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KEYWORDS

Visible-light-driven; Thermochromic materials; Copper mercury iodide; Superionic conductors; Sonochemical pathway Abstract These days, an important concern in water contamination is the remaining dyes from various sources (for instance, dye and dye intermediates industries, pulp and paper industries, textile industries, craft bleaching industries, tannery, and pharmaceutical industries, etc.), and a broad range of persistent organic contamination has been entered to the wastewater treatment systems or natural water supplies. Indeed, it is extremely hazardous and toxic to the living organism. Therefore, it is necessary to remove these organic pollutants before releasing them into the environment. Photocatalysis is a quickly growing technology for sewage procedures. For this purpose, Cu₂HgI₄ nanostructures were prepared via facile, and cost-effective sonochemical method. The effect of varied circumstances, such as various surfactants, sonication power, and sonication time was considered on the crystallinity, structure, shape, and particle size of products. Cu₂HgI₄ possesses a suitable bandgap (2.2 eV) in the visible area. The photocatalytic performance of the Cu_2HgI_4 was surveyed for the elimination of various organic dyes under visible radiation and exposed that this compound could degrade and remove methyl orange about 94.2% in an acidic medium after 160 min under visible light. Besides, the result showed that various parameters, including, pH, dye concentration, types of dyes, catalyst dosages, and time of irradiation affected the photocatalytic efficiency. © 2021 The Author(s). Published by Elsevier B.V. on behalf of King Saud University. This is an open

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1. Introduction

Water is a crucial component of all living organisms. The Earth contains 70 % of water, of which only less than 2.5 % is available in the form of fresh water that is exploited in industry, agriculture, and for drinking purpose (Arumugam et al., 2021a; Arumugam et al., 2021b; Altaee, et al., 2020; Alshamsi, et al., 2021; Alshamsi and Alwan, 2015; Hussain, et al., 2020; Al-Bedairy and Alshamsi, 2018). Therefore, the demand of fresh water has increased gradually, resulting

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in the creation of water pollution. "Leaving No One Behind," stated by UN World Water Development Report in 2019, indeed demonstrates the importance of water resource management and wastewater treatment (Arumugam & Choi, 2020; Arumugam et al., 2021c; Chen et al., 2019). Excessive demand for pharmaceutical, personal care, agricultural and industrial products driven by the continued growth of the world population has inevitably escalated the discharge of organic contaminants into the environment (Shenoy et al., 2021b; Sridharan et al., 2021). The steadily increasing concentration of organic contaminants primarily originating from pharmaceutical and personal care products in municipal wastewaters of many urban cities globally is making microorganisms resistant to drugs (Chen et al., 2020; Shenoy et al., 2021a). Undoubtedly, these organic contaminants pose a huge threat to the environment and human health as they have demonstrated severe ecological risk for mutagenesis, teratogenesis and carcinogenicity (Shenoy et al., 2020).

Textile colorants and other manufactured colorants comprise probably the biggest groups of organic compounds, indicating an expanding ecological threat. Approximately 1-20% of the total global dye production is wasted through the dyeing process and is delivered into the textile sewages (Houas et al., 2001; Konstantinou & Albanis, 2004; Nasir et al., 2021; Weber & Stickney, 1993). The abandonment of those dyed effluents in the environment is a significant cause of non-elegant contamination and eutrophication and can create hazardous byproducts within hydrolysis, oxidation, or other chemical reactions occurring in the sewage phase (Bianco Prevot et al., 2001; Hussain et al., 2021; Neppolian et al., 2002; Saquib & Muneer, 2003). Therefore, the degradation of dye sewages has gained much consideration. Conventional physical procedures (ion exchange on synthetic adsorbent resins, ultrafiltration, adsorption on activated carbon, coagulation by chemical agents, reverse osmosis, etc.) can frequently be applied efficiently to remove dye contaminants (Badvi & Javanbakht, 2021; Galindo et al., 2001; Kuo & Ho, 2001; Meshko et al., 2001; Mittal & Khanuja, 2021). However, these methods are not destructive, as they only transport organic mixtures from water to another phase, so producing secondary contamination. Accordingly, reproduction of the adsorbent substances and solid wastes post-treatment, which are costly procedures, are required (Beura et al., 2021; Su et al., 2021). Traditional biological wastewater treatment processes are inefficient for degradation and decolorization owing to the high degree of aromatic substances present in colorant molecules and the durability of modern dyestuffs (Aziz et al., 2020; Luque et al., 2021). Moreover, most of the colorants are just adsorbed on the mud and are not destroyed (Konstantinou & Albanis, 2004). Ozonation and chlorination are also applied to remove specific colorants only at slower speeds since they have a poor impact on the carbon content and often high operating costs (Slokar & Le Marechal, 1998; Surendra et al., 2020).

