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Effect of Glycine and Citric Acid Fuels on Thermochemical Profiles in ZnO Nanoparticle Combustion Synthesis

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ABSTRACT

This study explores the effect of fuel type and combustion parameters on the synthesis efficiency and material characteristics of zinc-based nano metal oxides produced via the solution combustion process (SCP). Glycine and citric acid were used as organic fuels to drive redox reactions with zinc nitrate acting as the oxidizer. A systematic evaluation of thermal behavior, combustion kinetics, and fuel-to-oxidizer ratios (Φ) was conducted to assess their influence on combustion temperature, particle morphology. Characterization techniques such as flame analysis, X-ray diffraction (XRD), scanning electron microscopy (SEM), and UV-Visible spectroscopy were employed to investigate crystallinity, particle size distribution, and the overall effectiveness of each fuel. The results demonstrate that the choice of fuel significantly impacts flame temperature and the exothermic nature of the reaction, thereby affecting the structural and morphological attributes of the resulting ZnO nanoparticles. Combustion with glycine resulted in a highly exothermic and rapid reaction, producing finer and more porous particles, whereas citric acid facilitated a slower, more uniform combustion, yielding nanoparticles with more consistent morphology. These findings highlight the pivotal role of fuel chemistry in optimizing material properties and improving energy efficiency in SCP-based nanomaterial synthesis.

Keywords: Metal oxide, SCS, Nano particles, exothermic fuels, organic fuels

INTRODUCTION

In the field of materials science, the synthesis of metal oxide nanoparticles has become a cornerstone for developing advanced functional materials with wide-ranging applications in electronics, catalysis, optoelectronics, environmental remediation, and biomedicine. Among the various synthesis strategies available—such as sol-gel, hydrothermal, co-precipitation, and microwave-assisted methods—Solution Combustion Synthesis (SCS) stands out due to its operational simplicity, low energy consumption, scalability, and the ability to produce homogeneous and nanocrystalline powders in a short reaction time [1,2]. SCS is a redox-based process that involves an exothermic reaction between a metal precursor, often a nitrate salt, and an organic fuel, typically an amino acid or polycarboxylic acid. The process initiates upon heating, leading to self-sustained combustion and the formation of oxide products. The thermochemical behavior of the reaction is highly dependent on the type of fuel used, its stoichiometry, and its interaction with the metal precursor [3]. Among a variety of fuels explored, glycine and citric acid are particularly prominent due to their dual roles as both fuel and complexing agents, which contribute to a homogeneous reaction medium and enhance control over particle morphology and size.

Glycine (NH_2CH_2COOH), being the simplest amino acid, is known for its rapid ignition and highly exothermic combustion due to the presence of both amino and carboxylic groups. These functional groups facilitate the coordination with metal ions and promote redox reactions with metal nitrates, yielding fine oxide powders with high surface area and porosity [4]. In contrast, citric acid ($C_6H_8O_7$) possesses three carboxylic acid groups and one hydroxyl group, making it a stronger chelating agent. Its combustion proceeds more gradually, often resulting in better crystallinity and lower residual carbon content in the final product [5].

Zinc oxide (ZnO) is a well-established II-VI semiconductor material with a direct wide bandgap (~3.37 eV) and large exciton binding energy (~60 meV), which makes it suitable for a broad spectrum of applications, including UV light emitters, gas sensors, varistors, piezoelectric devices, and photocatalysts [6]. Its nanoscale form further enhances these properties due to increased surface-to-volume ratio and quantum size effects. Therefore, controlling the morphology, size, and surface structure of ZnO nanoparticles is of paramount importance. The choice of fuel in the SCS process has a decisive role in determining these attributes, as it directly influences the combustion temperature, gas evolution, reaction enthalpy, and phase formation [7].

