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TiO₂ Encapsulated into Zeolitic Imidazolate Framework (TiO₂@ZIF-8) as an Efficient Nanophotocatalyst for Degradation of Paraquat Herbicide

Fariba Dashtestani¹, Vahid Mohagheghi¹, Leila Ma'mani^{*1}, Kobra Maafi²

 1- Department of Nanotechnology, Agricultural Biotechnology Research Institute of Iran (ABRII), Agricultural Research Education and Extension Organization (AREEO), Karaj, Iran.
4- Islamic Azad University, West Tehran Branch, Tehran, Iran.

leila.mamani@abrii.ac.ir

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Abstract

In this research, preparation, characterization, and evaluation of TiO_2 encapsulated into zeolitic imidazolate framework ($TiO_2@ZIF-8$) nanophotocatalyst was investigated as an efficient photo-degradation of paraquat (PQ) herbicide from aqueous samples. This study was performed using a ZIF-8-based nanophotocatalyst and a reactor consisting of an ultraviolet (UV) source and a reaction chamber. The effects of various parameters including contaminant concentration, amount of nanophotocatalyst, and pH reaction time were investigated on the removal efficiency of contaminant by the TiO₂@ZIF-8 nanophotocatalyst. The results showed by increasing the amount of the TiO₂@ZIF-8 nanophotocatalyst and pH, the removal of paraquat showed an increase. The optimal condition was found as nanophotocatalyst concentration (0.05 g.L⁻¹), pH (7) at room temperature for 15 min for removal of 99.8% paraquat. According to the results, TiO₂@ZIF-8 emerged as an efficient, robust, and recyclable nanophotocatalyst, which is a potential and environmentally friendly process for the removal of toxic chemical herbicide as hazardous organic contaminants from aqueous samples. The facile fabrication approach and the enhanced photocatalytic activity of TiO₂@ZIF-8 were highlighted and notably showed good reusability in 8 consecutive cycles.

Keywords: TiO₂, Zeolitic Imidazolate Framework, Photocatalyst, Paraquat.

Introduction

Recently, due to the growth of human technology with the increase of agricultural and industrial activities, food demand has been water and increased exponentially. Consequently, the high volume of activities leads to contaminate natural resources such as and soil. The uncontrolled water discharge of the effluents containing large amounts of harmful pollutants threatens human and aquatic life when the tolerance levels exceeds. Hence, these water resources pollutions especially different agrochemicals, drugs, heavy metals, etc. are worldwide concern, which makes serious risks to the environment and human life qualities (1-3).Among different hazardous contaminant, agrochemicals especially pesticides has been recognized as a The ubiquitous problem. pesticide residuals can contaminate our ecosystem and their accumulations are very toxic to biotic and abiotic components of our ecosystem. The elimination of these toxic agrochemical substances residual from water is difficult and requires water treatment. Paraquat (PQ), biа

pyridinium agrochemical with IUPAC N,N'-dimethyl-4,4'-bipyridinium name dichloride and the chemical formula $[(C_6H_7N)_2]Cl_2$, is known as a nonherbicide. selective Due to the price reasonable and acceptable efficiency, PQ is one of the commonly used herbicides in plantations (rice, sugar cane, coffee, beans, and the other crops) (4-6) as well as in defoliation (grass and weed) (7).

As shown in Figure 1, the presence of the cationic charges on the bi-pyridinium molecule makes PO water-soluble (620 g.L⁻¹ at 25°C), which eradicates plants by interrupting photosynthesis. Nevertheless, PQ is very dangerous for health such as dermal exposure (8), respiratory failure (9), pulmonary fibrosis (10, 11), neurotoxicity (12), damage of digestive apparatus (13) and Parkinson's disease (14, 15). The PQ amount of 35 mg.kg⁻¹ displays lethal dose for human being owing to European standards (16). The PQ concentration of 0.1 and 1–3 μ g.L⁻¹ exhibits respectively the maximum permissible concentration for drinking water and for surface waters.



Figure 1. Chemical structure of Paraquat (PQ).

