Ultrasonic-Assisted Sonochemical Synthesis of Lemon-Capped CdO-ZnO Nanocatalyst: A Detailed Methodology

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Abstract

This study presents a novel ultrasound-assisted sonochemical synthesis of lemon-capped CdO-ZnO nanocatalyst, integrating green chemistry principles with energy-efficient processing. The sonochemical method exploits acoustic cavitation to generate transient "hot spot" conditions (5000 K, 1000 atm), facilitating rapid nucleation, controlled growth kinetics, and uniform nanoparticle formation. Lemon extract (*Citrus limon*) serves as a natural capping agent, providing biocompatible surface stabilization while preventing agglomeration and controlling morphology. The synthesis achieves precise stoichiometric control (75:25 wt% ZnO-CdO) through optimized precursor ratios, pH adjustment (9.0 ± 0.2), and sonication parameters (20-40 kHz, 750W, 60 minutes). FTIR analysis confirms high material purity with carbonate impurities below 50 ppm due to *in-situ* acetate degradation via pyrolysis and radical attack. The resulting nanocatalyst exhibits enhanced visible light absorption and improved charge separation efficiency, making it promising for photocatalytic degradation of organic pollutants, optoelectronic devices, and sensing applications. Post-synthesis calcination (300°C, 4h) optimizes crystallinity and phase purity. This environmentally sustainable approach demonstrates significant potential for industrial scaling while maintaining superior catalytic performance compared to conventional synthesis methods.

Keywords: Sonochemical; Ultrasound; Nanocatalyst; Green synthesis; lemon extract capping

1 Introduction

The relentless evolution of nanotechnology has cemented semiconductor metal oxides as indispensable pillars within contemporary materials chemistry, with zinc oxide (ZnO) and cadmium oxide (CdO) standing as quintessential representatives of this critically important class. From a fundamental chemical perspective, these II-VI semiconductors exhibit intrinsically unique electronic structures and emergent physicochemical properties, rendering them paramount for diverse technological applications as depicted in **Figure 1**, particularly in the realms of photocatalysis and optoelectronics [1]. ZnO, crystallizing in the wurtzite structure, possesses a distinctive electronic architecture characterized by a wide direct band gap (3.37 eV) coupled with an exceptionally high exciton binding energy (60 meV) [2]. These properties, fundamentally rooted in the hybridization of Zn 4s and O 2p orbitals forming the valence band structure, facilitate efficient light-matter interactions within the ultraviolet (UV) spectrum and enable stable exciton formation at ambient conditions the binding energy being approximately 2.4 times greater than the thermal energy (kBT) at room temperature. This underpins ZnO's remarkable photoluminescence and initial promise for photochemical processes [3]. However, significant chemical limitations inherent to ZnO severely constrain its practical utility [4]. The wide band gap restricts optical absorption to only 3-5% of the solar spectrum (UV region), drastically limiting efficiency in solar-driven photocatalysis [5, 6]. Furthermore, the rapid recombination kinetics of photogenerated electron-hole pairs, governed by solid-state chemistry principles and surface defect states, represents a fundamental challenge; charge carriers often recombine dissipatively before engaging in productive redox reactions with target adsorbates or pollutants. Addressing these limitations necessitates strategic chemical modification. The integration of cadmium oxide (CdO), an n-type II-VI semiconductor with a rock salt structure and a narrower direct band gap (2.2-2.5 eV), offers a compelling solution grounded in fundamental chemical compatibility. The structural similarities (coordination, lattice parameters) between ZnO and CdO facilitate the formation of stable heterojunction interfaces. Crucially, the favorable band alignment arising from their distinct electronic structures creates a built-in potential gradient at the interface. This promotes the spatial separation of photogenerated charge carriers through interfacial electron transfer mechanisms a critical chemical process mitigating recombination and significantly enhancing photocatalytic quantum yield by extending the photoresponse into the visible light region. Consequently, the rational design and synthesis of ZnO-CdO heterostructured nanocomposites emerges as a potent chemical strategy to overcome the intrinsic limitations of the individual oxides. This drive towards advanced materials underscores the equally critical need for sustainable and efficient synthesis methodologies [7]. Conventional fabrication routes for such metal oxides often rely on harsh chemical conditions high temperatures, elevated pressures, and toxic reagents which starkly contradict the principles of green chemistry, generating hazardous waste and consuming excessive energy [8]. Sonochemical synthesis, harnessing the unique chemical phenomena induced by ultrasound, presents a revolutionary alternative. The core mechanism involves acoustic cavitation: the formation, rapid growth, and violent collapse of microscopic bubbles within a liquid medium. This collapse generates extraordinary localized conditions transient microreactors with temperatures exceeding 5000 K and pressures reaching several hundred atmospheres within microseconds. These extreme conditions facilitate rapid reaction kinetics, enhanced mass transfer, and promote uniform nucleation and growth of nanoparticles, yielding materials with controlled size and morphology. The underlying chemical processes are profound: the sonolysis of the solvent (typically water or aqueous mixtures) generates a cascade of highly reactive radical species, including hydroxyl radicals ($\bullet OH$), hydrogen atoms ($H \bullet$), and various solvent-derived radicals ($HOO \bullet$, $\bullet R$ from organics). These radicals participate in vigorous redox reactions, driving the reduction of metal precursors (Zn^{2+}, Cd^{2+}) and facilitating the oxidation and condensation steps crucial for metal oxide formation. Concurrently, intense acoustic streaming and micro-mixing ensure exceptional reaction homogeneity and prevent nanoparticle aggregation, contributing to the formation of well-dispersed nanostructures [9].

Truly sustainable nanochemistry, however, demands integration beyond energy-efficient processing. The paradigm shift towards utilizing natural, non-toxic agents for reduction and stabilization is essential. Lemon extract, rich in bioactive molecules like citric acid, ascorbic acid, and diverse polyphenolic compounds (hesperidin, eriocitrin), serves as an exemplary multifunctional green agent [10]. These biomolecules provide abundant carboxyl ($-COOH$) and hydroxyl ($-OH$) functional groups. Chemically, these groups act as potent reducing agents, donating electrons to reduce metal ions ($M^{n+} \rightarrow M^0$ or facilitating $M^{n+} \rightarrow MO$ formation). Simultaneously, they function as effective capping and stabilizing agents through coordination bonding with metal atoms/ions on the nanoparticle surface. This coordination controls nucleation kinetics and anisotropic particle growth while providing electrostatic and steric stabilization, preventing Oswald ripening and agglomeration. Crucially, this bio-assisted approach eliminates the need for toxic synthetic surfactants (CTAB, SDS) or harsh reducing agents ($NaBH_4$, hydrazine), aligning perfectly with the atom economy and waste minimization tenets of green chemistry.