Thermochemical analysis of combustion reactions is crucial for understanding the underlying reaction mechanism and optimizing the synthesis process. Techniques such as Thermogravimetric Analysis (TGA), Differential Thermal Analysis (DTA), and Differential Scanning Calorimetry (DSC) provide insights into the thermal stability, mass loss behavior, and exothermicity of the fuel-oxidizer system. Additionally, Fourier Transform Infrared Spectroscopy (FTIR) and X-ray Diffraction (XRD) studies aid in confirming the bonding behavior and phase purity of the synthesized product. Several studies have demonstrated that fuels like glycine tend to produce highly porous and smaller nanoparticles, whereas citric acid often yields denser and more uniform morphologies due to its higher complexation and slower combustion kinetics [8,9]. Moreover, the fuel-to-oxidizer ratio (φ), often expressed in terms of the equivalence ratio, significantly affects the combustion outcome. A fuel-lean mixture generally leads to higher combustion temperatures but may result in incomplete reactions or undesired secondary phases. Conversely, a fuel-rich mixture can create a more reducing environment, impacting the oxidation state and morphology of the final product. Understanding these thermochemical dynamics is essential for tailoring the ZnO properties for specific end-use applications [10].

In this study, we aim to conduct a comparative thermochemical analysis of glycine and citric acid-fueled SCS routes for the synthesis of zinc-based nano oxides. By examining thermal decomposition behavior, reaction enthalpies, evolved gas species, and resulting nanoparticle characteristics, the work seeks to elucidate how different fuel types influence combustion behavior and product properties. Additionally, this research contributes to the broader understanding of green and energy-efficient synthesis routes for metal oxides, aligning with the principles of sustainable chemistry and materials engineering.

The significance of this work lies in its potential to offer a comprehensive understanding of fuel-dependent combustion mechanisms and their correlation with material characteristics. The outcomes are expected to facilitate better design strategies for nanomaterial synthesis using thermally activated, low-cost, and scalable combustion processes.

Materials & Methods:

A structured approach of synthesis of zinc based nano metal oxides through Solution Combustion Synthesis (SCS) is performed to achieve consistency and reproducibility along with high product quality. First, precursor solutions containing zinc nitrate are replaced by the oxidizer and a selected fuel : citric acid, glycine are used. The composition is established, so that fuel and oxidizer are dissolved in deionized water in precise molar ratios, in order to keep a controlled fuel to oxidizer balance.

For approximately 30 minutes, the solution is stirred using a magnetic stirrer so that homogeneity and proper complexation of the metal ions with the fuel molecules occurs. After obtaining a uniform solution, the solution is transferred to a ceramic crucible and placed inside a preheated muffle furnace, which is itself set at 500°C [11]. On the other hand claimed that high temperature results into automatic combustion reaction by undergoing the exothermic redox interaction between the fuel and oxidizer. The reaction is rapid and self sustained, and the flame resulting is intense and is followed by large volumes of gas by products such as CO_2, NH_3 and N_2. These gases contribute to porosity of the final product in two ways, first they contribute to voids in forming metal oxide network and second they inhibit the formation of crystals in the oxide by limiting oxygen transport. Once the combustion reaction is completed in less than minutes it leaves a voluminous highly porous zinc based metal oxide powder.

Once the reaction completes, the synthesized nanoparticles are cooled to room temperature naturally. The ground powder is broken down into a fine uniform material using a mortar and pestle in order to break up any agglomerates. The nanoparticles are then calcined at 600°C for 1 hour in order to eliminate any residual organic matter remaining and to improve the crystallinity of the nanoparticles. After being collected, stored in airtight containers, their final product is prepared for characterization.

The metal precursor ($Zn(NO_3)_2{\cdot}6H_2O$) is a zinc nitrate hexahydrate (From: Merck), which is chosen for use in this study as it possesses high solubility in water, strong oxidizing properties and rapid combustion. Zinc nitrate acts as an oxidizer that is essential for promoting the redox reaction by providing the required oxygen to consume the fuel. It promotes formation of ZnO nanoparticles without impurities and unwanted secondary phases. The synthesis of nanoparticles depends on the chemistry of the final product, and as such, the choice and characteristics of the fuel also vastly alter the kinetics of the combustion reaction and heat release into the nanoparticles. The two chosen fuels (From: Merck) are good reducing agents and their impact on combustion efficiency. Due to strong chelating properties, citric acid is widely used for the uniform dispersion of metal ions in the precursor solution. For two roles as fuel and complexing agent of glycine, homogeneous precursor formation and efficient combustion is guaranteed.