Up to now, different approaches have been introduced to remove the PQ contaminated water such as physical methods (including adsorption, filtration, and ion exchange), biological method, and chemical methods (including oxidation, photocatalytic degradation, and electrochemical process) (17-25). Among the above-mentioned approaches, the photocatalytic-based methods have been improved as a highly efficient process for eliminating the PO contaminant from water samples. TiO₂ photocatalyst has been found as a promising photocatalyst because of its unique properties including high efficiency, low cost, stability, and nontoxicity. However, TiO2 nanocatalyst

would not be easily separated from the treated water and a part of TiO₂ nanocatalyst leaches in the treated water. Therefore the TiO₂ nanocatalyst recyclability cannot be acceptable. Hence, the expansion of a simple and efficient separable TiO₂ photocatalyst has recently become an emerging topic of research. To this, several adsorbents have been reported as support for immobilization of TiO₂ catalyst including graphene oxide clays, nanosheets, single & multi-walled CNTs, silica, zeolites, and magnetic hybrid nano-sorbent (26-33). Research on the application of nanomaterial in water treatment has experienced strong growth and an enhanced interest in recent decades. These materials has made great impacts in a wide range of fields due to their unique properties in adsorption, catalytic activity, optical, and thermal stability (34, 35). Researchers in science and engineering show an increased interest in the use of nanoparticles due to their physical and chemical properties. Metal organic frameworks (MOFs) (36specially zeolitic imidazolate 39) framework (ZIFs) (40-42),the coordination polymers with proper porosity and high stability, have been appeared as convenient materials for wide applications in different areas such catalysis, sensing, delivery, as immobilizing, separation, and imaging materials. As supporting material, ZIF-8 consisted of a high nanoporous structure; represent more potential over the other traditional materials such as zeolites. nanoporous This kind of material applicable represents an type of supporting material for immobilizing the photocatalyst offering a robust and reusable photocatalyst to remove specific contaminants from water.

The aim of this study was the preparation of TiO_2 encapsulated into zeolitic imidazolate framework

(TiO₂@ZIF-8) nanophotocatalyst and evaluation of its potential in the photocatalytic degradation of PQ residual from water samples. The effect of some parameters affecting the process of nano-photocatalysis and adsorption was analyzed.

Materials and Methods

1- General remarks

A stock solution of PQ was provided via dissolving the PQ in double distilled Before performing water. the experiment, the PQ concentration in the stock solution was measured. All the chemicals in this study were of extra pure or analytical grade. The particle size distributions, surface charges of nanoparticles were obtained by dynamic light scattering (DLS) (Brookhaven, USA). SEM technique was applied to of NPs. determine the size The topological characteristics of materials were observed using atomic force microscopy (AFM, DME-Ds95-50 Denmark) in ambient conditions at room temperature. HCl or NaOH was used to adjust the pH solution.

2- Synthesis of Nano-photocatalyst (TiO2@ZIF-8)

 $TiO_2(a)ZIF-8$ nanocomposite was synthesized by in-situ incorporation of TiO₂ NPs (anatase, 20 nm radius) onto the surface of ZIF-8 NPs. To this, zinc chloride (ZnCl₂, 0.34 g, 2.5 mmol) with 2-methylimidazole (2-MI, 1.64 g, 20 mmol) in methanol (MeOH, 45 mL) was stirred at room temperature (43). Then, 150 mL of a TiO₂ suspension was prepared by sonicating of TiO₂ NPs (20 mg, 0.25 mmol) in MeOH (10 mL). The prepared TiO₂ suspension was poured slowly to the above mixture. After 30 min stirring, the reaction mixture was left without disturbing overnight. The TiO₂@ZIF-8 product was separated, followed by washing with MeOH several times, and drying in a vacuum oven at 70°C for 12 h.

3- Photocatalytic Experiment

The removal of PQ from the solution samples was done utilizing a reactor equipped with a 15-watt UV lamp. Briefly, 100 mL solution containing PQ (5, 25, 50 and 100 mg.L⁻¹) with alteration pH (3-11) was mixed with given dosage of TiO2@ZIF-8 (0.005– 0.05 g.L^{-1}), and then UV light in the photoreaction apparatus irradiated the suspension for adequate time (5-30 min). After completion of reaction time, the nano-photocatalyst was removed using an external magnetic field and then washed thoroughly, dried to be ready for using at next run. The changes in the PQ concentration were evaluated using a double beam UV–Vis spectrophotometer at $\lambda_{max} = 257$ nm with a calibration curve based on Beer–Lambert law (44). By subtracting the initial and unreduced concentrations of the ions, where, the initial and residual concentrations of PQ shown as C_{in} and C_{out} respectively, the degree of PQ calculated as follow (Eq 1):

Equation 1:
$$R = \frac{c_{in} - c_{out}}{c_{in}} \times 100$$

Results and discussion

The nanophotocatalyst was prepared by immobilizing TiO_2 NPs onto the surface of the inorganic support. Forasmuch as catalyst immobilization on the solid surface, the ZIF-8 nano-framework was synthesized and then TiO_2 was encapsulated (shown $TiO_2@ZIF-8$ nanophotocatalyst). The $TiO_2@ZIF-8$ nanophotocatalyst structure was characterized by different techniques such as AFM, DLS, and SEM.

