Performance Evaluation of a Photovoltaic-Driven Electrocoagulation System for Methylene Blue Degradation

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ABSTRACT
Synthetic dyes in textile wastewater are persistent pollutants due to their high stability and low biodegradability. This study investigates a photovoltaic-driven electrocoagulation (PV-EC) system using aluminum electrodes in series for methylene blue (MB) removal. A 400 mL solution containing 10 mg/L MB was treated at initial pH values of 3, 7, and 11, with electrical energy supplied directly by a photovoltaic panel (19–20 V) without an external DC power source. Residual MB concentration was measured using UV–Visible spectrophotometry at 664 nm. The results show that initial pH strongly affects treatment efficiency. MB removal increased from about 50% at pH 3 to 80% at pH 7 and reached approximately 90% at pH 11, indicating that alkaline conditions enhance the formation of aluminum hydroxide flocs responsible for dye adsorption and coagulation. These findings demonstrate that the PV-driven electrocoagulation system is an effective and energy-efficient method for methylene blue removal while utilizing renewable solar energy. The proposed approach offers a sustainable alternative for decentralized wastewater treatment with reduced dependence on conventional electrical power.

ABSTRAK
Zat warna sintetis dalam limbah tekstil merupakan polutan persisten karena memiliki stabilitas kimia tinggi dan sulit terurai secara hayati. Penelitian ini mengevaluasi sistem elektrokoagulasi berbasis energi fotovoltaik (PV-EC) menggunakan elektroda aluminium yang disusun seri untuk menghilangkan metilen biru (MB). Larutan MB 10 mg/L sebanyak 400 mL diolah pada pH awal 3, 7, dan 11 dengan sumber listrik langsung dari panel surya (19–20 V) tanpa catu daya DC eksternal. Konsentrasi MB sisa dianalisis menggunakan spektrofotometer UV–Vis pada panjang gelombang 664 nm. Hasil penelitian menunjukkan bahwa pH awal berpengaruh signifikan terhadap efisiensi penyisihan. Efisiensi meningkat dari sekitar 50% pada pH 3 menjadi 80% pada pH 7 dan mencapai sekitar 90% pada pH 11, menunjukkan bahwa kondisi basa mendukung pembentukan flok aluminium hidroksida yang berperan dalam adsorpsi dan koagulasi zat warna. Hasil ini membuktikan bahwa sistem PV-EC merupakan metode yang efektif, hemat energi, dan memanfaatkan energi surya terbarukan sehingga berpotensi menjadi solusi berkelanjutan untuk pengolahan air limbah secara terdesentralisasi.

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INTRODUCTION

Industrial textile manufacturing is recognized as one of the largest contributors to global economic growth, yet it remains a major source of wastewater containing high concentrations of synthetic dyes. During textile dyeing processes, approximately 10–20% of the applied dyes fail to bind to textile fibers and are discharged into aquatic environments through industrial effluents. The release of these persistent organic pollutants not only deteriorates water quality by reducing light penetration and inhibiting photosynthetic activity, but also poses severe ecological and human health risks due to their complex aromatic structures, high chemical stability, and resistance to conventional biological degradation. Consequently, developing efficient, environmentally sustainable, and energy-conscious technologies for the treatment of dye-contaminated wastewater has become an

urgent challenge in modern environmental engineering. Synthetic dye pollution is therefore considered a priority target for achieving sustainable industrial wastewater management and supporting global carbon-neutral strategies (Sarayu & Sandhya, 2012; Al-Tohamy et al., 2020).

Among numerous synthetic dyes, methylene blue (MB) has been widely used as a representative model pollutant due to its high aqueous solubility, excellent chemical stability, and recalcitrant aromatic molecular structure. In aquatic systems, MB significantly increases chemical oxygen demand (COD), decreases light transmission through water columns, and suppresses photosynthetic activity of aquatic organisms. Long-term exposure to methylene blue has also been associated with toxicological effects on aquatic ecosystems and adverse impacts on human health. Owing to these characteristics, MB has become one of the most widely accepted probe molecules for evaluating the performance of emerging wastewater treatment technologies, particularly electrochemical processes, where degradation efficiency can be quantitatively assessed through spectrophotometric analysis (Tiandho et al., 2021; Khan et al., 2022).

