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Article

Photodegradator for Photocatalytic Enhancement of Laboratory Wastewater Quality

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Abstract

Laboratory activities such as practical courses, research experiments, and sample analyses often generate waste, with liquid effluents being the most prevalent. Proper treatment of liquid waste before environmental discharge is essential to prevent contamination. Photocatalysis, a process that employs photon-activated semiconductor oxides, has emerged as a promising approach for wastewater treatment. This study developed bismuth oxide as an alternative photocatalyst capable of operating under UV and visible light. The material was synthesized via the sol–gel method and deposited using a spray-coating technique. The fabricated photocatalytic reactor was designed with integrated reaction chambers, control systems, and adjustable light intensity to enhance wastewater purification. This study systematically optimizes reactor parameters to determine the most effective configuration for pollutant degradation. Experimental results demonstrated that higher light intensities significantly reduced the absorbance of liquid effluents, indicating a substantial decrease in contaminant concentration. Furthermore, treated wastewater's chemical oxygen demand (COD) and biological oxygen demand (BOD) decreased by 24% and 64%, respectively. These findings highlight the potential of Bi_2O_3-based photocatalysis as a practical and scalable solution for improving laboratory wastewater management, thereby supporting sustainable environmental practices in educational and research institutions.

Keywords: Photocatalyst; Bismuth oxide; Laboratory wastewater

INTRODUCTION

Laboratory wastewater is a type of effluent generated from experimental research activities conducted in laboratories. Currently, wastewater produced by educational institutions such as universities is often discharged directly into sinks or drainage systems without prior treatment. Directly releasing untreated laboratory wastewater into the environment can cause severe ecological damage, including soil degradation, ecosystem imbalance, and potential health risks [1]. Some institutions channel their laboratory wastewater to certified

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independent agencies with professional treatment facilities. However, these services require relatively high operational costs, consequently increasing the institutions' environmental maintenance burden.

The organic and inorganic constituents of laboratory wastewater must meet regulatory discharge standards prior to release into the environment. Organic contaminants commonly include chemical oxygen demand (COD), biological oxygen demand (BOD), total suspended solids (TSS), and total dissolved solids (TDS). In contrast, inorganic components may comprise nutrients such as sulfate, nitrate, nitrite, ammonia, phosphate, and heavy metals. Conventional wastewater treatment approaches include physical, biological, and chemical methods [2]. Physicochemical treatments such as sedimentation, filtration, and coagulation, while effective in some cases, tend to generate secondary residues. Biological treatments are often less effective, as many compounds are resistant to microbial degradation into simpler molecules.

Photocatalytic techniques employing oxide-based semiconductors have attracted increasing attention for wastewater degradation. Titanium dioxide (TiO_2) is the most widely used photocatalyst due to its high photocatalytic activity, excellent stability, low cost, and long service life [3], [4]. Nevertheless, TiO_2 suffers from a wide band gap and is only photoactive under ultraviolet irradiation, representing a limited fraction of the solar spectrum [5]. As an alternative, bismuth oxide (Bi_2O_3) has emerged as a promising photocatalyst candidate, particularly for applications in water-splitting reactions and the decomposition of organic molecules [6].

In this study, thin films of Bi_2O_3 were synthesized via the sol–gel method and deposited onto glass substrates using a spray-coating technique. High-pressure gas atomized precursor solutions are placed on the substrate surface during deposition. The coated glass substrates were assembled into a photocatalytic reactor for laboratory wastewater degradation. The fabricated system consists of a glass chamber coated with Bi_2O_3, a sample stirrer with its controller, and adjustable light sources for both visible and ultraviolet irradiation, integrated into a single reactor unit. The reactor's operating parameters will be optimized to determine the most effective operating conditions for pollutant degradation in wastewater. The findings of this work are expected to contribute to scientific advancement and provide a reference framework for laboratory wastewater treatment strategies in Indonesia.