Comparison of the effects of combustion of these fuels on nanoparticle properties such as crystallinity, area, and morphology is possible due to the differences in combustion behavior of these fuels.

The first set of samples has an oxidizer rich condition ($\phi<1$), that is, oxygen rich criterium in a reaction medium. The second set keeps a stoichiometric balance ($\phi = 1$) so that it will burn completely under optimal conditions. The third set of samples has a fuel excess, $\phi > 1$, and the completeness of the reaction and the structural features of the synthesized nanoparticles are affected by excess fuel. Such systematic variation permits detailed analysis of the effect of combustion parameters on final product.

The synthetic nanoparticles subsequently go through extensive characterizations with different analytical methods. The crystallinity of the synthesized metal oxides are examined by XRD. The morphology and particle size distribution are analyzed by means of Scanning Electron Microscopy (SEM). Flame during combustion & color observation of synthesized materials are studied to analyse the thermal stability and the optical properties are determined using UV-Vis spectroscopy. The use of this experimental design allows the evaluation of the influence of fuel efficiency parameters on the synthesis of zinc based nano metal oxides. By means of the approach, the reaction mechanism is understood systemically and the role of different fuels and their influence on properties of nanoparticles is valuable.

In this study, three different fuel-to-oxidizer ratios are explored:

- **Oxidizer-Rich Condition ($\phi < 1$):** In this particular case, the reaction temperature is expected to becomes lower and is slower due to excess oxidizer present. Incomplete reduction of metal ions may result in phase impurities and reduced crystallinity due to this condition.
- **Stoichiometric Condition ($\phi = 1$):** In this condition, fuel and oxidizer are at their correct balanced amounts. It makes sure that combustion is complete, resulting in heal crystallized nanoparticles with little defects[12].
- **Fuel-Rich Condition ($\phi > 1$):** The higher flame temperatures occur when more fuel is used than necessary, because then the combustion reaction, in becoming more exothermic, burns more fuel. Rapid nucleation and crystallization are encouraged by this condition, but nonburned carbon residues can also be introduced, affecting both the purity and surface properties of the nanoparticles. Following formula used to calculate f/o ratio:

oxidizer/fuel ratio = ∑all oxidizing & reducing elements in oxidizer ÷

(-1) ∑ oxidizing & reducing elements in fuel

Two set of experiments with 3 samples in each with different fuels performed (Table 1).

Experiment I: Oxidizer-Rich Condition ($\phi < 1$)

Experiment II: Stoichiometric Condition ($\phi = 1$)

Experiment III: Fuel-Rich Condition ($\phi > 1$)

Experiment I: Oxidizer-Rich Condition ($\phi < 1$)

Here zinc nitrate and fuel ratio is chosen so that only 60 % of quantity of fuel used in reference to the stoichiometric Condition i.e. is $\phi = 0.6$. Three sample precursor each for glycine and citric acid were prepared as per standard mechanism of SHS.

Experiment II: Stoichiometric Condition ($\phi = 1$)

Here zinc nitrate and fuel ratio is taken as equal to stoichiometric Condition i.e. is $\phi = 1$. Three sample precursor each for glycine and citric acid were prepared as per standard mechanism of SHS.

Experiment III: Fuel-Rich Condition ($\phi > 1$)

Here zinc nitrate and fuel ratio is taken as 140% of fuel as used in stoichiometric Condition i.e. $\phi = 1.4$. Three sample precursors each for glycine and citric acid were prepared as per standard mechanism of SHS.

Experiment No.	Sample type	Fuel type	F/O ratio (stoichiometric Condition)	Fuel % from stoichiometric Condition
I	Oxidizer-Rich Condition	Glycine	$\phi < 1$	60
		Citric Acid	$\phi < 1$	60
II	Stoichiometric Condition	Glycine	$\phi = 1$	100%
		Citric Acid	$\phi = 1$	100%
III	Fuel-Rich Condition	Glycine	$\phi > 1$	140%
		Citric Acid	$\phi > 1$	140%

Table 1: Variation in F/O ratio in reference to stoichiometric Condition for two fuels.