A wide range of treatment technologies, including adsorption, membrane filtration, biological treatment, chemical coagulation, and advanced oxidation processes (AOPs), has been investigated for dye removal. Although many of these techniques exhibit high removal efficiencies under controlled conditions, their large-scale implementation is often constrained by high chemical consumption, secondary sludge generation, membrane fouling, complicated operational requirements, and elevated operating costs. Electrocoagulation (EC) has recently emerged as a promising alternative because it generates coagulant species in situ by electrochemically dissolving sacrificial electrodes, thereby eliminating the need for continuous chemical dosing. In aluminum-based EC systems, anodic dissolution produces Al^{3+} ions, which subsequently hydrolyze into amorphous aluminum hydroxide flocs that destabilize, adsorb, and remove dissolved organic contaminants through simultaneous coagulation, adsorption, flotation, and sedimentation mechanisms. These inherent advantages make electrocoagulation an attractive technology for treating highly colored industrial wastewater while minimizing chemical usage and sludge production (Jing et al., 2021; López-Guzmán et al., 2021).

Despite these advantages, electrocoagulation performance strongly depends on operating conditions, including current density, applied voltage, electrode configuration, electrode spacing, electrolyte composition, electrolysis time, pollutant concentration, and solution pH. Among these variables, pH plays a particularly critical role because it governs aluminum speciation and consequently determines the formation, stability, and adsorption capacity of aluminum hydroxide flocs. Near-neutral conditions generally promote the formation of amorphous $Al(OH)_3$ species with large specific surface areas and excellent coagulation properties, whereas strongly acidic or alkaline environments favor soluble aluminum complexes that substantially reduce contaminant removal efficiency. In addition, electrical parameters influence electrode dissolution rates, ohmic resistance, hydrogen bubble generation, and mass transfer within the reactor, collectively affecting the overall electrocoagulation performance. Therefore, identifying optimal operating conditions remains essential for maximizing pollutant removal while minimizing energy consumption (Mouedhen et al., 2008; Lu et al., 2021; Jing et al., 2021).

Although electrocoagulation is considered an energy-efficient electrochemical technology, its large-scale deployment remains hindered by electricity demand. Conventional EC systems are commonly powered by laboratory DC power supplies or electrical grids, making operational costs highly dependent on electricity prices and limiting their sustainability in remote or off-grid locations. Integrating photovoltaic (PV) systems with electrocoagulation has therefore attracted increasing attention as a strategy to reduce fossil energy consumption while maintaining satisfactory treatment performance. Unlike conventional power supplies, photovoltaic modules directly convert solar radiation into electricity, without greenhouse gas emissions, enabling decentralized wastewater treatment with a substantially lower environmental footprint. Previous studies have demonstrated that PV-driven electrocoagulation can effectively remove contaminants from textile and industrial wastewater while simultaneously decreasing energy costs and carbon emissions (Khemila et al., 2018; Mohamad et al., 2021; Louhichi et al., 2022).

Nevertheless, most previous investigations have primarily emphasized pollutant removal efficiencies or the economic benefits of photovoltaic-powered electrocoagulation systems, whereas the coupling between photovoltaic power fluctuations and electrocoagulation chemistry has received considerably less attention. In particular, studies systematically examining how solution pH influences the electrochemical generation of aluminum hydroxide species under direct-coupled photovoltaic operation remain scarce. This issue is scientifically important because photovoltaic output voltage continuously varies with solar irradiance, potentially altering electrode dissolution kinetics and, consequently, coagulant generation under different pH conditions. Understanding the interaction between photovoltaic electrical characteristics and electrocoagulation chemistry is therefore essential for designing reliable renewable-energy-driven wastewater treatment systems capable of maintaining stable performance under naturally fluctuating operating conditions.

In this study, a direct-coupled photovoltaic-driven electrocoagulation system employing series-connected

aluminum electrodes was developed to investigate the degradation of methylene blue under different initial pH conditions, without an external DC power supply. The treatment performance was evaluated using UV–Visible spectrophotometry through concentration decay and removal efficiency analyses. Unlike previous studies that primarily focused on removal efficiency under fixed electrical conditions, this work provides a systematic evaluation of pH-dependent electrocoagulation behavior under realistic photovoltaic operation. The findings are expected to provide new insights into the design of sustainable, low-energy electrochemical wastewater treatment technologies powered entirely by renewable solar energy.