METHODS

This experimental study comprises three main stages: synthesis of bismuth oxide thin films, assembly of the photodegradation apparatus, and photodegradation of contaminants in laboratory wastewater.

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Materials and Instruments

The materials employed in this study included bismuth (Sigma Aldrich, USA), nitric acid (Merck, Germany), sodium hydroxide (Merck, Germany), distilled water, ethylene glycol (Merck, Germany), acetone (Merck, Germany), methanol (Merck, Germany), glass slides, and laboratory wastewater. The instruments used were an analytical balance (Ohaus PA 224), hotplate (Scilogex MS7-HP550), airbrush sprayer (Krisbow KW1200273), compressor (Krisbow Airbrush Twin Cylinder CRDPA002), furnace (Thermolyne Industrial Benchtop Muffle Furnace FD1530M-33), magnetic stirrer, beakers, graduated cylinders, spatulas, droppers, UV light sensors, visible light sensors, lux meter, rotary controllers, UV–Vis spectrophotometer, and control buttons.

Preparation of Photocatalyst Thin Films

Figure 2 presents the sol–gel synthesis of Bi_2O_3 thin films. Briefly, dissolve 1 g of $Bi(NO_3)_3 \cdot 5H_2O$ in 100 mL of 5% HNO_3 and stir for 10 min at room temperature on a hotplate with a magnetic stirrer. Next, add 500 mL of NaOH solution (1 mol/L) and continue stirring for two hours; allow the mixture to sediment to form a suspension, then separate the precipitate. Redissolve the precipitate in 50 mL of 5% HNO_3. Add 10 mL of ethylene glycol ($C_2H_6O_2$, 99.0% purity) to initiate polymer chain formation. Finally, heat the mixture to 175 °C and stir at 670 rpm for 30 min until a transparent precursor solution forms.

Deposit the Bi_2O_3 precursor solution onto glass substrates (25.4 × 76.2 mm; thickness 1.0–1.2 mm) using a spray-coating technique. During deposition, place the substrates on a hotplate maintained at 450 °C [7]. Spray 50 mL of the precursor from a distance of 30 cm onto the substrate surfaces. High-pressure gas propels the atomized droplets and forms a uniform thin film. Subsequently, anneal the films in a furnace at 350 °C for two hours. To avoid cracking the glass substrates, gradually reduce the hotplate temperature after deposition.

Design of the Photodegradation Box

At this stage, a photodegradation box will be constructed to control irradiation conditions for wastewater treatment experiments. The system comprises three main components: the frame, the reaction chamber, and the environmental control unit.

Frame

The frame is rectangular with dimensions of 50 × 30 × 30 cm3. It was constructed from PVC board to ensure light impermeability, thermal resistance, and corrosion resistance.

Reaction Chamber

The reaction chamber employs a beaker coated with a Bi_2O_3 thin film. Under light irradiation, the Bi_2O_3 photocatalyst decomposes organic and

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inorganic compounds into simpler molecules. A magnetic stirrer enhances contact between the Bi_2O_3 surface and the wastewater.

Control Unit

The control system includes devices to regulate environmental conditions inside the reaction chamber, such as stirrer speed and the intensity of both UV and visible light. A digital anemometer (ST6816) was used to monitor motor speed, while UV and visible light intensities were measured using UV-meval 5w11w sensors and Hannochs LEDs, respectively. Four light-dependent resistors (LDRs) were installed to detect illumination from all sides of the chamber. An Arduino microcontroller processes input–output signals across the entire light intensity regulation system. Fuzzy logic was applied to implement control responses based on sensor feedback, and operational parameters were displayed on a 10 × 4 cm LCD panel.