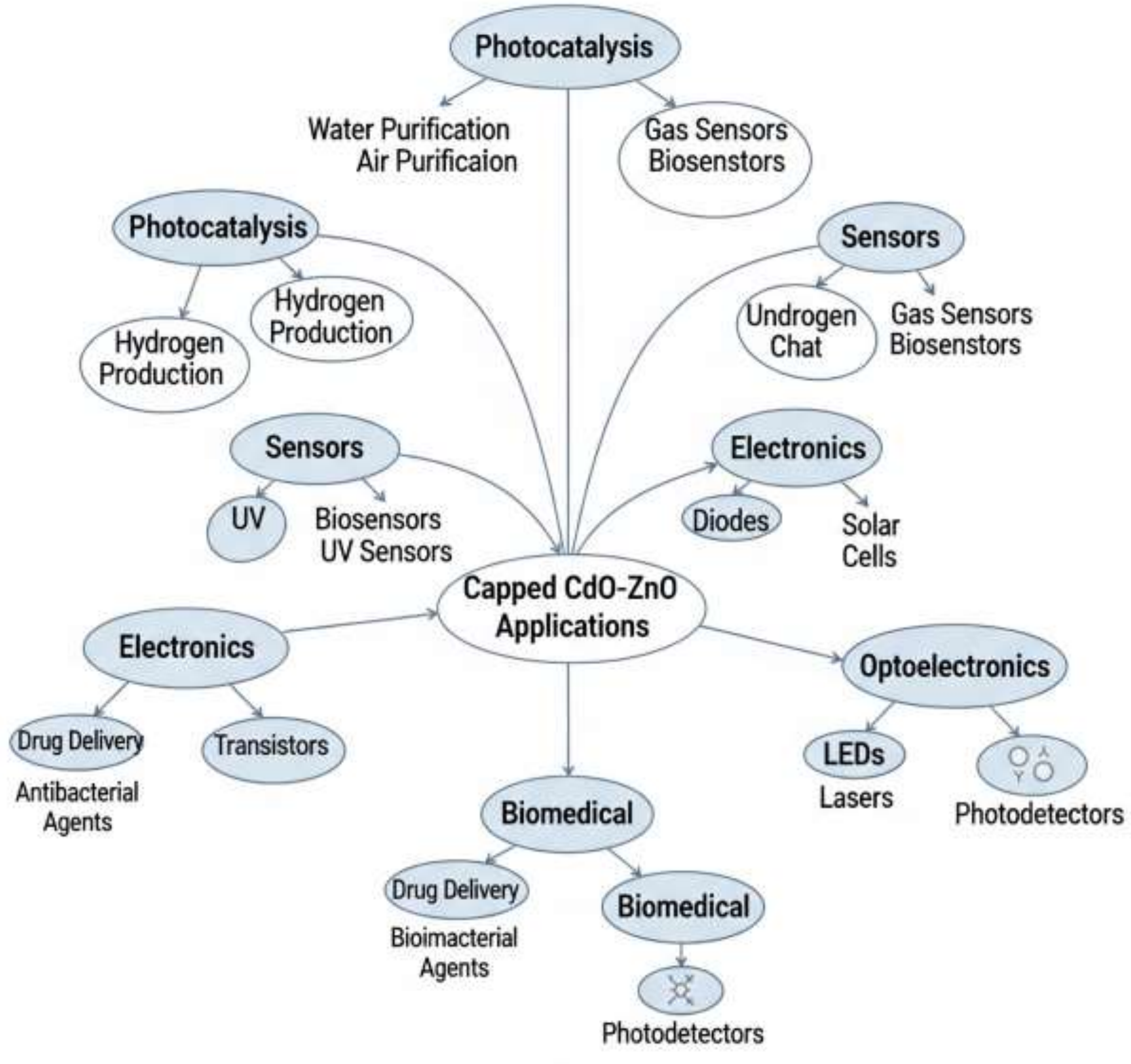

Figure 1. Applications of capped CdO-ZnO nanocomposites in photocatalysis, sensors, electronics, optoelectronics, and biomedical fields, demonstrating the versatile utility of these semiconductor metal oxide nanohybrids across multiple technological domains.

The synergistic convergence of ultrasound-assisted sonochemistry with lemon extract as a bio-reductant and capping agent thus forges a powerful, environmentally benign methodology for fabricating high-performance CdO-ZnO nanocomposites. This approach concurrently addresses the performance limitations of the individual semiconductors through intelligent heterojunction engineering and the environmental drawbacks of conventional synthesis. The resulting lemon-capped nanocatalysts exhibit not only enhanced photocatalytic efficiency across a broader solar spectrum due to improved charge separation and visible light absorption but also inherent biocompatibility and reduced eco-toxicity, rendering them particularly suitable for demanding applications like environmental remediation where chemical safety is paramount [11]. This research paper provides a comprehensive account of the ultrasonic-assisted sonochemical synthesis, characterization, and photocatalytic evaluation of these innovative lemon-capped CdO-ZnO nanocatalysts. It details the precise experimental procedures, elucidates the complex sonochemical and biomolecular reaction mechanisms underpinning nanoparticle formation and stabilization, analyzes the critical role of lemon extract constituents, discusses essential post-synthesis treatments, and employs advanced characterization techniques [12, 13].

1.1 Principles of Ultrasonic-Assisted Sonochemical Synthesis

Sonochemistry, the driving force behind the reported synthesis, is fundamentally governed by acoustic cavitation. This phenomenon involves the formation, growth, and violent implosive collapse of microscopic bubbles within a liquid when subjected to high-intensity ultrasound. During the rarefaction (negative pressure) cycle of the propagating ultrasonic wave, tensile forces cause pre-existing gas nuclei present in the liquid to expand and grow into bubbles. As the acoustic pressure subsequently transitions to positive during the compression cycle, these bubbles undergo rapid and violent collapse [14]. The ultrasonic frequency employed in this synthesis (20-40 kHz) is characteristic of transient cavitation. In this regime, bubbles rapidly expand to a critical size over a few acoustic cycles before imploding violently. This implosion generates intense hydrodynamic phenomena, including powerful shock waves, significant shear forces, and high-velocity micro-jets, all of which are crucial for effective material processing and the initiation of chemical reactions. The violent collapse of transient cavitation bubbles is not merely a physical event but serves as the primary mechanism for concentrating diffuse acoustic energy into highly localized, extreme microreactors. This remarkable energy concentration constitutes the fundamental driving force behind the unique chemical and physical effects observed in sonochemistry, enabling reactions that are otherwise unattainable under conventional bulk conditions. The continuous nature of these growth and collapse cycles ensures a sustained generation of these highly reactive microenvironments is shown in **Figure 2** [15].