These are the causes of how advanced oxidation processes (AOPs) have been developing over the past decade as they can overcome the difficulty of dye removal in aqueous operations. AOPs are based on the production of highly reactive species, including hydroxyl radicals (OH) that rapidly and non-selectively oxidize a wide range of contaminants. AOPs, including H₂O₂/UV processes (Bokhari et al., 2020; Rosa et al., 2020), photo-Fenton and Fenton catalytic reactions (Moradi et al., 2020; Raji et al., 2020), and photocatalysis (Mahmood et al.; Wang et al., 2021) have been investigated below a wide range of experimental states to decrease organic load and the color of dye comprising sewage. The essential benefit of this method is its inherently destructive nature: it does not include mass transference; it can be performed below ambient situations (oxygen (O₂) is utilized as an oxidizing agent) and may direct to complete organic carbon mineralization into carbon dioxide (CO₂) (Sakthivel et al., 2003; Stylidi et al., 2003; Wang, 2000; Ahmadian-Fard-Fini et al, 2019; Amiri et al, 2017).

Over the past decades, interest in superionic conductors has increased because of their application as solid electrolytes in solid-state batteries. The first fast ion conductors of silver ion type superionic conductors are Cu_2HgI_4 and Ag_2HgI_4 compounds

(Sudharsanan et al., 1984). Ketelaar (Ketelaar, 1934) in 1934 fabricated these materials and recognized great ionic conductivity in these compounds. One of the most notable perspectives in the comprehension of superionic solids is the movement of mobile ions. Besides, Cu₂-HgI₄ belongs to the thermochromic materials, since it reversibly alters color by temperature. Cu₂HgI₄ is in the ordered β-phase at room temperatures (300 K). Nevertheless, it changes from bright red (β-phase) to dark brown (disorder α-phase) at 343 K (Salem et al., 2008). There are several study about superionic and thermochromism properties of Cu₂HgI₄ (Chivian, 1973; Friesel et al., 1987; Lumsden et al., 1995; Salem et al., 2008; Sudharsanan & Clayman, 1985; Wong et al., 1981). According to its suitable bandgap (2.2 eV), we decided to study its photocatalytic activity under visible light for the first time. Besides, this is the first effort of preparing Cu₂HgI₄ by sonochemical method.

2. Experimental

2.1. Materials

All chemical agents employed in this research were furnished in superior quality. Lithium iodide (LiI·2H₂O), Copper sulfate (CuSO₄), Sodium thiosulfate (Na₂S₂O₃), Mercury (II) acetate (Hg(O₂CCH₃)₂), Sodium dodecylbenzene sulfonate (SDBS), Ethylenediaminetetraacetic acid (EDTA), Sodium dodecyl sulfate (SDS), Polyvinyl pyrrolidone (PVP-25000), Sodium salicylate (NaHSal) were acquired of Merck Company and employed without any refinement.