Wastewater Quality Analysis

In this stage, wastewater samples were obtained from the Wastewater Treatment Plant (WWTP) holding tank at the Laboratorium Terpadu Universitas Diponegoro, and artificial wastewater was prepared using dye solutions. Each wastewater sample was introduced into the fabricated photodegradation box. The degradation process was conducted within the Bi_2O_3-coated reactor under two different irradiation conditions: exposure to UV light (100–200 lux) and exposure to visible light (300–500 lux). The performance of the photodegradation device in improving laboratory wastewater quality was evaluated using several key parameters, including UV–Vis spectrophotometric analysis, chemical oxygen demand (COD), and biological oxygen demand (BOD). In addition, the degradation efficiency (Ef) was calculated using Equation (1):

$$\text{Ef}\,(\%) = \left(1 - \frac{C_t}{C_0}\right) \text{x } 100\% \qquad \textbf{(1)}$$

where Ef is the degradation efficiency (%), C_0 is the initial concentration, and C_t is the final concentration of the solution, both determined from absorbance data obtained using a UV–Vis spectrophotometer.

RESULT AND DISCUSSION

Fabrication of the Photodegradation Box

The wastewater photodegradation box comprises three main components: condition control, reaction-chamber control, and an activated photocatalytic film. The rectangular box frame measures 50 × 30 × 30 cm. The aluminum frame with PVC board fillers provides a light-tight enclosure and resists heat and corrosion. These features ensure that, during the photocatalytic reaction, both UV and visible (RGB) light irradiate the sample optimally. Figure 1 shows the assembled photodegradation device. The front section features control buttons and a monitoring display that allow users to adjust reactor-

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chamber conditions (Figure 1a). The rear section houses the power on/off switch and a cooling system that maintains component thermal stability (Figure 1b).

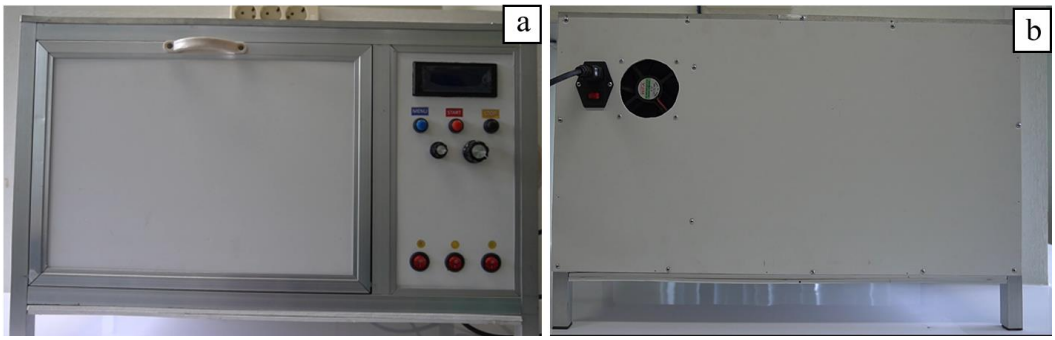

Figure 1. Photodegradation device showing (a) front view and (b) rear view

On the control panel shown in Figure 2, the LCD presents the desired parameters and real-time operating conditions while the device runs. The monitored parameters include the type of light source employed, light intensity, stirring speed, and irradiation/reaction duration. The blue button serves as the central control for selecting and setting reaction time, light mode, intensity, and stirring speed.

The red button (start/up) initiates the reaction and increases the value when adjusting the reaction time. The black button (stop/down) terminates the reaction and simultaneously decreases the value during time setting. In addition to these three buttons, the device includes two rotary knobs: the smaller knob adjusts light intensity, and the larger knob controls stirring speed. Additionally, three red buttons control the power to the stirrer in the reaction chamber.