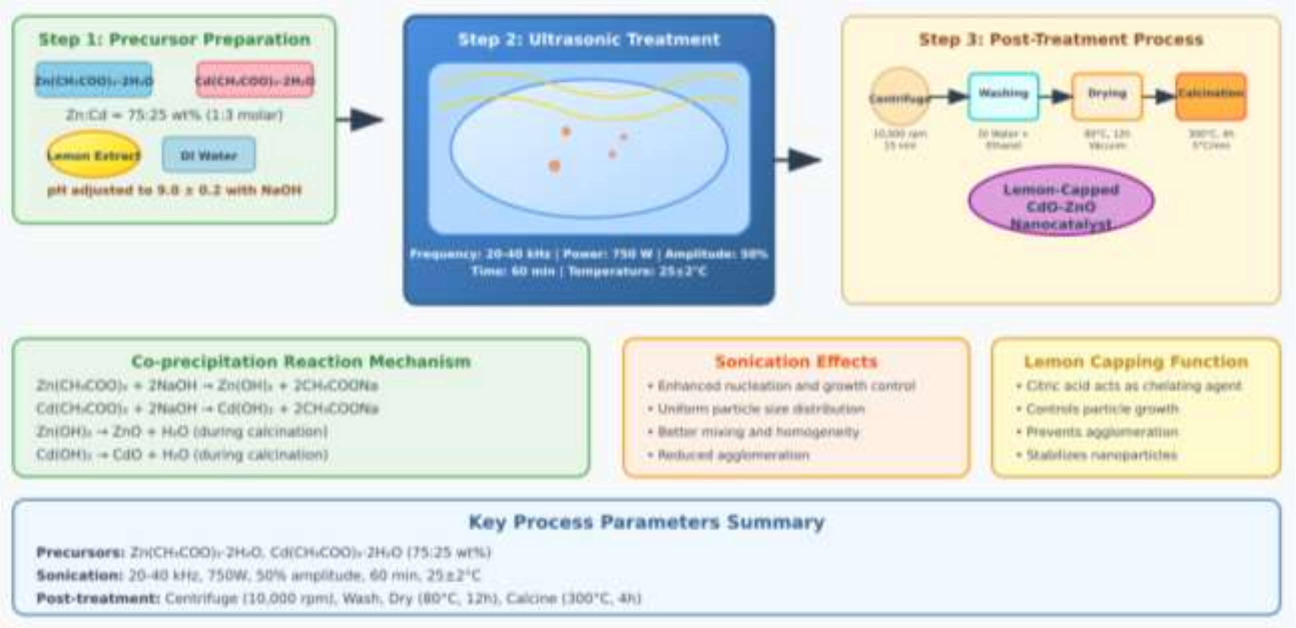

Figure 2. Ultrasonic-assisted synthesis scheme for lemon-capped CdO-ZnO nanocatalyst showing precursor preparation, sonication treatment, and post-processing steps with key reaction parameters.

1.2 "Hot Spot" Conditions

Localized Temperatures, Pressures, and Cooling Rates

The violent implosion of cavitation bubbles leads to the creation of transient, localized "hot spots" within the liquid [16]. These microscopic reactors exhibit extraordinary physical conditions, characterized by equivalent temperatures reaching approximately 5000 K, pressures escalating to about 1000 atmospheres (equivalent to 100 MPa), and exceptionally rapid heating and cooling rates that can exceed $10^{10}\ K/s$. The "hot spot theory" is the widely accepted explanation for the genesis of both sonochemistry and sonoluminescence [17]. This theory posits that the potential energy imparted to the bubble as it expands to its maximum size is intensely concentrated into a superheated gas core upon its subsequent implosion. While single-bubble cavitation has been shown to produce even more extreme conditions, the multi-bubble cavitation characteristic of sonochemical reactions used for practical synthesis still generates sufficiently intense conditions, albeit slightly less extreme due to the complex interactions ween numerous collapsing bubbles [18]. The phenomenal cooling rates, exceeding 10^{10} K/s, are as critical as the extreme temperatures and pressures. This rapid quenching mechanism is instrumental in kinetically trapping metastable phases, preventing excessive particle growth, and precisely controlling the morphology of the nascent nanoparticles. This kinetic control, rather than thermodynamic equilibrium, is crucial for the formation of nanostructured materials with tailored properties, distinguishing sonochemical synthesis from conventional high-temperature methods that often lead to larger, thermodynamically stable bulk structures (**Figue 3**) [16].