METHODS

Methylene blue (MB) was used as a model organic dye representative of textile wastewater. A stock solution was prepared using deionized water and subsequently diluted to obtain an initial concentration of 10 mg/L. For each experiment, 400 mL of the prepared solution was transferred into the electrocoagulation reactor. The initial solution pH was adjusted to 3, 7, and 11 using dilute hydrochloric acid (HCl) and sodium hydroxide (NaOH). These pH values were selected to investigate the influence of acidic, neutral, and alkaline conditions on the electrocoagulation performance of the photovoltaic-driven system. A laboratory-scale photovoltaic-driven electrocoagulation (PV-EC) system was constructed by directly coupling a photovoltaic (PV) module to an electrocoagulation reactor without employing an external DC power supply or battery storage. The experimental configuration is illustrated in Figure 1.

The reactor employed aluminum electrodes serving as both anode and cathode. The electrodes were connected in series with an inter-electrode distance of 3 cm to promote uniform current distribution and efficient coagulant generation. Electrical energy generated by the photovoltaic panel was supplied directly to the aluminum electrodes through conductive cables, allowing electrocoagulation to proceed solely under solar irradiation. This direct-coupled configuration minimizes electrical conversion losses while demonstrating the feasibility of renewable-energy-powered wastewater treatment.

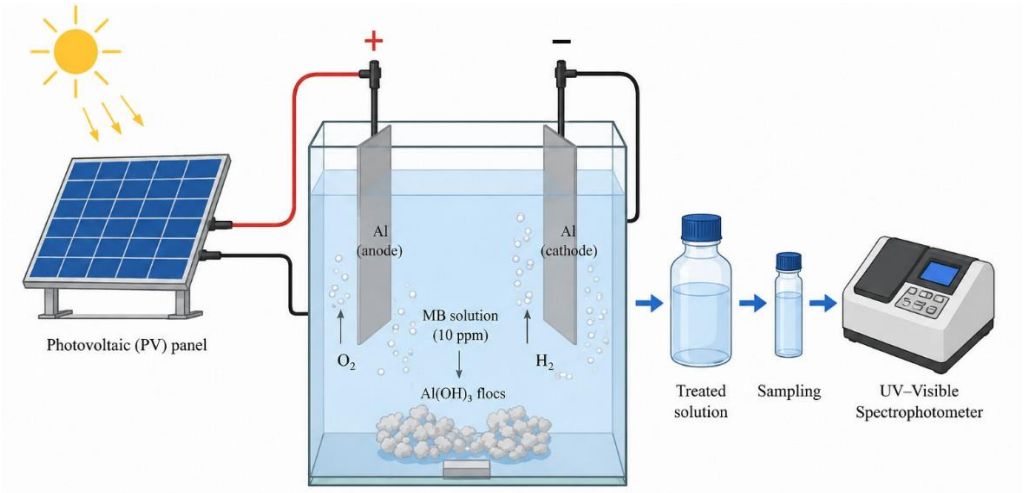


Figure 1. Schematic illustration of the photovoltaic-driven electrocoagulation system.

All experiments were conducted under natural sunlight. Prior to each experiment, the reactor was filled with 400 mL of methylene blue solution, after which the solution pH was adjusted to the desired value (3, 7, or 11). The photovoltaic module was then directly connected to the electrocoagulation reactor to initiate the treatment process. During operation, the photovoltaic module's output voltage remained within 19–20 V. Throughout all experiments, operating parameters, including solution volume, electrode configuration, electrode spacing, and reactor geometry, were held constant to ensure that the initial solution pH was the only experimental variable. Liquid samples were collected immediately before and after electrocoagulation for subsequent spectrophotometric analysis.

The concentration of methylene blue before and after treatment was determined by UV–Visible spectrophotometry, measuring absorbance at the maximum absorption wavelength (λ_{max}). Dye concentrations were calculated from a calibration curve established using standard methylene blue solutions of known concentrations. The removal efficiency (η) was calculated according to Equation (1):

$$\eta(\%) = \frac{C_0 - C_t}{C_0} \times 100 \quad (1)$$

where C_0 is the initial methylene blue concentration (mg/L) and C_t is the concentration after electrocoagulation treatment. The experimental results were analyzed to evaluate the influence of the initial solution pH on the

performance of the photovoltaic-driven electrocoagulation system and to identify the operating condition yielding the highest methylene blue removal efficiency.

RESULTS AND DISCUSSIONS

Prior to evaluating the performance of the PV–EC system, a UV–Visible spectrophotometric analysis was performed to establish the relationship between methylene blue concentration and absorbance. The calibration curve was subsequently employed to determine the residual dye concentration after electrocoagulation treatment. Absorption spectra were recorded over the wavelength range of 400–700 nm using standard methylene blue solutions with concentrations ranging from 0 to 10 mg/L.

