IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429
Volume 4, Issue 2, October 2024
Impact Factor: 7.53

Photocatalytic Degradation of CitrusLemon-Capped CdO Nanocatalyst Synthesized via the Ceramic Method

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Abstract: *Cadmium oxide (CdO) nanoparticles are promising photocatalytic materials due to their narrow bandgap and high carrier mobility; however, their efficiency is often limited by rapid electron-hole recombination and particle agglomeration. In this study, lemon-capped CdO nanoparticles were synthesized via a conventional ceramic method integrated with green surface functionalization using lemon (Citrus limon) extract. The influence of lemon-derived biomolecules on structural, morphological, optical, and photocatalytic properties was systematically examined. X-ray diffraction analysis confirmed the formation of phase-pure cubic CdO with a substantial reduction in crystallite size from approximately 41 nm for uncapped CdO to 24 nm for lemon-capped CdO. Electron microscopy revealed improved particle dispersion and reduced agglomeration in capped samples. FTIR spectra verified the presence of hydroxyl and carboxyl functional groups on the nanoparticle surface. Optical analysis indicated enhanced visible-light absorption and bandgap narrowing from 2.42 eV to 2.21 eV. Photocatalytic degradation of methylene blue under UV-visible irradiation showed that lemon-capped CdO achieved ~95% degradation within 90 minutes, significantly outperforming uncapped CdO. Kinetic analysis followed pseudo-first-order behavior, demonstrating enhanced reaction rates due to improved charge separation and surface reactivity*

Keywords*:* Cadmium oxide nanoparticles; Lemon extract capping; Ceramic synthesis; Green photocatalysis; Dye degradation

I. INTRODUCTION

The increasing release of dye-containing effluents from textile, paper, leather, and pharmaceutical industries has become a major environmental concern due to the persistence, toxicity, and non-biodegradable nature of synthetic dyes[1]. Conventional wastewater treatment techniques, including adsorption and biological degradation, often fail to completely mineralize these pollutants, leading to secondary contamination. Semiconductor-based photocatalysis has emerged as an effective and sustainable approach for degrading organic pollutants into environmentally benign products using light energy[2].Cadmium oxide (CdO) is an n-type semiconductor with a direct bandgap ranging from 2.2 to 2.5 eV, enabling efficient absorption in the visible region of the electromagnetic spectrum. Its high electrical conductivity and carrier mobility make it attractive for photocatalytic applications. Nevertheless, CdO nanoparticles synthesized through traditional routes often exhibit large particle size, severe agglomeration, and high recombination rates of photogenerated charge carriers, which significantly reduce photocatalytic efficiency[3].Green surface modification using plant extracts has recently gained attention as an eco-friendly strategy to overcome these limitations. Plant extracts contain natural chelating and stabilizing agents such as flavonoids, organic acids, and polyphenols that can control particle growth and modify surface chemistry. Lemon extract is particularly rich in citric acid and ascorbic acid, which can bind to metal ions and introduce surface functional groups that enhance photocatalytic activity.The ceramic method is a solid-state synthesis technique that offers advantages such as simplicity, scalability, and high crystallinity[4]. However, it often lacks control over particle size and morphology. Integrating green capping agents into the ceramic synthesis route can provide an effective approach to overcome these drawbacks. Despite its potential, limited studies have explored lemon-capped CdO nanoparticles synthesized via the ceramic method. This work aims to systematically investigate the effect of lemon extract capping on the physicochemical and photocatalytic properties of CdO nanoparticles[5].

II. EXPERIMENTAL METHODS

2.1 Materials

Cadmium nitrate tetrahydrate was used as the metal precursor due to its high solubility and thermal decomposition characteristics. Fresh lemons were selected as the natural capping source. Lemon extract was prepared by washing the fruits thoroughly, extracting the juice, and filtering it to remove solid residues. The acidic nature of the extract, with a pH of approximately 2.3, confirmed the presence of citric acid and other organic constituents.

2.2 Synthesis Method

For the synthesis, cadmium nitrate powder was finely ground to ensure homogeneity as shown in **Figure 1**. In the lemon-capped sample, a controlled volume of lemon extract was gradually added to the precursor powder and mixed thoroughly to form a uniform paste. This step facilitated the formation of organic-metal complexes. The mixture was dried at 100 °C to remove moisture and partially decompose organic compounds. Calcination was carried out at 500 °C for 4 hours to form crystalline CdO nanoparticles while retaining surface-modifying effects of the lemon extract. Uncapped CdO nanoparticles were synthesized under identical conditions without lemon extract to serve as a reference.