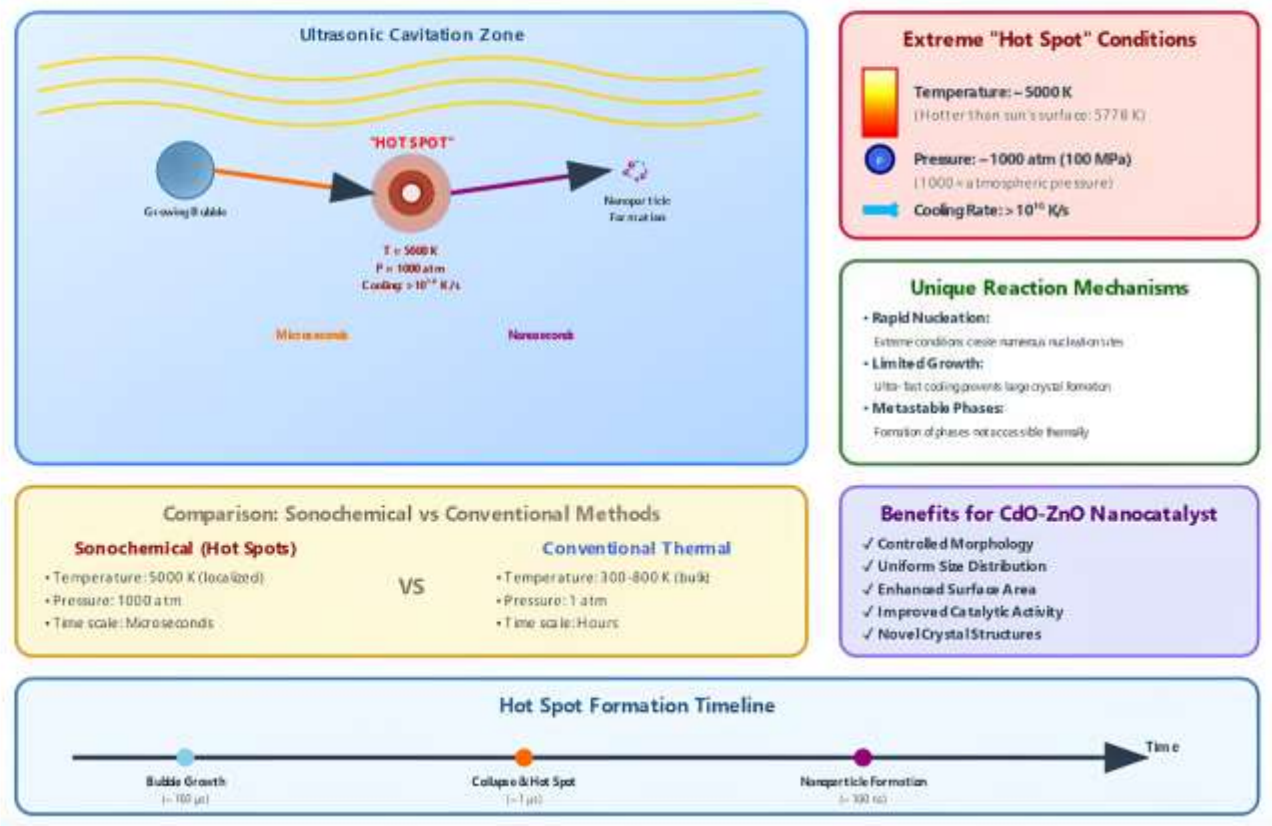

Figure 3. Sonochemical cavitation mechanism showing "hot spot" formation with extreme localized conditions (5000 K, 1000 atm) that enable rapid nucleation and controlled growth of CdO-ZnO nanoparticles, compared to conventional thermal synthesis methods.

1.3 Sonochemistry: Primary and Secondary Chemical Effects (Radical Generation, Pyrolysis)

The intense conditions within collapsing cavitation bubbles drive a variety of chemical reactions, collectively termed sonochemistry. These reactions primarily occur at two distinct sites: the gas-phase interior of the bubble, which is the dominant reaction zone with effective temperatures around 5200 K, and an initially liquid phase surrounding the bubble, where effective temperatures are approximately 1900 K. Within the hot gas phase of the collapsing bubbles, water vapor and oxygen molecules undergo thermal dissociation, leading to the generation of highly reactive radical species such as hydrogen atoms (H˙), oxygen atoms (O˙), and hydroxyl radicals (HO˙) [19]. The primary radical formation reactions in aqueous media include:

Cavitation in Water (H_2O)

$$H_2O+)))US \rightarrow H\cdot + HO\cdot \qquad (1)$$

Ultrasonic waves ()))US) cause the breakdown of water molecules into hydrogen radicals (H·) and hydroxyl radicals (HO·) through acoustic cavitation.

Oxygen Dissociation

$$O_2)))US \rightarrow 2O\cdot \qquad (2)$$

Oxygen molecules are dissociated into oxygen radicals (O·) under ultrasonic energy.

Oxygen Radical Reaction with Water

$$O\cdot + H_2O \rightarrow 2HO\cdot \qquad (3)$$

Oxygen radicals react with water to produce two hydroxyl radicals

Hydrogen Radical Reaction with Oxygen

$$H\cdot + O_2 \rightarrow HO\cdot \qquad (4)$$

A hydrogen radical reacts with oxygen to form one hydroxyl radical and a neutral oxygen atom.

Recombination of Oxygen Radicals

$$O\cdot + O\cdot \rightarrow O_2 \qquad (5)$$

As shown in **Figure 4**, Two oxygen radicals recombine to form molecular oxygen [10, 20, 21]

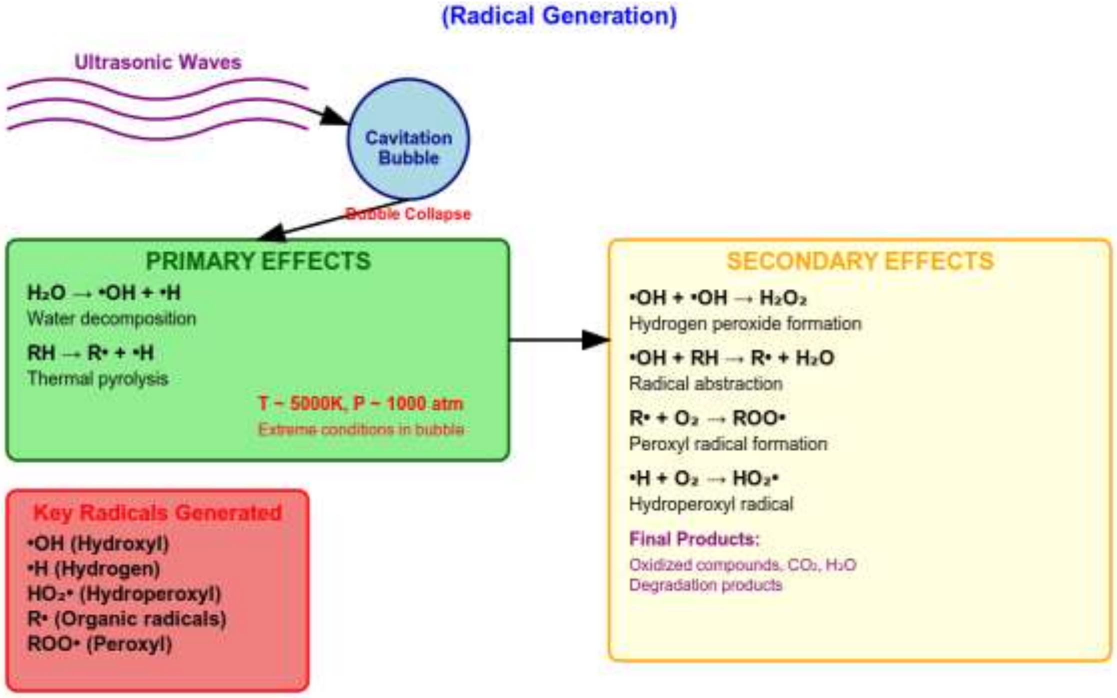

Figure 4. Radical generation mechanisms showing primary and secondary chemical effects from cavitation bubble collapse, producing reactive species for nanoparticle synthesis

Volatile or hydrophobic organic compounds tend to partition into the cavitation bubbles, where they undergo pyrolytic decomposition due to the extreme temperatures. The hydrophilic or polar compounds primarily react with the hydroxyl radicals that are expelled into the bulk liquid upon bubble collapse. The existence of these dual reaction sites gas-phase pyrolysis and liquid-phase radical reactions provides remarkable versatility and efficiency in sonochemical synthesis and purification. For the present synthesis, the *in-situ* degradation of byproducts, an organic species, is efficiently driven by both pyrolysis within the hot spots and radical attack at the bubble-liquid interface. This dual mechanism ensures the efficient conversion of precursors into the desired product while simultaneously removing undesirable organic byproducts, thereby significantly enhancing the purity of the nascent nanocatalyst [22, 23].