2.2. Synthesis of Cu₂HgI₄

Copper iodide (CuI) was fabricated by a facile co-precipitation method from LiI·2H₂O and CuSO₄. A specific quantity of CuSO₄ was dissolved in water, and a stoichiometric amount of sodium thiosulfate was joined to the CuSO₄ solution for reducing Cu²⁺ to Cu⁺. Afterward, a definite amount of surfactants (such as NaHSal, EDTA, SDS, SDBS, and PVP) was dissolved in water and combined with the above solution. Then, a certain amount of LiI·2H₂O was liquefied in water and added to the above solution to achieve white powder. The HgI₂ was similarly prepared by adding Hg(O₂CCH₃)₂ to LiI. The mixture containing copper iodide was added to the HgI₂ suspension and sonicated for 20 min. The light orange powder was filtered, washed by ethanol, and finally dried at 60 °C (Scheme 1). Table 1 represents multiple fabrication conditions of Cu₂HgI₄ for obtaining the desired condition.

The temperature of the mixtures was monitored versus time to estimate the power yield throughout the operations. dT/dt was computed from the plans of temperature (T) versus time (t) data. So the power (P) is estimated as (Karami et al., 2021b):

$$P = Mc_p \left(\frac{dT}{dt}\right) \tag{1}$$

M is the solvent mass (kg), and c_p is the thermal capacity of the solvent (J kg⁻¹K⁻¹). The power yield is estimated to be 16.2 W in distilled water, in 60 W of power entry.

2.3. Photocatalytic performance

The photocatalytic activity of Cu_2HgI_4 was examined by its potential for degradation of different organic colorants below visible radiation. An Osram light (150 W) was employed as the



Scheme 1 Schematic diagram of the fabrication of Cu₂HgI₄ nanostructures.

Table 1Preparation conditions for Cu_2HgI_4 .									
Sample No.	Type of capping agent	Time of sonication (min)	Power of sonication (W)	Products	Grain size(nm)				
1	-	20	60	Cu ₂ HgI ₄	30.4				
2	SDS	20	60	Cu2HgI4,HgI2	22.5				
3	SDBS	20	60	Cu ₂ HgI ₄	29.1				
4	EDTA	20	60	Cu ₂ HgI ₄ , HgI ₂	33.5				
5	PVP	20	60	Cu ₂ HgI ₄	19.4				
6	NaHsal	20	60	Cu ₂ HgI ₄	30.6				
7	PVP	10	60	-	-				
8	PVP	30	60	-	-				
9	PVP	20	40	-	-				
10	PVP	20	80	_	-				

radiation source, containing a wavelength in the range of 400– 780 nm for the photocatalytic process. The experiments were conducted without catalyst and light, and almost no dye was destroyed after 90 min. Different dosages of Cu_2HgI_4 (30, 50, and 70 mg) were added to 50 mL 10 ppm of dye solutions for every experiment. The suspension was mixed in the dark for 0.5 h before turning on the visible light. A 5 mL specimen is removed from the suspension every 15 min during irradiation and centrifuged at 12000 rpm for 3 min. The buoyant was collected, separated, and observed with a UV–Vis spectrophotometer.

3. Result and discussion

3.1. Characterization

One of the best ways for understanding what is in the compounds is the X-ray diffraction pattern. The XRD patterns of as-prepared products are illustrated in Fig. 1. Sample 1 was formed from Copper Mercury Iodide 00-034-0422 with Tetragonal structure and a small quantity of Mercury Iodide 00-001-1217 with Tetragonal structure (Fig. 1a). Fig. 1(b-f) displays the effect of different surface-active agents (surfactants) on the purity of products. Cu₂HgI₄ was formed in the presence of all surfactants, but there is a small amount of HgI2 as an impurity in the presence of SDS and EDTA. The diffraction peaks at the $2\theta = 25.3, 33.7, 41.8, \text{ and } 49.6^{\circ}$ relate to the corresponding crystal planes (112), (211), (204), and (312) well-matched with the JCPDS No. 034-0422. Therefore, the desired condition was selected in the presence of PVP as a polymeric surfactant for further experiments. Scherrer formula was utilized to determine the crystallite size; $D = K\lambda/\beta \cos\theta$ (2) (Ghanbari & Salavati-Niasari, 2021) to be between 22 and 33 nm (Table 1). The production and explosion of bubbles raise the temperature, which boosts the reaction toward the product. The reaction progress is synopsized below:



Fig. 1 XRD patterns of the samples (a) 1, (b) 2 (c) 3, (d) 4, (e) 5, and (f) 6.