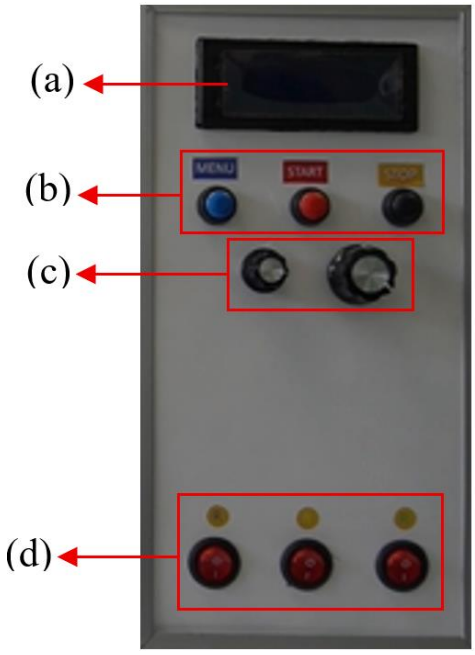

Figure 2. The control panel consists of (a) LCD; (b) control buttons; (c) Knop; (d) Power stirrer

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The reaction chamber serves as the compartment for photocatalytic degradation, shown in Figure 3. RGB and UV lamps provide visible and ultraviolet illumination during wastewater degradation. The chamber also incorporates sensors that connect to the LCD for real-time monitoring.

Six stirrers are positioned at the bottom of the chamber to ensure effective mixing, while a door provides a secure enclosure for the chamber. The sample container is a glass vessel coated with a bismuth oxide photocatalyst.

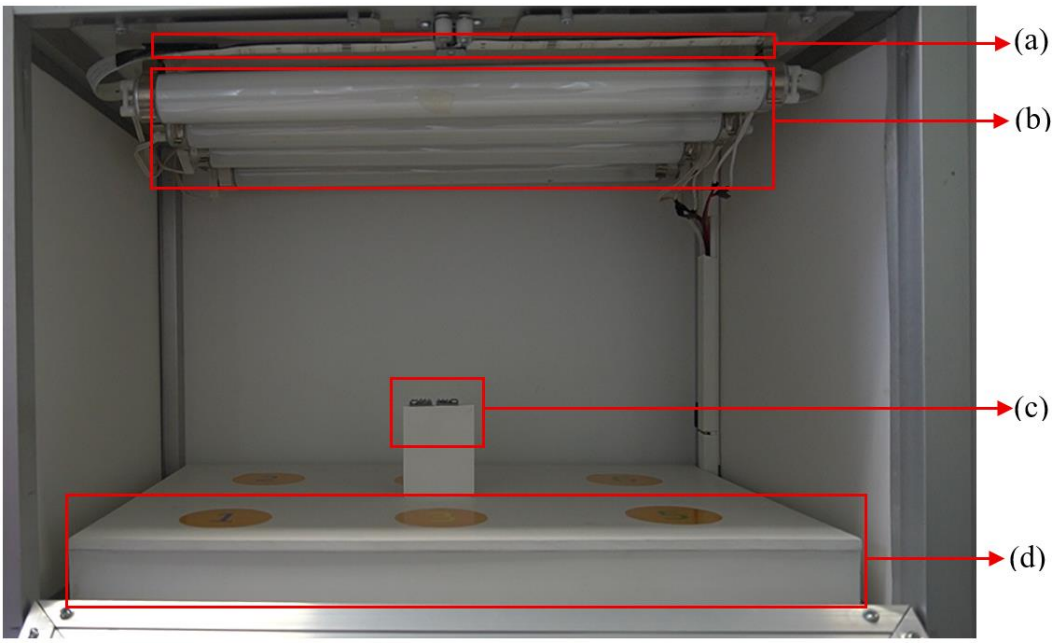

Figure 3. Reaction chamber consisting of (a) RGB lamp; (b) UV lamp; (c) sensor; (d) stirrer

Wastewater Quality Analysis

This study evaluated the degradator's effectiveness by examining four parameters: light source, exposure intensity, wastewater rotation speed, and degradation time. The experiment used visible and ultraviolet (UV) illumination for the light-source parameter to approximate solar irradiation. As shown in Figure 4, UV irradiation produced higher photodegradation efficiency than visible light. This difference is attributable to UV's shorter wavelength relative to visible light; consequently, UV photons carry higher energy and generate a larger population of excited electrons.