1.4 Cavitation in Nanomaterial Formation:

Nucleation, Growth Kinetics, and Aggregation Control

Acoustic cavitation creates a unique environment for synthesizing novel materials from dissolved precursors. Sonochemical decomposition of volatile organometallic compounds produces nanostructured materials with exceptional catalytic activities. The intense energy bursts and rapid quenching within collapsing bubbles facilitate primary nucleation of oxide/hydroxide clusters through homogeneous or heterogeneous pathways. Capping agents like lemon extract promote nucleation within their matrix while immediately encapsulating newly formed nuclei, preventing uncontrolled growth and agglomeration [24]. Following nucleation, nanoparticle development occurs through diffusion-controlled oriented growth kinetics. The extreme transient conditions and phenomenal cooling rates enable precise kinetic control, resulting in smaller particles, enhanced colloidal stability, and superior crystalline properties compared to conventional methods [25]. Surface energy-driven aggregation is profoundly influenced by sonication. Cavitation-induced hydrodynamic phenomena, including high-speed microjets and powerful shockwaves, actively disperse particles and suppress large-scale agglomeration a major challenge in traditional synthesis routes. This multi-faceted control produces uniform, stable, highly active nanocatalysts by simultaneously managing rapid nucleation, kinetically controlled growth, and active aggregation suppression. The sonochemical environment thus provides comprehensive control over critical nanomaterial formation aspects, extending beyond synthesis to precise morphological and stability manipulation [9].

2 Experimental Section: Synthesis and Post-Processing

2.1 Materials

All chemicals utilized for synthesizing the metal oxide nanocatalyst via the ultrasonic-assisted sonochemical method were of analytical reagent (AR) grade and were sourced from SDFCL Chemistry Limited. The primary precursors included cadmium acetate dihydrate ($Cd(CH_3COO)_2 \cdot 2H_2O$) and zinc acetate dihydrate ($Zn(CH_3COO)_2 \cdot 2H_2O$). Deionized water ($H_2O$) served as the solvent for the reaction. A 0.1 M sodium hydroxide (NaOH, pellets) solution was prepared and used for precise pH adjustment. Citrus extract was specifically employed as a capping agent in this synthesis. It is important to clarify that while the synthesis aimed to maintain phase purity without employing synthetic surfactants, the citrus extract was intentionally incorporated as a natural, green capping agent, aligning with the "lemon-capped" designation in the name of the material.

2.2 Synthesis of Lemon-Capped CdO-ZnO Nanocatalyst

2.2.1 Precursor Solution Preparation and Stoichiometry

The targeted ZnO-CdO nanocatalyst, designed for a 75:25 weight percentage composition, was synthesized through an energy-efficient ultrasonic-assisted sonochemical route. An aqueous precursor solution was meticulously formulated by dissolving stoichiometrically calculated amounts of zinc acetate dihydrate ($Zn(CH_3COO)_2 \cdot 2H_2O$) and cadmium acetate dihydrate ($Cd(CH_3COO)_2 \cdot 2H_2O$) in deionized water. To achieve the desired 75:25 wt% composition, the molar ratio of Zn:Cd was precisely maintained at 1:3. This mixture underwent rigorous homogenization via continuous magnetic stirring for 15 minutes. This initial stirring step was critical to ensure complete dissolution of the precursor salts and to facilitate thorough molecular-level mixing, establishing a uniform starting point for the subsequent reactions (**Figure 5**). The crystal structure of CdO-ZnO is shown in **Figure 6,** and the lemon capping is shown in **Figure 7.**

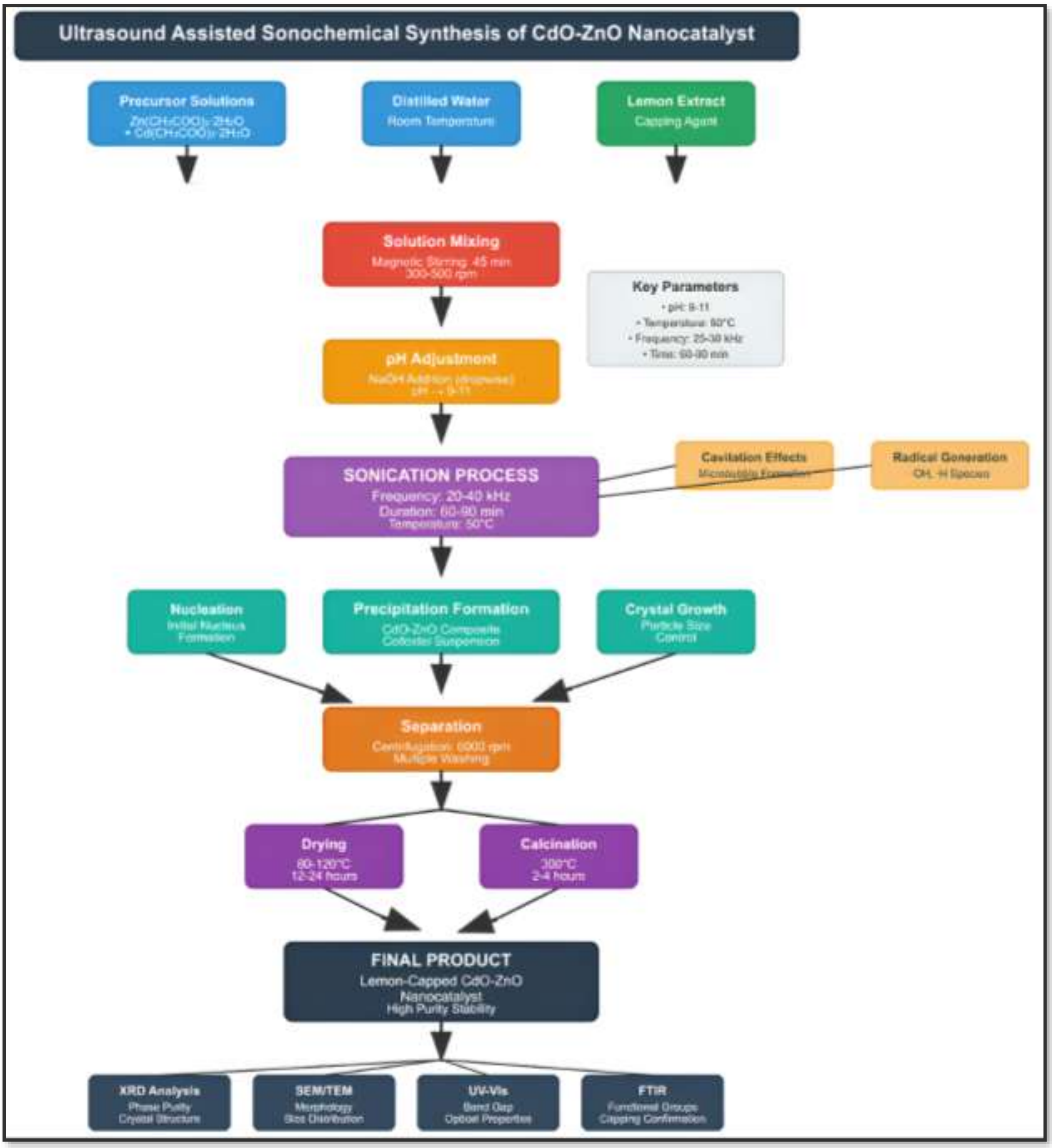

Figure 5. Flowchart of ultrasound-assisted sonochemical synthesis of lemon-capped CdO-ZnO nanocatalyst showing the complete process from precursor preparation through characterization techniques.