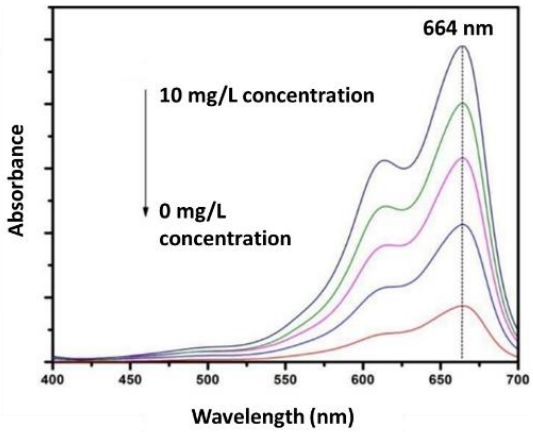


Figure 2. UV–Visible absorption spectra of methylene blue at different concentrations

As shown in Figure 2, all methylene blue solutions exhibited a characteristic absorption maximum at approximately 664 nm, corresponding to the π–π* electronic transition of the aromatic chromophore. Increasing the dye concentration resulted in a proportional increase in absorbance intensity without any observable shift in the absorption maximum. The absence of wavelength displacement indicates that the molecular structure of methylene blue remained unchanged over the investigated concentration range and that no significant aggregation occurred under the experimental conditions. Such behavior is consistent with the Beer–Lambert law, where absorbance is directly proportional to solute concentration at a constant optical path length.

The calibration curve demonstrates excellent linearity ($R^2 = 0.9961$), confirming the reliability of UV–Visible spectroscopy for the quantitative determination of methylene blue concentration. The high linear correlation indicates that more than 99% of the absorbance variation can be explained by concentration changes, thereby minimizing analytical uncertainty in concentration determination after electrocoagulation. Consequently, the regression equation obtained from the calibration curve was used throughout this study to calculate the residual methylene blue concentration and evaluate the removal performance of the PV–EC system.

In addition to quantitative spectrophotometric measurements, the electrocoagulation process was visually evaluated through changes in the color intensity of the methylene blue solution. Visual observation provides qualitative evidence of dye removal and reflects the progressive decrease in dissolved chromophore concentration during electrocoagulation.

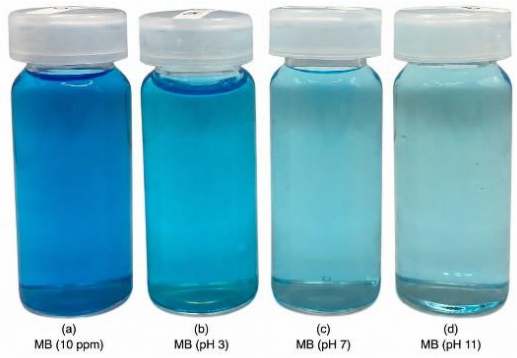


Figure 3. Visual appearance of methylene blue solution before and after electrocoagulation under different initial pH conditions.

As illustrated in Figure 3, the untreated solution exhibited a deep blue color characteristic of concentrated methylene blue. Following electrocoagulation, the color gradually faded, with the degree of discoloration depending strongly on the initial solution pH. The most pronounced color removal was observed at pH 11, whereas the solution treated at pH 3 retained a relatively darker blue appearance.

The discoloration results from the electrochemical dissolution of aluminum electrodes, producing Al^{3+} ions that subsequently hydrolyze into amorphous aluminum hydroxide flocs. These freshly generated flocs possess high adsorption capacity and efficiently capture methylene blue molecules through charge neutralization, adsorption, and sweep coagulation mechanisms before settling from the aqueous phase. Therefore, the progressive reduction in blue color qualitatively confirms the formation of effective coagulating species during electrocoagulation.

More importantly, the visual observations closely agree with the quantitative UV–Visible measurements presented in the following section, indicating that color fading serves as a rapid qualitative indicator of methylene blue removal efficiency across different operating conditions.

The quantitative removal efficiencies calculated from the UV–Visible calibration curve are presented in Figure 4. As shown in Figure 4, the initial solution pH exerted a pronounced influence on methylene blue removal efficiency. The removal efficiency increased from approximately 50% at pH 3 to 80% at pH 7, reaching nearly 90% under alkaline conditions (pH 11). These results demonstrate that alkaline media substantially enhance the performance of the photovoltaic-driven electrocoagulation process.