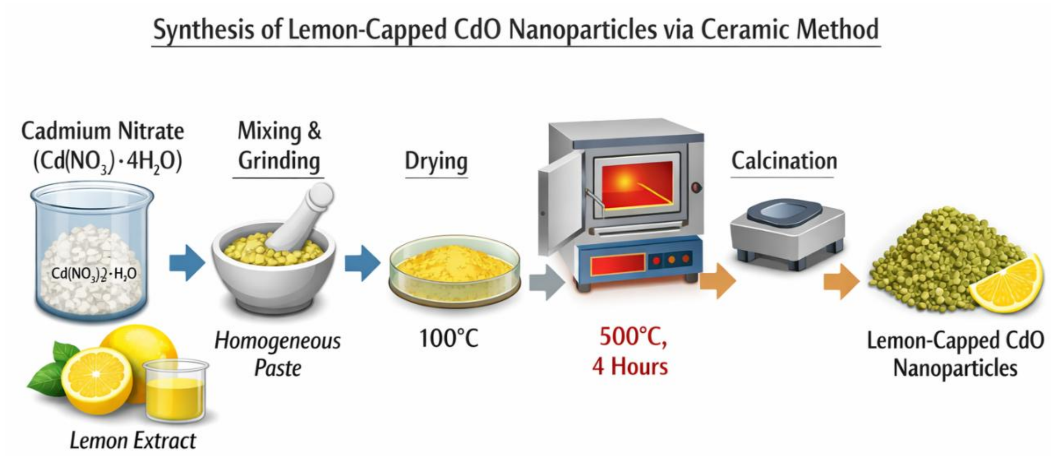

Figure 1 Schematic representation of lemon-capped CdO nanoparticle synthesis via the ceramic method

2.3 Characterization Techniques

Structural, morphological, and optical characterizations were conducted using XRD, SEM, TEM, FTIR, UV-Vis spectroscopy, and thermogravimetric analysis. Photocatalytic activity was evaluated using methylene blue as a model dye pollutant under UV-visible light irradiation. Prior to irradiation, adsorption-desorption equilibrium was established to ensure accurate evaluation of photocatalytic performance.

III. RESULTS AND DISCUSSION

X-ray diffraction patterns

X-ray diffraction patterns confirmed the formation of single-phase cubic CdO in both samples, with no detectable impurity phases as shown in **Figure 2**. The diffraction peaks of lemon-capped CdO were slightly broadened compared to uncapped CdO, indicating reduced crystallite size[6].The diffraction peaks observed at 2θ values correspond to the

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(100), (002), (101), (102), (110), (103), (200), (112), (201), and (202) planes respectively [7, 8].Using eq. (4), the lattice constant 'a' of the prepared ZnO NPs samples was determined [9];

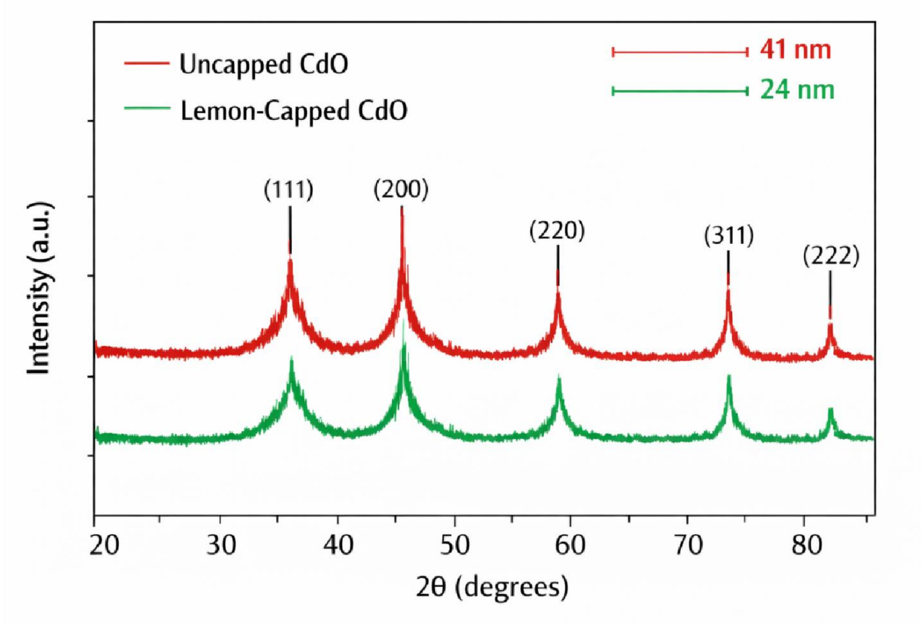

Figure 2 XRD patterns of uncapped and lemon-capped CdO nanoparticles.

$$d_{hkl} = \frac{a}{(h^2+k^2+l^2)^{1/2}} \quad (4)$$

Where (h k l) are the planes and d is the interplanar distance.The lattice strain is determined by (6) [10];

$$\varepsilon = {}^{\beta s}/_{4\tan\theta} \quad (6)$$

Here, βs represents the full width at half maximum (FWHM), which indicates the broadening of the peak, and θ is the angle. Lattice strain (ε) generally increases with diffraction angle (2θ), varying from 0.51×10^{-3} to 1.33×10^{-3}. Calculations using the Scherrer equation showed that lemon capping effectively reduced crystallite size by approximately 40%, which can be attributed to the growth-inhibiting effect of lemon-derived organic molecules during thermal treatment. The reduced dislocation density in lemon-capped CdO further indicates improved crystal quality and structural stability[11].