(3)

 $2CuCl + LiI \rightarrow 2CuI$

 $Hg(CH_3COO)_2 + LiI \rightarrow HgI_2$ (4)

 $2CuI + HgI_2 \xrightarrow{\text{Ultrasound radiation}} Cu_2HgI_4$ (5)

The shape, morphology, uniformity, and particle size of products were carried out through the FESEM micrographs (Fig. 2). Without surfactant, aggregate particles with an average size of 65 nm using Digimizer software can be seen in Fig. 2a. Fig. 2(b-f) represents the effect of different types of surfactant on particle size and morphology of products. In the presence of SDS and SDBS, plate structures with large par-



Fig. 2 SEM images of the samples (a) 1, (b) 2 (c) 3, (d) 4, (e) 5, (f) 6, (g) 7, (h) 8, (i) 9 (j) 10 and (k) size distribution of samples.

ticles were formed (Fig. 2b and 2c). Irregularly aggregate particles were composed using EDTA (Fig. 2d). Using PVP as a polymeric capping agent caused uniform aggregate nanoparticles with an average particle size of 42 nm (Fig. 2e). Fig. 2f shows that the addition of NaHSal as a surfactant increased the particle size of the product. Fig. 2(g-j) shows the influence of power and time of sonication on the morphology of products. Decreasing the sonication time and power prevents the reaction temperature from rising too high, thus reducing the particle size in the samples (Fig. 2g and 2i). Besides, long time (30 min) and high power (80 W) boosts the temperature of reaction, which causes irregular large particles (Fig. 2h and 2j). Hence, the desired condition was chosen in the presence of PVP as a polymeric capping agent at medium power of sonication (60 W) for 20 min. Fig. 2k displays the histogram size distribution of samples 1-10 obtained using Digimizer software, indicating that most particles are between 40 and 60 nm.

One of the analytical techniques utilized for the chemical characterization or elemental analysis of a sample is Energydispersive X-ray spectroscopy (EDX). Fig. 3 demonstrates the EDX spectra of Cu₂HgI₄, indicating all peaks are attributed to Cu, Hg, and I elements. Consequently, the products are perfectly purified and related to the XRD results. Besides, the uniform distribution of elements in the samples was confirmed by the EDX result.

Fig. 4 indicates the TEM photographs of Cu_2HgI_4 nanostructures (sample 5) in two scales 120, and 60 nm. The uniform nanoparticles with average size of 39 nm are observed in this figure, which corresponds to the SEM and XRD outcomes.

To calculate the specific surface area and pore volume of samples, the BET surface area analysis is a standard tool. There is no need to investigate the BET surface area of all products due to the similar morphology of samples prepared in different conditions. The nitrogen adsorption–desorption isotherm for sample 5 is depicted in Fig. 5a. Based on the IUPAC category sample 5 reveals the isotherm type III with H3-type hysteresis loop (Fig. 5a), which is ascribed to microporous materials. The specific BET surface area was calculated to be 14.2 m² g⁻¹, and the average pore diameter is 8.6 nm. From the BJH plot, the pore volume average and pore diameter are 0.02234 cm³ g⁻¹ and 3.01 nm, respectively (Fig. 5b).