The SEM image of TiO₂@ZIF-8 shows that the modifying and loading process have no impact on the morphology. The average diameter of TiO2@ZIF-8 was around 100 nm, respectively Figure 2a. imaging of TiO₂@ZIF-8 The AFM Figure 2b. The uniform showed in morphology with high dispersity occupied for TiO₂@ZIF-8. The particle size of TiO₂@ZIF-8 was determined using DLS. As seen, the average diameters of TiO₂@ZIF-8 was 120 nm.



Figure 2. The SEM (a) and AFM (b) images of $TiO_2@ZIF-8$.

Due to the fact of the photocatalytic degradation of PQ is affected by the amount of pH, the different pH value (from 3 to 11) was investigated in the PQ concentration, the amount of TiO₂@ZIF-8 nano-photocatalyst, and the irradiation time were 50 mg.L-1, 0.5 g.L-1, and 15 min, respectively. Figure 3 illustrated the efficiency of TiO₂@ZIF-8 photocatalytic conversion of PQ was affected according to the pH values was. Due to these results, the photocatalytic efficiency of $TiO_2(a)ZIF-8$ was obtained at the highest level at pH of 7 and the lowest level at pH of 3. In accordance with this result, the remarked increase in efficiency was

reported by increasing the pH value from 6.5 to 11 (45-47). Rationally, in aqueous solution of the hydroxyl radical production maximizes at neutral and alkaline pH values, which helps to enhance the photocatalytic conversion of PQ. With decreasing pH value from 9 to 7, the photocatalytic efficiency is shown a negligible decrease. Because the pH of wastewaters is about 8 which it consider as nearly neutral (48), and based on our results, pH value of 7 was selected as the optimal and eco-friendly value for keeping on the further investigations of TiO_2 (*i*)ZIF-8 as nano-photocatalyst.



Figure 3. The effect of the pH value of the reaction mixture, while the PQ concentration, the amount of $TiO_2@ZIF-8$ nano-photocatalyst, and the irradiation time were 50 mg.L⁻¹, 0.05g.L⁻¹ and 15 min, respectively.

Figure 4 presents the effects of the initial concentration of PQ, as the target contaminant, on the nanophotocatalytic efficiency of TiO₂@ZIF-8 nanophotocatalyst. To this, the initial PQ concentration was varied 5-100 mg.L⁻¹, while between the photocatalytic reaction time, pН value, and the amount of TiO₂@ZIF-8 nanophotocatalyst were 15 min, and 7, and 0.5 g.L⁻¹, respectively. Based on the obtained results, the TiO₂@ZIF-8 nanophotocatalyst efficiency was decreased by increasing the initial concentration of PQ. In fact, the high contaminant concentrations lead to turbidity and reduce the transparency of the reaction media. So, the efficiency of the nanophotocatalyst would be decreased because of the lower adsorption of light source irradiation by the photocatalyst and subsequently the lower level of hydroxyl radical. It was reported that as the level of generated radicals is constant during a photocatalysis process, the photocatalyst efficiency decreases with growing the initial contaminant concentration (49). As a limitation, with increasing the initial PQ concentrations the competition reactions are more possible due to producing higher amounts of intermediates (50, 51). According to these results, the initial PQ concentration of 50 mg.L⁻¹ was chosen as favorite value for further studies.



Figure 4. The effect of the PQ concentration, while the amount of $TiO_2@ZIF-8$ nano-photocatalyst, pH, and the irradiation time were 0.05 g.L⁻¹, 7 and 15 min, respectively.

The effects of the amount of $TiO_2@ZIF-8$ as nanophotocatalyst on the photocatalytic efficiency within a reaction time of 10 min and pH 7 is shown in Figure 5. The results indicated

that the optimal dosage of the nanophotocatalyst was 50 mg. L^{-1} . Additional amounts of the semiconductor materials makes energy loss, which leads to more activity (52).



Figure 5. The effect of the amount of $TiO_2@ZIF-8$ nano-photocatalyst, while the PQ concentration, pH, and the irradiation time were 50 mg.L⁻¹, 7 and 15 min, respectively.

Figure 6 also shows the effects of the reaction time on the efficiency of $TiO_2@ZIF-8$ nanophotocatalyst. In this step, the initial PQ concentration, pH value, and nanophotocatalyst dosage

were adjusted to 50 mg.L⁻¹, 7 and 0.05 g.L⁻¹, respectively. As the time increased the nanophotocatalyst efficiency enhanced, therefore the best results were taken between 15 min.