For the second parameter, the experiment varied the exposure intensity for each light type. The intensities were set to low, medium, and high—100, 150, and 200 lux for UV light, and 300, 400, and 500 lux for visible light. UV–Vis spectrophotometric analysis showed that light intensity significantly affected wastewater degradation efficiency: as intensity increased, absorbance decreased under both UV and visible irradiation. This behavior arises because

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intensity reflects the number of photons interacting with pollutant molecules; a higher photon flux enhances redox processes and accelerates pollutant degradation. Consequently, increasing the applied intensity during degradation reduced absorbance, corresponding to a lower pollutant concentration in the wastewater.

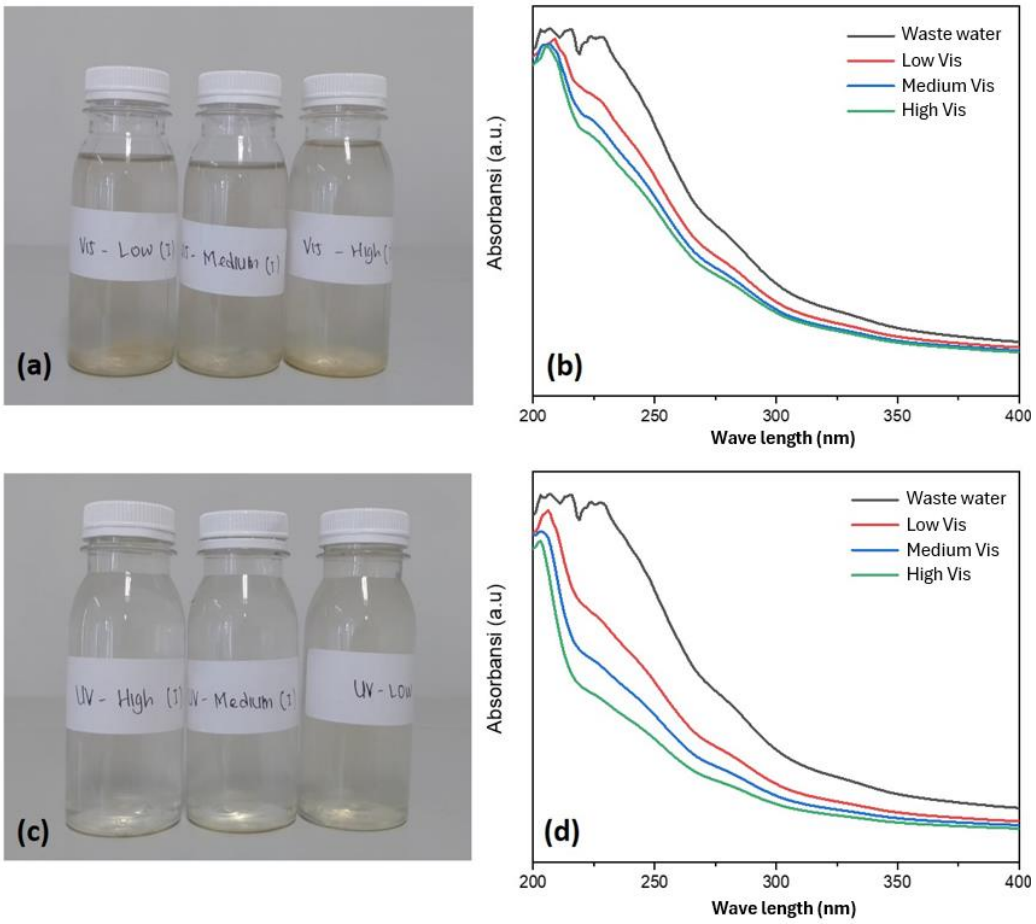

Figure 4. Decrease in absorbance intensity: (a) effect of visible light intensity; (b) effect of UV light intensity

For the third parameter, the stirring speed of the wastewater was varied at 200, 400, and 600 rpm, as shown in Figure 5. UV-Vis spectrophotometric analysis of the liquid waste samples indicated that stirring speed did not produce a significant effect. The absorbance spectra overlapped without noticeable differences at low, medium, and high stirring speeds. These findings suggest that stirring speed does not influence the degradation of the wastewater samples.