Fig. 5(c-d) represents the optical properties of sample 5 using UV–Vis diffuse reflectance spectroscopy (DRS). Cu₂-HgI₄ nanostructure displays normal absorptions in the range of 215–415 nm. The bandgap (B.G.) can be defined by the following equation (Ghanbari & Salavati-Niasari, 2018): A(hv-B.



Fig. 3 EDS spectrum of the samples (a) 1, (b) 2 (c) 3, (d) 4, (e) 5, (f) 6, (g) 7, (h) 8, (i) 9 and (j) 10.



Fig. 4 TEM photographs of sample 5.

G.) = $(\alpha h \upsilon)^{1/r}$ (3); That A is a material constant, h υ is the light energy, r is 2 or 1/2 for indirect and direct allowed transitions, and α is absorption factor, respectively (Ghanbari & Salavati-Niasari, 2018). The bandgap was determined 2.2 eV, which makes this compound suitable for visible photocatalytic activity.

3.2. Photocatalytic activity

The photocatalytic activity of Cu_2HgI_4 nanostructures (sample 5) was studied by monitoring the degradation of cationic and anionic organic dyes, such as Acid Black 1 (AB1), Methyl Orange (MO), Eosin (Es), Methylene Blue (MB), Methyl Vio-

let (MV), and Rhodamine B (RhB) in an aqueous solution, under visible radiation (Fig. 6). Without Cu_2HgI_4 or radiation, virtually no colorants were degraded after 90 min, exposing the self-degradation part was irrelevant. The percentage of degradation (%D) was defined as follows:

$$\%D = (C_0 - C_t)/C_0 \times 100 \tag{4}$$

where C_t and C_0 are the solution absorbance of sample after and before decolorization, separately. The impact of several dyes and the dosage of catalysts was conducted to gain better performance. Fig. 6a exhibits the photocatalytic degradation of 0.03 g Cu₂HgI₄ in the presence of AB1, MO, Es, MB, MV, and RhB. The decolorization percentages of mentioned



Fig. 5 (a) Low temperature N₂ adsorption/desorption isotherm, (b) BJH plot, (c) DRS spectrum and (d) optical density $(\alpha h\nu)^2$ vs. energy (E) plot of the sample 5.

dyes are about 42.5%, 54.6%, 46.2%, 39.1%, 36.3%, and 27.9% after 90 min, respectively. Using 0.05 g Cu₂HgI₄ has increased the photocatalytic degradation of all dyes (47.2%, 59.1%, 52.1%, 46.0%, 44.0%, and 32.1%). Fig. 6e reveals that increasing Cu₂HgI₄ dosage to 0.07 g has enhanced the degradation percentage to 52.0%, 63.0%, 57.0%, 54.0%, 48.0%, and 41.1%, respectively. Therefore, enhancing the Cu₂HgI₄ doses increase the surface of catalyst and enhances the dye adsorption on the Cu₂HgI₄ surface (Karami et al., 2020). Also, this compound can degraded the anionic dyes better than cationic ones (Scheme 2) due to the presence of positively charged copper ions (Cu⁺) in the nanostructure.

Furthermore, the possible reaction rate constants of dyes were determined depending on the Langmuir–Hinshelwood mechanism (Hosseinpour-Mashkani et al., 2012). $\ln(C_0/C) = kt$ (5); Where C is the concentration of dyes at t time; C_0 is the initial concentration of coloring agents; and k is the Pseudo-first order rate constant (min⁻¹). The Pseudo rate constant (k) has been determined from $\ln(C_0/C)$ linear correlations vs. reaction time. As seen in Fig. 6b, 6d, and 6f, the better photocatalytic performance was achieved in a bigger reaction rate constant.

