Volume 12, Issue 3, July 2025 ISSN: 2348-8565 (Online)
International Journal of Modern Engineering and Research Technology
Website: http://www.ijmert.org Email: editor.ijmert@gmail.com

Solar-Driven Advanced Oxidation Processes (AOPs) for the Removal of Industrial Pollutants from Municipal Wastewater

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Abstract

This paper presents the development and experimental evaluation of solar-driven advanced oxidation processes (AOPs) for the efficient removal of industrial pollutants from municipal wastewater, with a focus on textile industry wastewater. The research integrates solar photovoltaic (PV)-based electrolysis and solar thermal treatment technologies to achieve simultaneous hydrogen production and wastewater remediation. Innovative solar desalination systems, including parabolic troughs and heat pipe evacuated tube collectors (HP-ETCs), are incorporated with phase change materials (PCMs) to enhance thermal storage, treatment efficiency, and potable water output. Results demonstrate pollutant removal efficiencies exceeding 90% for contaminants such as dyes, chemical oxygen demand (COD), biological oxygen demand (BOD), and heavy metals. Treated wastewater shows potential for reuse in agriculture and algal biomass production. The paper also discusses energy and economic analyses, validating the sustainability and scalability of these hybrid solar treatment systems.

Keywords:—*Solar energy, Advanced Oxidation Process, Wastewater treatment, Photocatalysis, Solar electrolysis, Textile wastewater, Hydrogen production, Phase change materials, Solar desalination.*

I. Introduction

Water scarcity and environmental pollution caused by industrial wastewater are pressing global challenges, especially in rapidly developing economies where textile industries consume considerable freshwater and discharge high volumes of colored and polluted effluents. Traditional wastewater treatment methods—though widely used—are energy-intensive and inefficient against persistent contaminants such as dyes and heavy metals. Harnessing solar energy for advanced oxidation processes (AOPs) offers a clean, sustainable solution for simultaneous energy recovery and wastewater remediation.

This study explores solar-driven AOPs via solar PV- based electrolysis and solar thermal treatment, including novel solar still designs and heat pipe evacuated tube collectors (HP-ETCs) integrated with phase change materials (PCMs) to improve treatment efficiency, operational stability, and water productivity. The work focuses on textile industry wastewater treatment, hydrogen generation, and resource recovery, contributing to clean development goals and sustainable water-energy management.

II. Background and Related Work

A variety of treatment methods—including physicochemical, biological, and advanced oxidation techniques—have been studied for industrial wastewater detoxification. Solar photocatalysis using TiO_2 catalysts, solar electrolysis for hydrogen generation coupled with pollutant degradation, and solar desalination represent promising directions enhanced by renewable energy input.

Phase change materials (PCMs) embedded in solar stills improve thermal storage, allowing extended operation beyond peak sunlight hours. Recent advances in solar still configurations and hybrid heat pipe evacuated tube collectors (HP-ETCs) enable higher water yields and energy efficiencies. Microbial fuel cells and algal bioremediation also offer complementary wastewater treatment and resource recovery opportunities.

III. Methodology

A. Wastewater Sampling and Characterization Wastewater samples were collected from textile dyeing and degumming processes. Parameters measured included pH, total dissolved solids (TDS), chemical oxygen demand (COD), biological oxygen demand (BOD), heavy metals, and dye concentration, following standard protocols.

B. Solar-Driven Treatment Systems

1. Solar PV Electrolysis: Utilized solar panels powering an electrolytic cell with varied electrode materials (carbon, steel, platinum) across multiple voltages to optimize hydrogen production and pollutant removal.

2. Solar Parabolic Concentrator-Based Desalination: Constructed a parabolic trough system to concentrate solar radiation for wastewater desalination with real-time performance monitoring.

3. HP-ETC Integrated Solar Still: Developed a hybrid solar still coupled with heat pipe evacuated tube collectors and stearic acid PCM for enhanced thermal storage and continuous potable water output.

C. Analytical Methods

Pollutant removal efficiencies and energy consumption were quantified. Treated water was evaluated for reuse potential in agriculture and microalgal biomass cultivation. Economic feasibility and environmental impact assessments were performed.

IV. Results and Discussion

- Hydrogen Production: Maximal hydrogen yield reached 16.4 mL/hr using steel electrodes at 12 V, with peak energy efficiency (~67.8%) achieved at moderate voltage (3 V). An inverse relationship was observed between hydrogen yield and system efficiency.
- Pollutant Removal Efficiency: Up to 99% removal was recorded for TDS,

COD, BOD, and heavy metals.

- Desalination Performance: The parabolic concentrator-based system achieved potable water yields of 5.5 to 8.3 L/day with energy efficiency between 40% and 52%.
- HP-ETC-SS Performance: Potable water output increased by up to 162% over conventional stills, with energy efficiencies ranging from 22% to 40%. PCM integration extended operational hours, reduced start-up times, and enhanced hot water production.
- Reuse Potential: Treated wastewater supported healthy growth of Vigna radiata plants and Chlorella pyrenoidosa algae, facilitating water and nutrient recycling.
- Economic Analysis: Unit production costs for potable water and hot water were competitive and favorable compared to fossil-fuel based systems.

V. Conclusion

This study confirms that solar-driven AOPs combining PV electrolysis, solar thermal desalination, and PCM-enhanced hybrid systems effectively remove industrial pollutants from municipal wastewater while producing renewable hydrogen and potable water. The integration of renewable energy with advanced wastewater treatment supports sustainable resource management, with significant environmental and economic benefits. Future work should focus on system scale-up, integration with smart controls, and expanding pollutant scope.

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