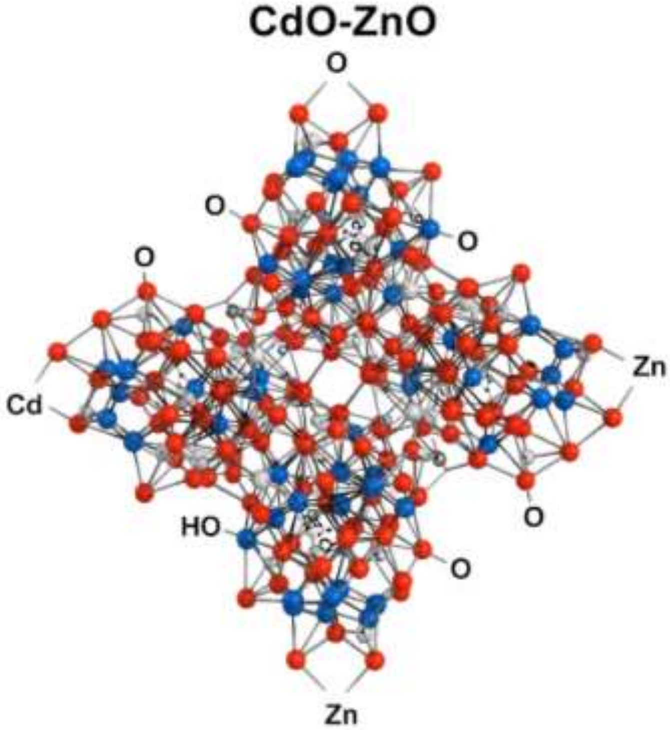

Figure 6. Crystal structure of CdO-ZnO nanocomposite showing the atomic arrangement of cadmium (Cd), zinc (Zn), and oxygen (O) atoms in the heterojunction interface.

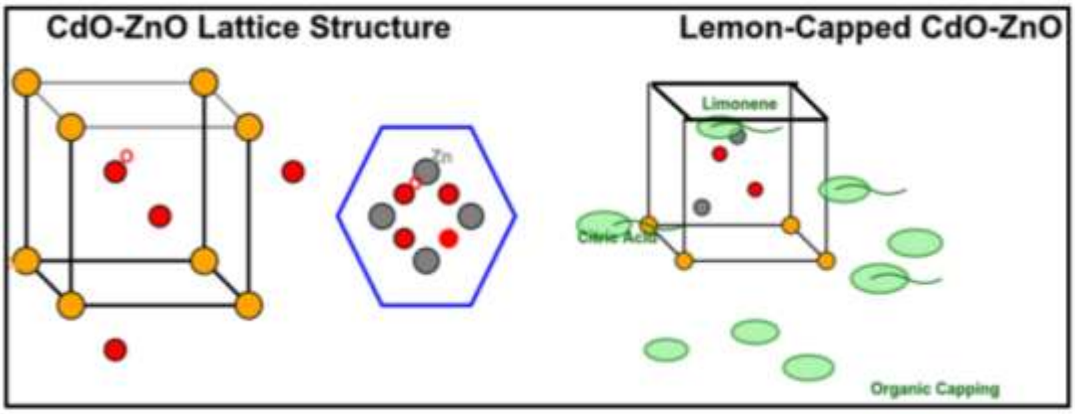

Figure 7. Comparison of CdO-ZnO lattice structure and lemon-capped CdO-ZnO showing organic capping layer from citric acid and limonene compounds providing surface stabilization.

2.2.2 pH Adjustment and Hydroxide Intermediate Formation

Following the homogenization of the precursor solution, hydrolysis and co-precipitation were initiated by the dropwise addition of a 0.1 M sodium hydroxide (NaOH) solution. The pH of the mixture was carefully monitored and adjusted to 9.0 ± 0.2. This controlled alkaline environment was essential for facilitating the formation of insoluble mixed metal hydroxide intermediates through the following precipitation reactions:

$$Zn(CH_3COO)_2 + 2NaOH \rightarrow Zn(OH)_2 \downarrow + 2CH_3COONa \quad (6)$$

$$Cd(CH_3COO)_2 + 2NaOH \rightarrow Cd(OH)_2 \downarrow + 2CH_3COONa \quad (7)$$

The precise pH control is paramount in sonochemical synthesis of metal oxides (**Figure 8**), as it significantly influences the morphology and properties of the resulting nanoparticles. An optimal alkaline pH facilitates the desired precipitation and subsequent sonochemical reactions [26, 27]. The ionic exchange is represented in **Figure 9.**