Increasing the time of radiation from 90 min to 160 min, enhanced the photocatalytic efficiency from 63.0% to 84.1%. Besides, Fig. 7a reveals the effect of different dye concentrations (5, 10, and 15 ppm) of methyl orange after 160 min. The result unveils that decreasing dye concentration from 10 ppm to 5 ppm increases the degradation percentage from 84.1% to 89.8%, and enhancing the dye concentration reduces dye decolorization. Many numbers of MO molecules saturate the binding sites on the Cu_2HgI_4 surface in 15 ppm of MO. Obviously, the degradation percentage reduces by enhancing the initial dye concentration (de Luna et al., 2013). Fig. 7b exhibits the effect of pH on the decolorization of MO. The degradation percentages of MO are about 84.1, 92.4, and 67.0% in neutral, acidic, and alkaline media, respectively. The outcomes reveal that the highest efficiency is at pH = 3. Since MO is an anionic organic dye, it is more efficient in pH less than 7 than in pH > 7. The logic for this aspect is that the concentration of H^+ groups increased by decreasing pH. In other words, the generation of H⁺ extended in the solvent, and the photocatalytic efficiency improved (Karami et al., 2020; Kazeminezhad & Sadollahkhani, 2014). Table 2 compared the photodegradation of different iodide compounds under visible and UV light. As demonstrated in this table, Cu2-HgI4 can compete with other iodide compounds as a photocatalyst. We can nominate Cu₂HgI₄ as a novel catalyst for the water purification process.

3.2.1. Mechanism of photocatalytic oxidation

It is completely confirmed that valence band (VB) holes (h^+) and conduction band (CB) electrons (e⁻) are produced when aqueous catalyst suspension is lighted by light energy higher than its bandgap (2.2 eV). The photoinduced electrons can reduce the colorant or react with electron acceptors, for example, O₂ dissolved in water or adsorbed on the catalyst surface,



Fig. 6 Photocatalytic degradation of different dyes and Plots of $\ln(C_0/C)$ vs time over sample 5 with different dosages of Cu_2HgI_4 (a and b) 0.03 g, (c and d) 0.05 g, and (e and f) 0.07 g under visible-light irradiation.

reducing it to O_2^{-} (radical of superoxide anion). The photoinduced holes can react with H₂O or OH⁻ oxidizing them into OH radicals or oxidize the organic dves to produce R^+ . They have been reported to be responsible for the photodegradation of organic dyes together with other high oxidant species (peroxide radicals). Multiple initial reactive species, including, ${}^{1}O_{2}$, H⁺, h⁺, HO⁺, and O_2^{-} can be created through photocatalytic degradation methods in UV-Vis/semiconductors. The formation of O₂⁻ can prevent the recombination of photogenerated charge carriers. The HO might be produced just within the $e^- \rightarrow O_2^{--} \rightarrow H_2O_2 \rightarrow OH'$ way. Besides, the OH' radicals are created by several stage reduction O₂⁻ in the process. It was reported that the water separated in subsequent molecular layers and on the TiO_2 surface have three roles (1) preserving charges (inhibiting recombination of electron-hole), (2) performing as an electron acceptor (creation of H atoms in a reaction of photoinduced electrons with protons on the surface, - OH_2^+), and (3) performing as an electron donor (reaction of water with photoinduced holes to produce OH radicals). As claimed by prior investigations (Jiang et al., 2015), the principal active oxygen species produced through photocatalytic, and oxidation reactions are OH and ${}^{1}O_{2}$ radicals, respectively. Relving on the above thoughts, we can suggest that the possibility of creating OH should be much higher than the O₂⁻ formation. Nevertheless, OH is a powerful, unselective oxidant that drives to the complete or incomplete mineralization of numerous organic compounds. According to the above statements, OH, ${}^{1}O_{2}$, and O_{2}^{-} are the active species in the mechanism of photocatalytic degradation of organic dyes. Therefore, the literatures have been indicated that the reactive 'OH performs the main role and, ${}^{1}O_{2}$ and O_{2}^{-} perform an insignificant role in the photocatalytic degradation of organic dyes (Tzeng et al., 2016). The OH may be produced by an h^+ with H₂O. The ${}^{1}O_{2}$ may be created by an h⁺ with O_{2}^{-} species. The O_{2}^{-} may be formed through an e^- with O_2 and/or 1O_2 with e^- species (Rahimzade et al., 2021). Therefore, OH can help as the most essential active species in this research.