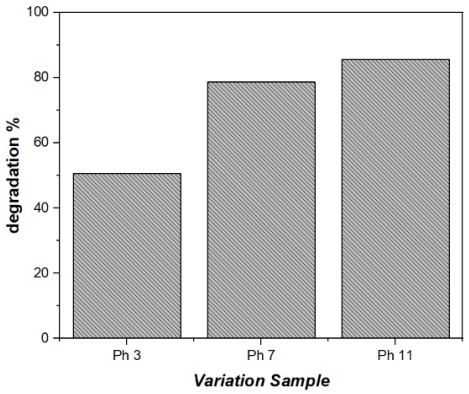


Figure 4. Removal efficiency of methylene blue under different initial pH conditions using the photovoltaic-driven electrocoagulation system.

The observed trend can be explained by the pH-dependent hydrolysis chemistry of aluminum ions generated during anodic dissolution. Under acidic conditions, aluminum predominantly exists as soluble Al^{3+} and partially hydrolyzed species, limiting the formation of insoluble aluminum hydroxide flocs responsible for pollutant removal. As the solution becomes alkaline, hydrolysis reactions proceed more extensively, producing abundant amorphous $Al(OH)_3$ with large specific surface areas and numerous active adsorption sites. These hydroxide flocs efficiently destabilize dye molecules through electrostatic attraction and adsorption while simultaneously promoting sweep coagulation and sedimentation, thereby substantially improving methylene blue removal efficiency.

In addition to influencing aluminum speciation, alkaline conditions may also enhance hydrogen evolution at the cathode. The generated hydrogen microbubbles facilitate electroflotation, promoting the upward transport of dye-loaded flocs and increasing the overall separation efficiency. Consequently, pollutant removal in electrocoagulation is governed not only by adsorption onto aluminum hydroxide but also by the synergistic effects of coagulation, flotation, and sedimentation.

The superior performance observed at pH 11 is consistent with previous studies reporting that aluminum-based electrocoagulation generally exhibits optimal dye removal under neutral-to-mildly alkaline conditions, where amorphous aluminum hydroxide becomes the dominant coagulating species (Mouedhen et al., 2008; Jing et al., 2021; Lu et al., 2021). Nevertheless, the present study demonstrates that such high removal efficiency can also be achieved using a direct-coupled photovoltaic power source without relying on an external DC power supply. This finding indicates that fluctuations in photovoltaic output voltage within the 19–20 V operating range did not adversely affect coagulant generation or overall treatment performance.

Furthermore, the quantitative removal efficiencies are fully consistent with the visual observations shown in Figure 3, where the solution treated at pH 11 exhibited the palest coloration, while the acidic condition retained a noticeable blue tint. The excellent agreement between visual inspection and spectrophotometric analysis confirms the robustness of the experimental methodology and demonstrates the photovoltaic-driven electrocoagulation system's capability to achieve effective dye removal solely using renewable solar energy.

Overall, the results highlight the feasibility of integrating photovoltaic technology with electrocoagulation for sustainable wastewater treatment. By eliminating dependence on external electrical grids while maintaining high

removal efficiencies, the proposed system offers a promising pathway toward decentralized, low-carbon treatment of dye-containing industrial effluents.

CONCLUSIONS

This study demonstrated the feasibility of a direct-coupled photovoltaic-driven electrocoagulation (PV–EC) system for removing methylene blue from aqueous solution without an external DC power supply. The integrated PV–EC configuration, operating solely on solar energy and delivering an output voltage of approximately 19–20 V, demonstrated efficient dye removal, highlighting its potential as a sustainable wastewater treatment technology. Among the investigated operating conditions, the initial solution pH was identified as the dominant factor governing electrocoagulation performance. The removal efficiency increased from approximately 50% at pH 3 to 80% at pH 7, reaching nearly 90% at pH 11, indicating that alkaline conditions favor the formation of amorphous aluminum hydroxide flocs, which are responsible for effective adsorption, coagulation, and separation of methylene blue molecules.

These findings contribute to the development of low-carbon, decentralized wastewater treatment technologies by demonstrating that photovoltaic-powered electrocoagulation offers an environmentally friendly, energy-efficient alternative for the remediation of dye-contaminated wastewater, particularly in off-grid or resource-limited regions. Future studies should focus on evaluating specific energy consumption, current efficiency, electrode consumption, sludge characteristics, treatment economics, and the system's performance under variable solar irradiance using real textile wastewater to further assess its practical applicability and scalability.

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