Experimental Set Up:

All experiments were performed under controlled laboratory conditions so that the same conditions can be produced to ensure consistency and reproducibility. Dissolving zinc nitrate and the selected fuel in deionized/Distilled water is how the precursor solutions are prepared. Magnetic stirrer (Make: REMI, Model: 2MLH) is used to continuously stir the solution for 30 minutes to get complete homogenization. This monitoring of pH of the solution helps in proper complexation of the metal ion with the fuel molecules. After preparing the precursor solution, it will be transferred to a ceramic crucible and placed inside a preheated muffle furnace (Make: METREX , Model: MF-Microprocessor controlled), whose temperature is set at 500°C. The exothermic redox reaction between the fuel and oxidizer causes spontaneous ignition of the solution within minutes. Metal oxide powder is prepared with the fast burning process and becomes voluminous and highly porous in structure [13]. The product is allowed to go to completion and then allowed to cool to room temperature naturally. Post synthesis heat treatment is made to the synthesized nanoparticles at 600°C for an hour in order to eliminate any residual organic contaminants. The first calcination step in this process serves the purpose of the removal of the unreacted fuel residues and increases the crystallinity of the metal oxide nanoparticles. Powder is then collected, ground with a mortar and pestle, and placed into airtight containers for later characterization.

Characterization of Samples:

Following synthesis, the metal oxide nanoparticles undergo comprehensive characterization to evaluate their structural, morphological, and functional properties. The synthesized material is divided into portions for analysis using various techniques. X-ray diffraction (XRD) is employed on a selected portion to determine the phase composition and estimate crystallite size. Another portion is analyzed using scanning electron microscopy (SEM) to investigate particle morphology, size distribution, and surface characteristics. Additionally, the optical properties of the nanoparticles are assessed through ultraviolet-visible (UV-Vis) spectroscopy.

Results and Discussion:

Experimental observations indicate that variations in the fuel-to-oxidizer ratio (ϕ) significantly influence flame temperature, combustion intensity, and gas evolution, all of which directly impact the dynamics of particle formation. Under **oxidizer-rich conditions** ($\phi < 1$), the combustion process is incomplete, resulting in lower reaction temperatures and reduced nucleation rates. Consequently, the synthesized particles tend to be larger, irregular in shape, and poorly crystallized due to insufficient thermal energy to drive rapid crystallization. **SEM analysis** reveals agglomerated structures, attributed to the sluggish growth of particles in such environments. Additionally, the reduced flame temperature under these conditions inhibits complete decomposition of precursors, often leading to residual organic content and the formation of secondary phases in the final product [14].

In contrast, at a **stoichiometric fuel-to-oxidizer ratio** ($\phi = 1$), the combustion reaction is highly exothermic, producing an optimal flame temperature that supports controlled nucleation and crystal growth. These conditions favor the formation of nanoparticles with uniform morphology and well-defined crystallite sizes. However, despite the enhanced reaction kinetics, the rapid energy release can lead to increased nucleation rates and the incorporation of defects, thereby reducing phase purity.

Under **fuel-rich conditions** ($\phi > 1$), the presence of excess fuel leads to incomplete oxidation, often resulting in unburned carbon residues that degrade the surface properties of the nanoparticles. The high fuel content also promotes excessive gas evolution, creating voids within particles and enhancing porosity. While this increased porosity can be advantageous for applications such as catalysis and adsorption, it also introduces structural defects that reduce crystallinity and mechanical stability [15]. SEM and complementary analyses confirm a higher degree of structural imperfections in fuel-rich samples, correlating with diminished mechanical integrity.

5.1 Phase Purity and Crystallinity Trends

The phase purity and crystallinity of ZnO nanoparticles synthesized at different fuel-to-oxidizer ratios were assessed using X-ray diffraction (XRD) analysis. The diffraction patterns of samples prepared at the stoichiometric ratio ($\phi = 1$) exhibit sharp and well-defined peaks corresponding to the hexagonal wurtzite ZnO structure, indicating high crystallinity. Although minor impurity phases are present, they are negligible under these conditions. In contrast, oxidizer-rich samples ($\phi < 1$) show additional diffraction peaks attributed to unreacted precursors and secondary metal oxide phases. The reduced combustion temperature and incomplete reaction in these samples favor the formation of intermediate compounds such as $Zn(OH)_2$ and $ZnCO_3$, which typically require further calcination to transform into pure ZnO [16].