A series of scavengers was added to scavenge the important effective agents to estimate the effect of active species in the photodegradation of dyes. The scavengers utilized in this



Scheme 2 Schematic diagram of the mechanism for the photocatalytic degradation of Cu_2HgI_4 nanostructures over different dyes.



Fig. 7 Photocatalytic degradation of MO with 0.07 g of Cu_2HgI_4 in a) different concentrations (5, 10, and 15 ppm), b) various pH (3, 7, and 10), c) various scavengers, and d) cycling runs in the photocatalytic degradation of 10 ppm MO under visible irradiation.

research comprised benzoic acid (BA) for 'OH, Ethylenediaminetetraacetic acid (EDTA) for h⁺, and 1,4-Benzoquinone (BQ) for O_2^- (Ansari, et al., 2016). The process is similar to the photocatalytic procedure. As indicated in Fig. 7c, the photodegradation performance was slightly reduced after adding BQ as when no scavenger was added. Nevertheless, an evident decrease in the photocatalytic efficiency was perceived when EDTA and BA were utilized to scavenge 'OH and h⁺, verifying the effect of OH and h^+ in the photo-oxidation method. In brief, the effects of different of various scavengers revealed that the OH and h^+ performed the main roles, and O_2^- performed a minor role in MO degradation. Therefore, the corresponding reactions at the surface of the catalyst causing the dye degradation can be represented as follows (Karami et al., 2021a; Karami et al., 2020; Konstantinou & Albanis, 2004, Salavati-Niasari, 2005a,b; Salavati-Niasari et al.,

Sample	Highest degradation (%)	Lowest degradation (%)	Catalyst dosage (g)	Source of light	Ref.
Cu ₂ HgI ₄ nanostructures	92.4 (MO)	41.1 (RhB)	0.07	Vis	This work
Rb ₂ HgI ₄ nanostructures	72.1 (AB1)	48.1 (RhB)	0.07	Vis	(Abkar et al., 2021)
Tl ₄ HgI ₆ nanostructures	76.9 (RhB)	48.9 (ThB*)	0.07	UV	(Karami et al., 2021a)
Tl ₄ Cdl ₆ nanostructures	85.7 (AB1)	49.1 (MB**)	0.05	UV	(Ghanbari & Salavati-Niasari, 2018)
CsPbl3 nanostructures	81.7 (MV)	33.0 (AB1)	0.07	Vis	(Karami et al., 2020)
Cu ₂ CdI ₄ /CuI nanocomposites	66.0 (MB)	29.1 (MO)	0.05	UV	(Ghanbari et al., 2016)
Ag ₂ CdI ₄ nanostructures	95.3 (RhB)	57.1 (AB1)	0.05	UV	(Ghanbari et al., 2017b)
TlCdI ₃ nanostructures	94.6 (MB)	27.0 (MO)	0.05	UV	(Ghanbari et al., 2017a)
Ag ₂ ZnI ₄ /AgI nanocomposites	89.3 (MO)	_	0.05	UV	(Razi et al., 2017)
Tl ₄ PbI ₆ nanostructures	72.6 (ThB)	47.8 (RhB)	0.05	Vis	(Rahimzade et al., 2021)

 Table 2
 The photocatalytic activity of different iodide compounds.

* Thymol Blue. **Methylene Blue.



Fig. 8 XRD pattern of Cu₂HgI₄ after photocatalytic reaction.