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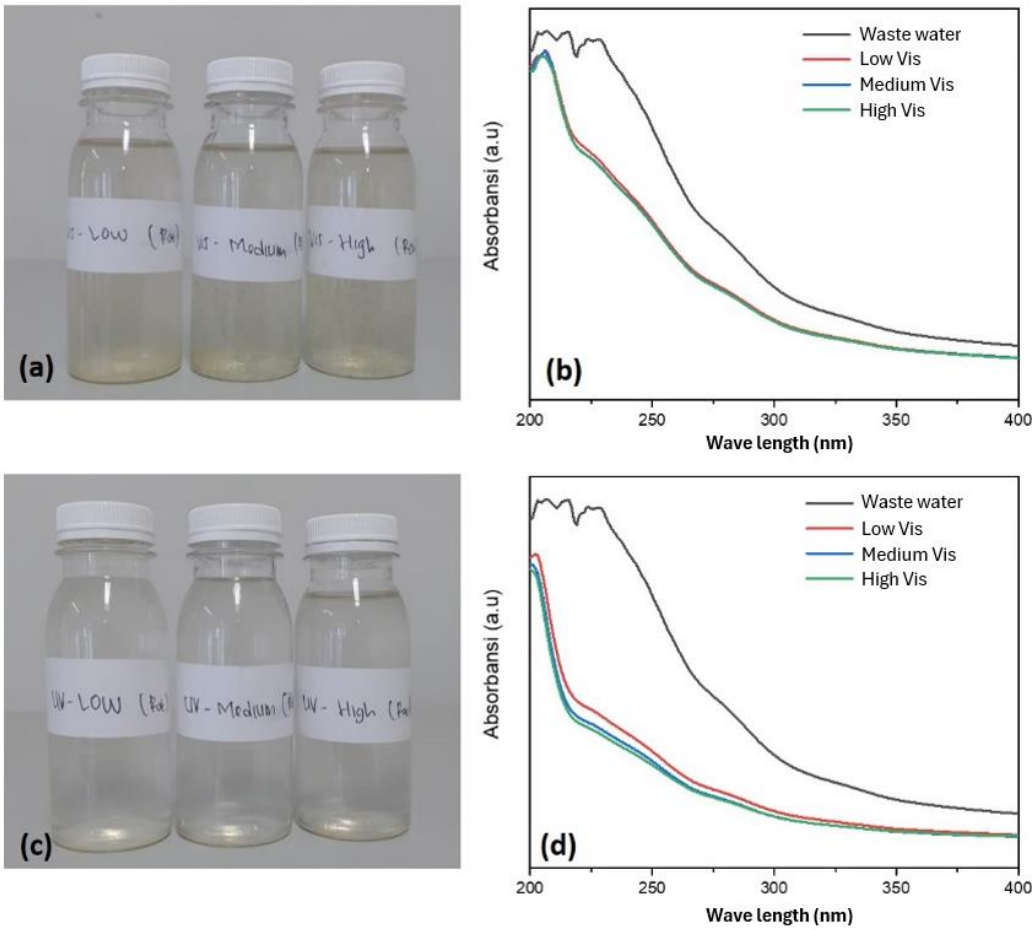

Figure 5. Decrease in absorbance intensity: (a) effect of stirring speed under visible light; (b) effect of stirring speed under UV light

The Bi_2O_3 catalyst can significantly degrade organic dyes in synthetic dye wastewater. The photocatalytic process involves light absorption by Bi_2O_3, which generates electron–hole pairs [8]. These pairs participate in oxidation reactions that decompose the dye molecules into safer and non-hazardous products. Observations on liquid waste samples containing rhodamine-B dye, degraded using a bismuth oxide-based photocatalytic reactor, demonstrated significant results. Figure 6a shows a distinct color change in the sample, from deep pink (before degradation) to pale pink (after degradation). This visual change indicates that bismuth oxide photocatalysis effectively decomposes dye pollutants. Further analysis using a UV–Vis spectrophotometer (Figure 6b) revealed a substantial decrease in the absorbance of rhodamine-B after degradation compared to the untreated sample.