For fuel-rich samples ($\phi > 1$), the XRD patterns display broadened peaks, reflecting low crystallinity. This reduction in crystallinity is primarily due to excess carbonaceous residues generated from incomplete combustion, which hinder the nucleation and growth of crystalline ZnO. Furthermore, the presence of amorphous phases suggests partial oxidation of the fuel, leading to structural disorder. These variations in crystallinity significantly affect the optical and electronic properties of the material. Therefore, precise control over the fuel-to-oxidizer ratio is essential to optimize nanoparticle quality and enhance performance for targeted applications.

5.2 Variation in Combustion Temperature and Reaction Dynamics

Solution Combustion Synthesis (SCS) is highly sensitive to the type of fuel employed, as it directly affects combustion temperature, reaction kinetics, and overall synthesis efficiency. The nucleation and growth of nanoparticles are influenced by the combustion temperature, while the dynamics of the reaction determine the final product’s homogeneity, porosity, and crystallinity. The nature of the fuel impacts the combustion process through its decomposition behavior, calorific value, and the volume and type of gaseous byproducts generated. Among commonly used fuels in SCS, glycine and citric acid exhibit distinct effects on the combustion characteristics and final product properties.

Glycine functions both as a fuel and a chelating agent. It forms stable complexes with zinc ions, facilitating a controlled combustion process with a moderate flame temperature. The gradual decomposition of glycine leads to a slower reaction rate, which enhances phase control and improves the crystallinity of the synthesized nanoparticles. The presence of both amine (-NH_2) and carboxyl (-COOH) groups enables better precursor mixing, resulting in a narrower particle size distribution. However, this slower combustion can also cause a slight increase in particle size.

Citric acid, another frequently used fuel, has a lower calorific value and consequently produces a lower combustion temperature. Though the reaction remains exothermic, it is less intense and more prolonged, leading to greater porosity in the final product. However, incomplete combustion may leave behind carbonaceous residues, requiring additional post-synthesis heat treatment to achieve phase purity and eliminate contaminants. The lower flame temperature can also hinder the degree of crystallinity initially attained.

Experimental data confirm that glycine leads to higher combustion temperatures than citric acid [17]. While glycine provides a moderately high combustion environment conducive to better crystallinity and reaction control, citric acid yields a more porous product with lower initial crystallinity and combustion temperature. These variations significantly influence the physical and chemical properties of the resulting nanoparticles. Thus, careful selection of fuel is essential for optimizing SCS parameters for specific applications. Table 2 shows observations made during the combustion process for two fuels with different F/O ratio for two sets of samples. Figures (1 & 2) shows different flame observation conditions from smouldering to very high flame during combustion.

Table 2: Flame observations made during the combustion process for two fuels with different F/O ratio for two sets of samples

Experiment No. /Sample Type	Fuel type	Combustion Flame cycle time (seconds)	Reaction processing observation	Product color appearance
I/ Oxidizer-Rich Condition	Glycine	2-3 (sparking type)	Negligible reactant rising in beaker during combustion	Brownish foam
	Citric Acid	1-2 (smouldering type)	Negligible reactant rising in beaker during combustion	Light yellow
II/ Stoichiometric Condition	Glycine	4-6	Litle reactant rising in beaker during combustion	White foam
	Citric Acid	3-4 (sparking type)	Negligible reactant rising in beaker during combustion	White foam
III /Fuel-Rich Condition	Glycine	7-9	Reactant rising upto opening of beaker	Black foam
	Citric Acid	5-7	Litle reactant rising in beaker during combustion	Black foam

Figure 1: Flame characteristics observed during the combustion process, illustrating the average operating temperature near the combustion stage (top image), smouldering behavior (middle images), and minimal or negligible flame presence (bottom images).