Morphological analysis

Morphological analysis using SEM revealed that uncapped CdO nanoparticles formed dense, irregular agglomerates due to uncontrolled grain growth during calcination. In contrast, lemon-capped CdO exhibited relatively uniform, loosely packed nanoparticles with reduced agglomeration as shown in **Figure 3**[4]. TEM analysis confirmed nanoscale particle sizes in the range of 22-28 nm for lemon-capped CdO, consistent with XRD results. The improved dispersion is attributed to the presence of organic functional groups that prevent particle coalescence[5].

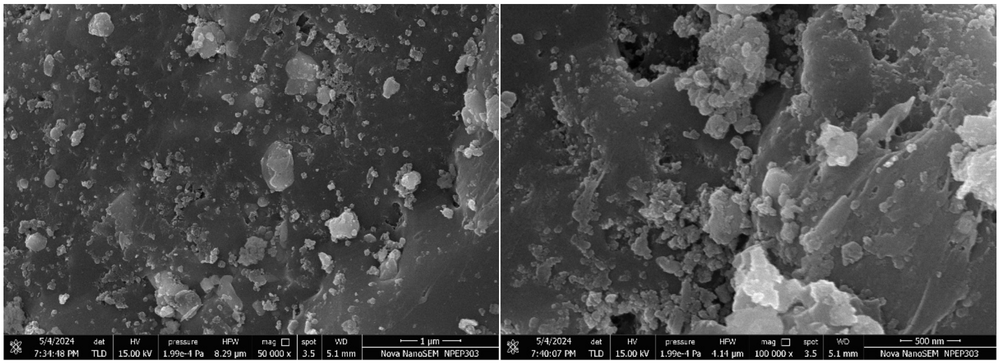

Figure 3 SEM images of uncapped and capped CdO nanocatalyst

FTIR spectra

FTIR spectra provided evidence of surface functionalization in lemon-capped CdO nanoparticles. In addition to characteristic Cd-O vibrations below 600 cm^{-1}, capped samples exhibited absorption bands associated with hydroxyl and carboxyl groups[12]. These functional groups increase surface hydrophilicity and enhance adsorption of dye molecules, thereby improving photocatalytic efficiency[13][31].

UV-Vis absorption spectra

UV-Vis absorption spectra demonstrated enhanced visible-light absorption for lemon-capped CdO. The absorption edge shifted toward longer wavelengths, and Tauc plot analysis revealed bandgap narrowing from 2.42 eV to 2.21 eV. This reduction in bandgap energy facilitates more efficient utilization of incident light and promotes charge carrier generation under visible irradiation[14].

Photocatalytic studies

Photocatalytic studies showed that lemon-capped CdO achieved approximately 95% degradation of methylene blue within 90 minutes, whereas uncapped CdO achieved only about 82% under identical conditions. The degradation followed pseudo-first-order kinetics, with the rate constant of lemon-capped CdO being significantly higher[12, 15, 16]. The enhanced photocatalytic performance can be attributed to reduced crystallite size, increased surface hydroxyl groups, improved adsorption of dye molecules, and suppressed electron-hole recombination.The photocatalytic mechanism involves the generation of electron-hole pairs upon light irradiation[17].

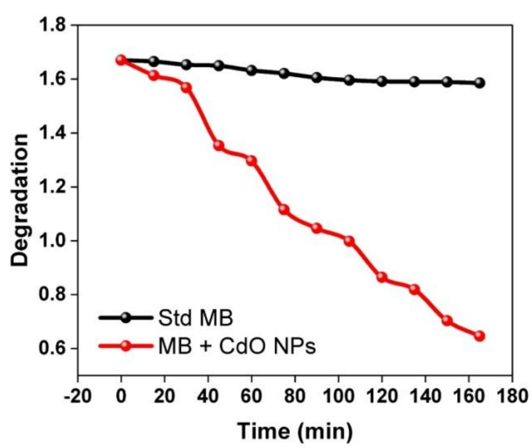

Figure 4 Photocatalytic degradation of methylene blue under UV light

Surface hydroxyl groups facilitate the formation of highly reactive hydroxyl radicals, while photogenerated electrons interact with dissolved oxygen to produce superoxide radicals. These reactive oxygen species oxidize dye molecules into harmless end products such as carbon dioxide and water[18, 19].

IV. CONCLUSIONS

Lemon-capped CdO nanoparticles were successfully synthesized via a ceramic method combined with green surface functionalization. Structural analysis confirmed phase-pure cubic CdO with a significant reduction in crystallite size due to lemon extract capping. Morphological studies revealed improved particle dispersion and reduced agglomeration, while FTIR analysis confirmed the presence of bio-derived functional groups on the nanoparticle surface. Optical investigations showed enhanced visible-light absorption and bandgap narrowing, contributing to improved photocatalytic performance. The lemon-capped CdO nanoparticles exhibited superior photocatalytic degradation of methylene blue compared to uncapped CdO, following pseudo-first-order kinetics. The enhanced activity is attributed to synergistic effects of reduced particle size, increased surface hydroxylation, improved adsorption capacity, and suppressed charge carrier recombination. This study demonstrates that integrating green capping agents with the ceramic synthesis route is an effective strategy for developing efficient and environmentally friendly photocatalysts for wastewater treatment applications.

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