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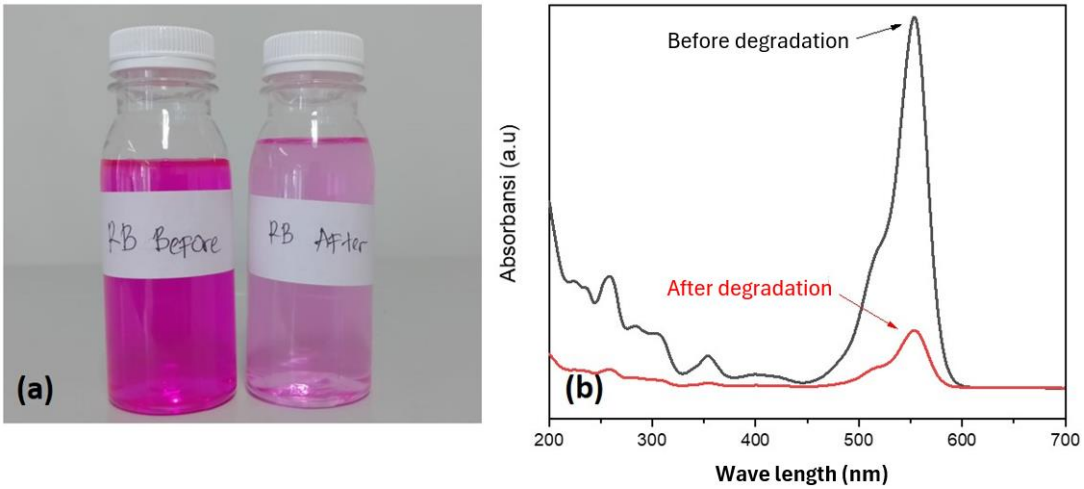

Figure 6. Degradation results of wastewater containing rhodamine-B dye

In addition to UV–Vis spectrophotometric analysis, this study measured the wastewater's biochemical oxygen demand (BOD) and chemical oxygen demand (COD) before and after degradation. BOD and COD are key indicators for determining whether effluents meet quality standards for safe discharge. Table 1 reports that COD decreased 24% after degradation, while BOD decreased 64%.

Table 1. Results of BOD and COD Analysis

Sample	Test Parameters	
	BOD (mg/L)	COD (mg/L)
Before Photodegradation	252	1020
After Photodegradation	191.4	366.67

The degradator was operated for 5 hours for the fourth parameter, with sample conditions monitored every hour. The photocatalytic activity exhibited a continuous decrease in absorbance and a corresponding increase in degradation efficiency. This trend is illustrated in Figure 7, which shows that degradation efficiency improved progressively with prolonged irradiation. These observations indicate that the photocatalytic process effectively and continuously reduced the concentration of pollutants in the wastewater over time.