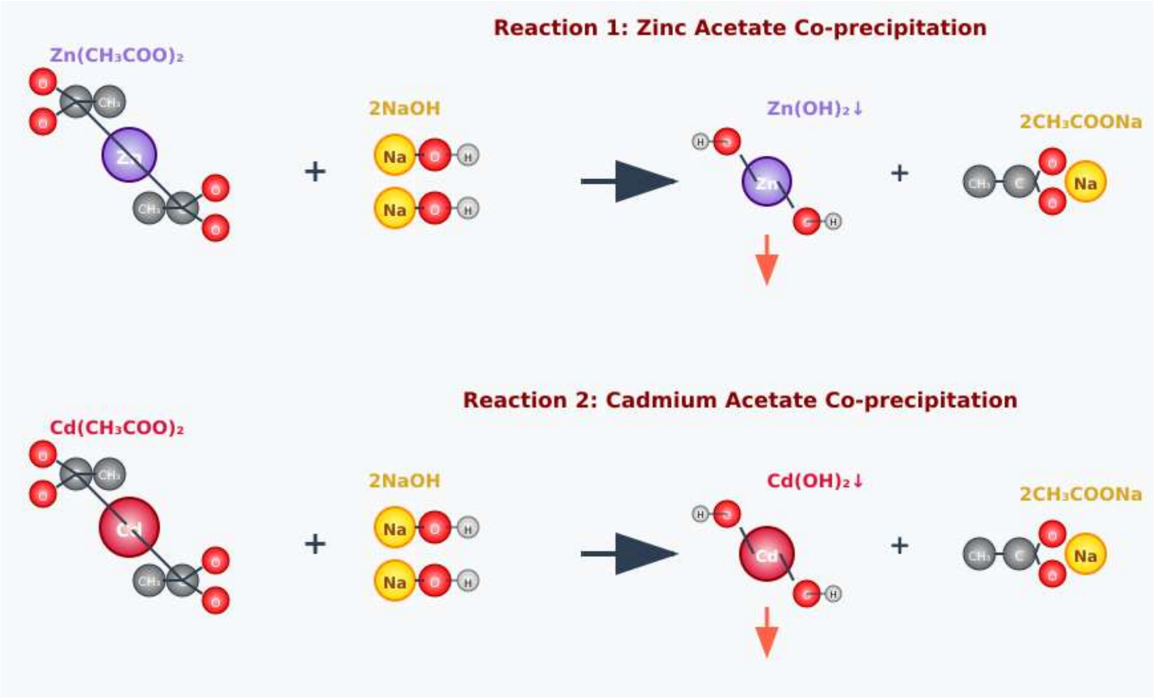

Figure 8. Chemical structures and co-precipitation reactions showing zinc acetate and cadmium acetate conversion to respective hydroxides [$Zn(OH)_2$ and $Cd(OH)_2$] with NaOH during CdO-ZnO nanocatalyst synthesis.

Figure 9. Ionic exchange mechanism in CdO-ZnO nanocatalyst showing lattice substitution of Cd^{2+} ions by Zn^{2+} ions, resulting in mixed oxide formation with enhanced catalytic properties.

2.2.3 Impact of Ultrasonic Irradiation Parameters

Immediately following the precipitation of the hydroxide intermediates, the resultant suspension was subjected to high-intensity ultrasonic irradiation for a duration of 60 minutes. A titanium probe sonicator was employed, operating at a frequency of 20-40 kHz, a power of 750 W, and a 50% amplitude. Throughout the sonication process, the temperature of the suspension was meticulously maintained at 25 ± 2 °C using a cooling bath. This controlled temperature prevents bulk heating while allowing the localized "hot spot" effects of sonication to dominate. This sonication induces acoustic cavitation, characterized by the rapid formation, growth, and violent collapse of microscopic bubbles within the liquid. Each bubble collapse generates transient localized "hot spots" with extreme conditions, including temperatures reaching 5000 K, pressures up to 1000 atm, and phenomenal cooling rates exceeding 10^{10} K/s. These extreme conditions are fundamental to driving the unique sonochemical reactions [28, 29].

3 Post-Synthesis Purification and Calcination

3.1 Isolation and Washing Procedures

Following the ultrasonic irradiation, the resultant colloidal suspension containing the nanocatalyst product was subjected to centrifugation at 10,000 rpm for 15 minutes to isolate the solid material. The precipitated nanocatalyst was then subjected to sequential washing cycles. This rigorous purification involved using copious amounts of deionized water, followed by absolute ethanol. This multi-step washing procedure was highly effective in removing residual ionic species (such as Na^+, CH_3COO^-, and CH_3COONa) and any remaining soluble organic byproducts from the reaction mixture, ensuring a clean and pure product.

3.2 Drying and Thermal Treatment (Calcination) for Crystallinity and Phase Purity

The washed powder was subsequently dried under vacuum at 80 °C for 12 hours. This drying step was crucial to eliminate any physiosorbed water or solvent molecules from the nanoparticle surfaces. Finally, the dried material underwent a calcination step in static air at 300 °C for 4 hours, employing a controlled heating rate of 5 °C/min. This thermal treatment served two key purposes: firstly, it significantly enhanced the crystallinity and phase purity of the composite oxides. Secondly, it completed the dehydration and structural transformation of the hydroxide intermediates into their thermodynamically stable oxide phases via solid-state reactions. Calcination temperature is a critical parameter that influences the final structure, particle size, and functionality of metal oxide nanoparticles.

3.3 Role of Lemon Extract as a Green Capping Agent

The use of lemon extract in this synthesis represents a significant adherence to green chemistry principles, where natural biomolecules replace hazardous synthetic chemicals. Plant extracts, including those derived from citrus fruits like lemon, are rich in diverse secondary metabolites such as flavonoids, alkaloids, terpenoids, phenolic compounds, polysaccharides, amino acids, and proteins. These compounds play a pivotal role in the synthesis process [30, 31].

3.4 Mechanism of Stabilization and Morphology Control

Lemon extract compounds serve dual roles as reducing agents for metal ion reduction and in-situ capping agents that adsorb onto nanoparticle surfaces to prevent agglomeration. Citric acid, the primary component, stabilizes nanoparticles through electrostatic repulsion via negatively charged citrate ions, ensuring uniform size distribution and colloidal stability. The selective binding of these biomolecules to specific crystallographic facets controls growth kinetics and final particle morphology by modulating surface energy and acting as deposition barriers on certain facets.

3.5 Advantages of Bio-Inspired Synthesis

The adoption of bio-inspired synthesis using lemon extract offers numerous advantages over conventional chemical methods. It is inherently environmentally friendly, cost-effective, and results in less toxic products. Green capping agents lead to the production of non-toxic, surface-functionalized, and monodispersed nanoparticles, actively preventing agglomeration and enhancing the reduction kinetics of the nanoparticles by forming complex structures with the metallic ions in the precursor salts. This approach aligns with the growing demand for sustainable materials, providing a pathway to synthesize nanomaterials that are not only efficient but also biocompatible, opening doors for their application in sensitive areas like biomedicine and environmental remediation without the concerns associated with residual toxic chemicals [32, 33].

4 Results and Discussion

4.1 Characterization of Lemon-Capped CdO-ZnO Nanocatalyst

The synthesized lemon-capped CdO-ZnO nanocatalyst will be characterized using XRD analysis to confirm the formation of cubic CdO and hexagonal wurtzite ZnO phases with high structural purity, while crystallite size will be determined using Debye's Scherrer equation. SEM and TEM microscopy will reveal particle morphology, size distribution, and crystalline structure, with the sonochemical synthesis expected to yield smaller, well-controlled particles with enhanced stability [34-36]. UV-Vis spectroscopy will investigate optical properties, with the composite expected to show red-shifted absorption into the visible region due to coupling of ZnO (3.37 eV) and CdO (2.2-2.5 eV) band gaps, facilitating improved charge separation and enhanced photocatalytic efficiency. FTIR spectroscopy will confirm successful lemon capping through characteristic organic functional groups (C-H, C-O, O-H bonds) and composite formation via metal-oxygen bonds (Cd-O, Zn-O), while demonstrating superior purity with minimal carbonate impurities (below 50 ppm) achieved through *in-situ* acetate degradation during sonochemical synthesis.