Figure 6. The effect of the irradiation time, while the PQ concentration, the amount of $TiO_2@ZIF-8$ nano-photocatalyst and pH were 50 mg.L⁻¹, 0.05 g.L⁻¹ and 7, respectively.

The nanophotocatalyst was recycled eight times with a negligible loss of phocatalytic activity (Figure 7). $TiO_2(a)ZIF-8$ nanophotocatalyst is appeared as a boosted and eco-friendly nanophotocatalyst that showed an robustness and catalytic excellent efficiency in removal of PQ. To rule out the leaching phenomena and existence of the homogeneous Ti species, 5 mg of the $TiO_2(a)ZIF-8$ nanophotocatalyst was prepared as optimal condition, and at the half of the reaction time, the nanophotocatalyst was separated magnetically. It was found that the amount of leached titanium ion was less than 1 mg.L⁻¹ for the separated liquid (measured by ICP-AES).



Figure 7. The recyclability test of TiO₂@ZIF-8 nano-photocatalyst in the optimal condition.

Conclusions

Summary, it can be concluded that, the simple recyclable encapsulated TiO_2 NPs within ZIF-8 nanopores provided a desirable mode of employing TiO_2 NPs for the photocatalytic degradation of

agrochemicals as here the efficiency and robustness of the photocatalysis process can enhance as well as the ability to reuse this nanoparticle-ZIF nanocomposite for several cycles improved much higher.

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مجله ایمنی زیستی دوره ۱۳، شماره ۳، پائیز ۱۳۹۹ ISSN 2716-9804 الکترونیکی، ISSN 2717-0632 چاپی TiO2 انکپسولهشده بر پایه چارچوب زیولیتی ایمیدازولیوم (8-TiO2@ZIF) به عنوان یک نانوفتوکاتالیزور مؤثر برای تجزیه علفکش پاراکوآت فریبا دشتستانی^۱، وحید محققی^۱، لیلا مأمنی^{۱*}، کبری مافی^۲ ایران ۱- بخش نانوتکنولوژی، پژوهشگاه بیوتکنولوژی کشاورزی (AREEO)، سازمان تحقیقات، آموزش و ترویج کشاورزی(AREEO)، البرز،

اب والسلامی می واسعد بهران عرب بهران مراه ایران leila.mamani@abrii.ac.ir ۱۴۰۰/۰۳/۲۵ تاریخ پذیرش: ۱۴۰۰/۰۳/۰۹ صفحه ۸۲–۷۱

چکیدہ

در این تحقیق، تهیه، مشخصه یابی و ارزیابی پتانسیل نانوفتو کاتالیزور TiO2 انکپسوله شده بر پایه چارچوب زیولیتی ایمیدازولیوم (TiO2@ZIF-8) تخریب کارآمد علف کش پاراکوات مورد بررسی قرار گرفت. این مطالعه با استفاده از یک نانوفو تو کاتالیزور برپایه ZIF-8 و یک راکتور متشکل از منبع ماوراء بنفش (UV) و محفظه واکنش انجام شد. برای تعیین راندمان حذف آلاینده پاراکوآت توسط نانوفتو کاتالیزور UV، و محفظه واکنش انجام شد. برای تعیین راندمان حذف آلاینده پاراکوآت توسط و زمان واکنش مقدار نانوفتو کاتالیزور، بازوفتو کاتالیزور BH و زمان مقدار اثر پارامترهای مختلف شامل غلظت آلاینده، مقدار نانوفتو کاتالیزور، و زمان واکنش مورد بررسی قرار گرفت. نتایج نشان داد که با افزایش مقدار نانوفوتو کاتالیزور پاراکوآت در مقدار ۵۰/۰ گرم در لیتر نانوفوتو کاتالیزور BIF-8@CIT با افزایش مقدار نانوفوتو کاتالیزور پاراکوآت در مقدار ۵۰/۰ گرم در لیتر نانوفوتو کاتالیزور BIF-2@ZIF-8 با موان یک نانوفوتو کاتالیزور بدست آمد که برابر با ۹۸/۹ بود. با توجه به نتایج، Bio2@ZIF-8 به عنوان یک نانوفوتو کاتالیزور کارآمد، مقاوم و قابل بازیافت ظاهر شد، که روشی توانمند و سازگار با محیط زیست برای از بین بردن بقایای این علف کش شیمیایی به عنوان آلاینده ای خطرناک در نمونههای آبی ارائه می کند. روش تهیه آسان و فعالیت فوتو کاتالیستی افزایشیافته از نکات برجسته این کاتالیزور بوده و قابل توجه بکارگیری نشان داد.

واژههای کلیدی: TiO₂، چارچوب زیولیتی ایمیدازولیوم، فوتوکاتالیزور، پاراکوآت.