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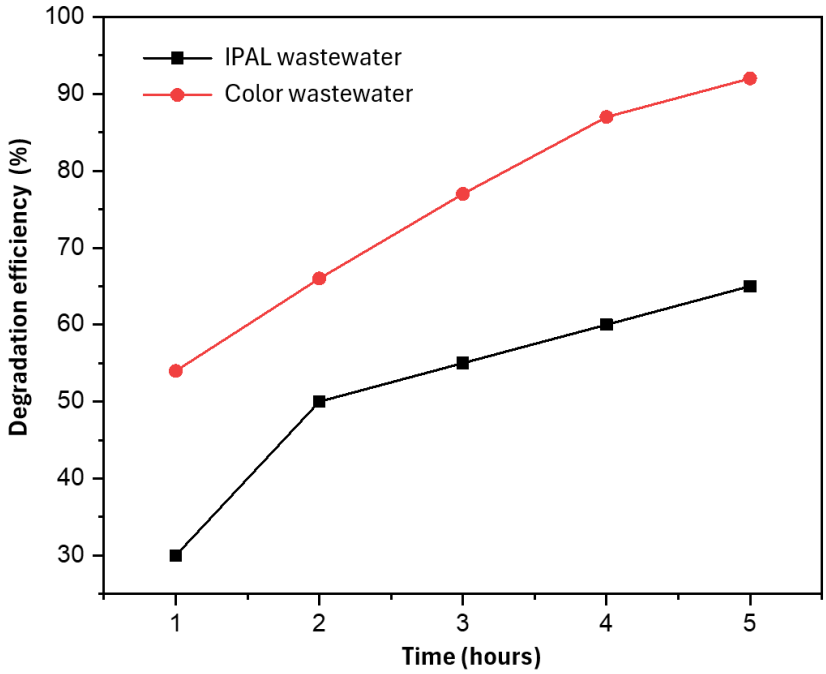

Figure 7. Degradation efficiency of IPAL wastewater and Rhodamine B wastewater

Within the photodegradator, the degradation mechanism proceeds through several steps. Excitation light (UV or visible) irradiates the glass-supported photocatalyst when the photon energy (E = hν) equals or exceeds the bandgap energy (hν ≥ E_g). Photon absorption induces excitation and electron transfer from the valence band to the conduction band, resulting in charge carrier separation and migration (e^- and h^+) to the material surface. Highly reactive electrons and holes at the photocatalyst surface participate in reduction and oxidation reactions, producing hydroxyl radicals (·OH) and superoxide radicals ($\cdot O_2^-$), respectively [9], [10]. The reactions can represent the photodegradation process using the Bi_2O_3 photocatalyst:

$$Bi_2O_3 + h\nu \rightarrow e^- + h^+ \quad (2)$$

$$O_2 + Bi_2O_3(\text{e-CB}) \rightarrow O_2^- \quad (3)$$

$$O_2^- + H^+ \rightarrow OOH \quad (4)$$

$$O_2^- + H^+ + OOOH \rightarrow H_2O_2 + O_2 \quad (5)$$

$$H_2O_2 + O_2^- \rightarrow OH + OH^- + O_2 \quad (6)$$

$$RB^+ + (OH, O_2^- + O_2) \rightarrow CO_2 + H_2O + \text{organic compounds} \quad (7)$$

$$h^+RB \rightarrow CO_2 + H_2O + \text{organic compounds} \quad (8)$$

The degradation process occurs through charge transfer by the charge carriers, namely hydroxyl radicals (·OH) and superoxide radicals ($\cdot O_2^-$), which act as oxidizing agents to reduce pollutants in the wastewater. Hydroxyl (·OH) and superoxide ($\cdot O_2^-$) radicals are the main oxidizing agents generated via charge transfer on Bi_2O_3 under UV [11], [12], [13]; oxygen vacancies and phase engineering enhance their formation and pollutant degradation. These reactive species oxidize the pollutants into CO_2, H_2O, and other inorganic components.

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During UV irradiation, the Bi_2O_3 material facilitates the binding and decomposition of pollutants in its vicinity, thereby effectively reducing the pollutant concentration in the wastewater [14], [15].

However, the present study was conducted on a laboratory scale and primarily tested on limited wastewater samples, which may not fully represent the complexity of real wastewater streams. Future research should therefore focus on scaling up the system to pilot-plant applications and evaluating its performance across diverse types of wastewater, including those containing heavy metals or complex organic compounds.

CONCLUSION

The photocatalyst-based degradator was successfully fabricated and significantly improved laboratory wastewater quality. The optimal conditions for wastewater degradation were achieved using UV light with high exposure intensity and high flow rate. Under these conditions, the degradator reached a maximum degradation efficiency of up to 92% and could continuously operate.

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