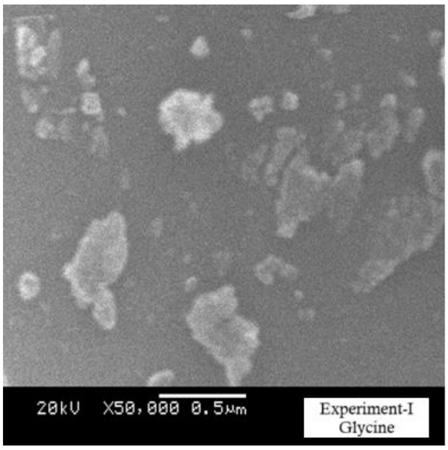
Figure 2: Flame observations recorded during the combustion process indicate flame duration and temperature—corresponding to a moderate to high level of exothermicity—lasting approximately 7 to 9 seconds across all experiments.

5.3 tructural and Optical Property Modifications

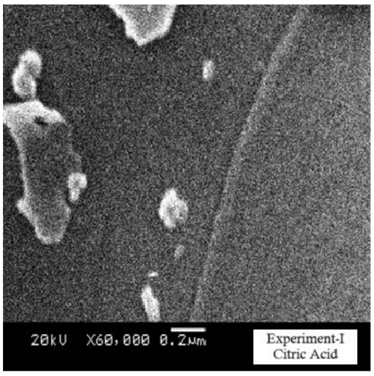
The choice of fuel in Solution Combustion Synthesis (SCS) has a significant impact on the structural and optical properties of the resulting nanoparticles, including their morphology, crystallinity, and bandgap energy. Different fuels influence nanoparticle formation, aggregation behavior, and light interaction—factors that are especially critical in applications such as optoelectronics, catalysis, and energy storage.

5.3.1. Scanning Electron Microscopy (SEM) analysis of nanoparticles synthesized using glycine as a fuel reveals that the combustion process is more controlled, producing particles with enhanced crystallinity and a slightly larger size distribution in the range of 30–70 nm. SEM images of glycine-derived ZnO nanoparticles exhibit well-defined morphology with fewer structural defects, indicating a more uniform growth process.

In contrast, nanoparticles synthesized using **citric acid** display irregular shapes and reduced porosity. The lower combustion temperature and incomplete oxidation associated with citric acid fuel lead to partial particle fusion and the presence of structural inconsistencies. These morphological differences highlight the critical role of fuel selection in tuning nanoparticle properties for targeted applications. SEM images for Experiment I, II, III are shown in figure (3 to 5) respectively (Model: ZEISS GeminiSEM 460, Make: ZEISS).

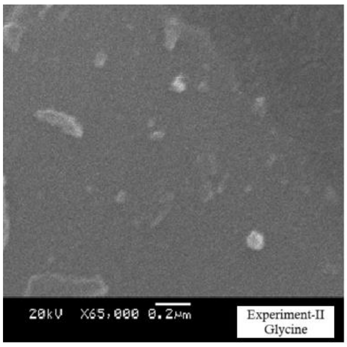


(a)

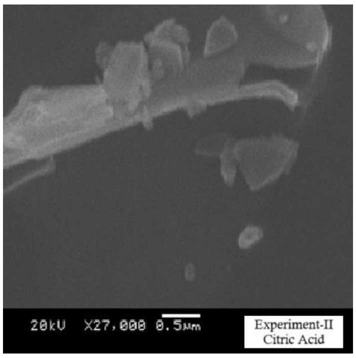


(b)

Figure 3: SEM images of Experiment-I for samples (a) Glycine (b) Citric Acid

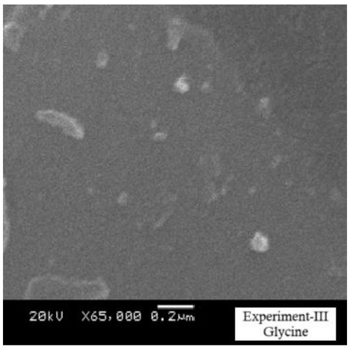


(a)

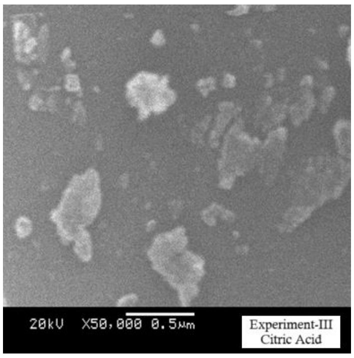


(b)