2009a,b; Zinatloo-Ajabshir et al., 2019; Zinatloo-Ajabshir et al., 2020).	$e^- + O_2 \rightarrow \cdot O_2^-$
$Cu_2HgI_4 \ + \ h\nu(Visible) \ \rightarrow \ Cu_2HgI_4 \ (e_{CB}{}^- \ + \ h_{VB}{}^+)$	$\cdot O_2^- + H^+ + e^- \rightarrow HOO^-$
$Cu_2HgI_4~(h_{VB}{}^+)~+~OH^-~\rightarrow~Cu_2HgI_4~+~OH^{\textstyle \cdot}$	$HOO^{\textrm{.}} \ + \ H_2O \ \rightarrow \ OH \ + \ H_2O_2$
$Cu_{2}HgI_{4}(h_{VB}{}^{+}) \ + \ H_{2}O \ \rightarrow \ Cu_{2}HgI_{4} \ + \ H^{+} \ + \ OH \cdot$	$\cdot O_2{}^- \ + \ 2H^+ \ \rightarrow \ H_2O_2$
$Cu_2HgI_4~(e_{CB}{}^-)~+~O_2~\rightarrow~Cu_2HgI_4~+~O_2{}^^-$	$H_2O_2 \ + \ e^- \ \rightarrow \ OH \ + \ OH^-$
$\mathrm{H^{+}}$ + $\mathrm{O_{2}}$ · ⁻ \rightarrow $\mathrm{HO_{2}}$ ·	$h^+ + OH^- \rightarrow \cdot OH$
$H_2O + h^+ \rightarrow H^+ + OH$	$h^+ \ + \ H_2O \ \rightarrow \ {}^{}}OH \ + \ H^+$

 h_{VB}^{+} + Dye \rightarrow oxidation products

 $OH \! \cdot \ + \ Dye \ \rightarrow \ degradation \ products \ (e.g., \ H_2O, CO_2)$

 $e_{CB}{}^- \ + \ Dye \ \rightarrow \ reduction \ products$

3.2.2. Recyclability and stability of Cu_2HgI_4

For checking the recyclability of Cu_2HgI_4 (sample 5), the catalyst was centrifuged, washed with ethanol and water, dried at 65 °C for 24 h, and reused five times under the equal situations. As shown in Fig. 7d, Cu_2HgI_4 is very stable and maintains its high photocatalytic performance across five reaction cycles. Indeed during the fifth period, the reduction in photocatalytic activity is 5.6%.

The XRD pattern of Cu_2HgI_4 nanostructures after the decolorization of MO is indicated in Fig. 8. As depicted in this figure, all diffraction peaks are coordinated with Cu_2HgI_4 (reference code: 00-034-422) having a tetragonal structure. It could be concluded the host composition lasts intact, after the destruction of organic colorant agents. As a result, the stability of Cu_2HgI_4 is high in an aqueous solution.

4. Conclusions

The Photocatalysis treatment process is one of the encouraging technology for removing numerous organic pollutants and dyes from nature due to its low cost, low energy utilization, and superior catalytic activity. Cu_2HgI_4 nanostructures were synthesized by a low cost, fast, and simple sonochemical pathway. Different conditions, including various surfactants, sonication power, and sonication time were affected the structure, purity, morphology, shape, and particle size. The bandgap of Cu_2HgI_4 was estimated at 2.2 eV, which makes it suitable for photocatalytic activity. The photocatalytic results revealed that Cu_2HgI_4 degraded 5 ppm methyl orange about 92.4% in an acidic medium after 160 min under visible light. This result showed that Cu_2HgI_4 alone or in combination with other semiconductors can be a good photocatalyst in the visible region for future water treatment.

CRediT authorship contribution statement

Elham Abkar: Investigation, Formal analysis, Methodology, Software. Elham Izadi: Software, Writing – review & editing. Omid Amiri: Writing – review & editing, Software, Formal analysis. Mojgan Ghanbari: Investigation, Formal analysis, Writing – original draft, Writing – review & editing. Masoud Salavati-Niasari: Writing – original draft, Investigation, Writing – review & editing, Conceptualization, Supervision, Visualization, Validation, Project administration, Funding acquisition, Resources, Data curation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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