation of naphthalene rapidly increased with increasing the pH from 3 to 8, resulting in an increased photocatalytic efficiency. At pH higher than 8, the formation of carbonate ions is favorable which are effective scavengers of hydroxyl ions and can reduce the efficiency of photocatalytic process [31, 32].

3.3. Effect of Catalyst Dose

The influence of CM-n-TiO\(_2\) dose on the photocatalytic production of H\(_2\) and degradation of naphthalene (10 ppm) in seawater under illumination of sunlight was investigated at the optimal pH value (pH 8) to ensure maximum absorption of efficient solar light photons as well as to avoid an ineffective excess amount of catalyst (Figure 4).

Both the photocatalytic degradation rate of naphthalene and the production of H\(_2\) increased with the increase in catalyst dose from 0.5 to 1.0 g·L\(^{-1}\). The increase in
catalyst amount actually increases the number of active sites on the photocatalyst surface thus causing an increase in the number of $e_{cb}$ and $h_{vb}$ which can take part in photocatalytic processes. Further increase in the catalyst loading to 1.5 g·L$^{-1}$ slightly decreased the photocatalytic efficiency. At catalyst loading beyond the optimum, the tendency toward particles aggregation increases, resulting in a reduction in surface area available for light absorption and hence a drop in photocatalytic degradation rate [33]. Additionally, the increase of the turbidity of the suspension reduces light penetration due to the enhancement of light scattering; the result is the decrease of the number of activated sites on the TiO$ _2 $ surface and shrinking of the effective photoactivated volume of suspension. The interplay of these two processes resulted in a reduced performance of photocatalytic activity with the overloaded catalyst [34,35]. In this study, the dosage of 1.0 g·L$^{-1}$ of CM-n-TiO$ _2 $ can be considered as the optimal catalyst loading.

3.4. Effect of Initial Naphthalene Concentration

The initial concentration of naphthalene is an important factor which needs to be taken into account. The effect of the initial naphthalene concentration on its photodegradation rate and the photocatalytic production of H$_2$ was investigated over the range of 5 to 20 ppm at the optimal conditions of pH 8 and 1.0 g·L$^{-1}$ of CM-n-TiO$ _2 $ (Figure 5). Both the photoinduced production of H$_2$ (Figure 5(a)) and degradation rate of naphthalene (Figure 5(b)) rapidly increased with the increase in naphthalene concentration from 5 to 10 ppm. Further increase of naphthalene concentration to 20 ppm, resulted in a remarkable decrease in the rate of degradation of naphthalene as well as the production of H$_2$.

This can be explained by the saturation of the limited number of accessible active sites on the photocatalyst surface and/or deactivation of the active sites of the catalyst. Several studies have reported that high organic substrate loadings induce the formation of intermediates that could be adsorbed onto the catalyst surface and deactivate the active sites [36,37].

3.5. Kinetics of Photodegradation

To study the kinetics of photocatalytic degradation of naphthalene in seawater using CM-n-TiO$_2$, Langmuir-Hinshelwood (L–H) model was applied. L–H model basically relates the degradation rate ($r$) and reactant concentration in water at time $t$ ($C$), which is expressed as follows:

$$ r = \frac{dc}{dt} = \frac{k_r K_{ad}}{1 + K_{ad} C} $$

where $k_r$ is the rate constant and $K_{ad}$ is the adsorption equilibrium constant [38-41]. When the adsorption is relatively weak and/or the reactant concentration is low, equation (10) can be simplified to the pseudo-first order kinetics with an apparent first-order rate constant $k_{app}$:

$$ \ln \left( \frac{C_i}{C} \right) = k_{app} t $$

where $C_i$ is the initial concentration. Figure 6 shows the plot of $\ln \left( \frac{C_i}{C} \right)$ versus illumination time for the
photocatalytic degradation of naphthalene (5 - 20 ppm) in seawater under natural sunlight illumination. CM-n-TiO₂ nanoparticles exhibited significant enhancement in the photocatalytic efficiency compared to unmodified n-TiO₂. The linearity of the plot confirmed that the photocatalytic degradation of naphthalene using CM-n-TiO₂ follows the L–H model, and can be described by pseudo-first order kinetics.

4. Conclusion

The photocatalytic production of hydrogen accompanied by the simultaneous degradation of naphthalene in seawater was successfully achieved using carbon-modified (CM)-n-TiO₂ nanoparticles under irradiation of natural sunlight. CM-n-TiO₂ nanoparticles exhibited significantly enhanced photocatalytic efficiency compared to unmodified n-TiO₂. This observed enhancement in the photocatalytic degradation of naphthalene was favorable at pH 8 and optimal catalyst dose of 1.0 g L⁻¹. The solar photocatalytic degradation of naphthalene in seawater using CM-n-TiO₂ successfully fitted using Langmuir-Hinshelwood model, and can be described by pseudo-first order kinetic model.

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REFERENCES