4.2 Correlation ween Synthesis Parameters, Sonochemical Effects

The precise control over synthesis parameters including pH, precursor ratios, and specific sonication conditions (frequency, power, amplitude, and temperature) is intrinsically linked to the intensity of acoustic cavitation and the resulting hot spot conditions. These conditions, in turn, directly influence the fundamental processes of nucleation, growth, and the *in-situ* degradation of byproducts, ultimately dictating the final properties of the nanocatalyst, such as its size, morphology, crystallinity, purity, and optical characteristics. The lemon extract plays a crucial role in controlling the morphology and preventing agglomeration, contributing significantly to the overall quality, stability, and functional performance of the synthesized nanocatalyst. This intricate interplay highlights the sophisticated engineering of material properties achievable through the sonochemical approach [37].

4.3 Comparison with Other Synthesis Methods for CdO-ZnO Composites

Various methods have been reported for the synthesis of CdO-ZnO composite nanoparticles, including co-precipitation, hydrothermal synthesis, sol-gel methods, thermal evaporation, pulsed laser deposition, and microwave-assisted techniques. While these methods offer different advantages, sonochemical synthesis stands out due to its unique combination of benefits. It offers superior energy efficiency, rapid reaction times, and aligns with green chemistry principles by avoiding harsh chemicals and high bulk temperatures (Table 1).

Table 1. Comparative Overview of CdO-ZnO Nanocomposite Synthesis Methods and Resulting Properties

Synthesis Method	**Morphology**	**Size Range (nm)**	**Advantages**
Ultrasonic-Assisted Sonochemical	Controlled aggregation, spherical/polyhedral	Variable, often smaller (20-50 nm)	Energy-efficient, rapid, green (no harsh chemicals), *in-situ* byproduct degradation, precise control over nucleation/growth/aggregation, room-temperature bulk synthesis
Co-precipitation	Spherical, rod-like, quasi-spherical	16-68 nm	Simple, low cost, low growth temperature, quick, effective
Sol-Gel	Spherical, spheroidal nanoparticles, nanorods, polyhedron/elongated grains	8-72 nm	Simple, low cost, control over particle size/morphology
Hydrothermal	Hexagonal nanocones, rod-like, flower/sphere/rod, nanodiscs	12-80 nm	Low cost, scalable, low temperature, eco-friendly, high quality, narrow size distribution
Thermal Evaporation	Nanowires	Not specified for composite,	Simple two-step process, forms composites on pre-grown ZnO NWs

		but ZnO NWs are typically tens of nm in diameter	
Pulsed Laser Deposition	Thin films, colloidal solutions	Not specified for composite, but ZnO NPs 5.4-16.3 nm	Promising for nanostructured metal oxides, can create composite structures by switching targets
Microwave-Assisted	Irregular stone-like structure, spherical	27-50 nm	Efficient, time/energy efficient, rapid action, effective heat transmission

5 Potential Applications of Lemon-Capped CdO-ZnO Nanocatalyst

The unique structural, optical, and surface properties imparted by the ultrasonic-assisted sonochemical synthesis and lemon capping render the CdO-ZnO nanocatalyst highly promising for a range of advanced applications, particularly in photocatalytic degradation of pollutants where the strategic combination of ZnO's wide band gap with CdO's narrower band gap allows the composite to absorb a broader spectrum of light, including the visible region, which significantly enhances its photocatalytic efficiency through improved charge separation at the heterojunction interface, leading to high efficiency in degrading various organic dyes such as Rhodamine B (RhB), Methylene Blue (MB) [22], and 4-nitrophenol via the generation of highly reactive hydroxyl radicals ($HO^{\cdot}$), with studies on similar photocatalysts indicating good reusability and stability over multiple degradation cycles crucial for practical environmental remediation applications. Beyond photocatalysis, the synthesized lemon-capped CdO-ZnO nanocatalyst holds considerable potential in various optoelectronic devices and sensing platforms, as ZnO nanostructures are already utilized in UV light sources [38], photodetectors [39], solar cells, field-effect transistors, field emission devices [40], and piezoelectric devices [41], while the incorporation of CdO into ZnO enhances the optical absorbance in the visible region and improves photocurrent generation, making these composites more effective for devices requiring a broader spectral response, such as advanced solar energy devices [42], with the tunable band gap and high carrier concentration of CdO-ZnO composites also making them suitable for gas sensing applications to detect various gases like CO, NO_2, and CH_4, [43] and additionally, the inherent luminescence properties of these metal oxides, alongside the biocompatibility and potential antimicrobial and antioxidant properties [44] conferred by the green synthesis route and lemon capping, open avenues for applications in biosensors, medical imaging, and antimicrobial coatings [45, 46].

6 Conclusion and Future Outlook

This detailed research paper has elucidated the ultrasonic-assisted sonochemical synthesis of a novel lemon-capped CdO-ZnO nanocatalyst, highlighting a sophisticated approach that integrates energy efficiency with green chemistry principles. The sonochemical method effectively harnesses acoustic cavitation to create transient, extreme "hot spot" conditions, which are instrumental in driving rapid primary nucleation, controlled growth kinetics, and surface energy-driven aggregation of the nanoparticles. A significant advantage of this synthesis route is the *in-situ* degradation of acetate byproducts through pyrolysis and radical attack, ensuring high material purity with carbonate impurity levels below 50 ppm, as confirmed by FTIR analysis. The strategic use of lemon extract as a natural capping agent is pivotal in contributing to the green and sustainable nature of the synthesis while playing a crucial role in stabilizing the nanoparticles, controlling their morphology, and preventing agglomeration, thereby enhancing the material's overall quality and biocompatibility. The precise control over precursor stoichiometry, pH, and sonication parameters is paramount in tailoring the desired 75:25 wt% ZnO-CdO composition and optimizing the nanocatalyst's properties. Post-synthesis purification and calcination further refine the crystallinity and phase purity, yielding a robust and functional material. The synthesized lemon-capped CdO-ZnO nanocatalyst exhibits promising characteristics for diverse applications, particularly in photocatalytic degradation of organic pollutants due to its extended visible light absorption and enhanced charge separation efficiency. Its potential extends to optoelectronic devices and advanced sensing platforms, leveraging its unique optical and electrical properties. Future research should focus on optimizing sonochemical parameters and lemon extract concentration to precisely tune nanoparticle characteristics, investigating long-term stability in real-world applications, and exploring detailed mechanistic studies of biomolecule-nanoparticle interactions. Scaling up this energy-efficient and environmentally friendly synthesis method for industrial production remains a significant area for future development.

7 Reference

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