Figure 4 : SEM images of Experiment-II for samples (a) Glycine (b) Citric Acid



(a)



(b)

Figure 5 : SEM images of Experiment-III for samples (a) Glycine (b) Citric Acid

5.3.2. X-ray Diffraction (XRD) analysis: Above findings were further supported by X-ray Diffraction (XRD) analysis. Glycine-based ZnO samples exhibit strong diffraction peaks, although slightly broadened, suggesting the presence of fine to moderately grown crystallites (Figure 6). In contrast, the XRD patterns of citric acid-derived samples display broader and less intense peaks, indicating smaller crystallite sizes and reduced phase purity (Figure 7). Due to the lower crystallinity and the presence of residual organic matter, citric acid-based nanoparticles often require additional post-synthesis calcination to improve their structural order and eliminate unreacted components.

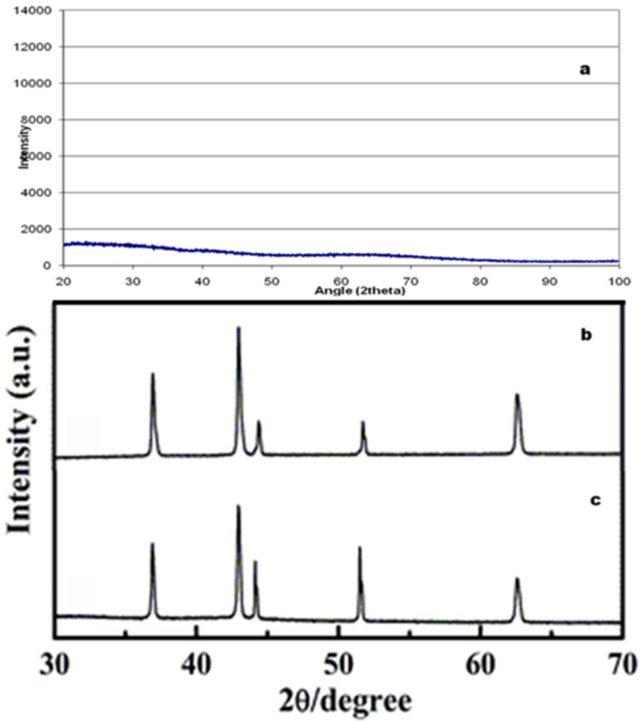


Figure 6 : XRD plots for three samples with glycine as fuel (a) ϕ > 1 (b) ϕ = 1 (c) ϕ < 1

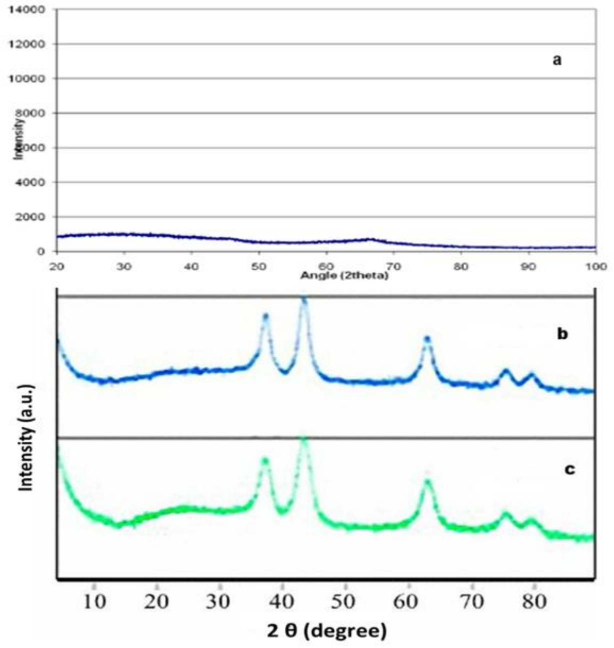


Figure 7 : XRD plots for three samples with citric acid as fuel (a) ϕ > 1 (b) ϕ = 1 (c) ϕ < 1

5.3.3. Ultraviolet-Visible (UV-Vis) spectroscopy: is used to analyze the optical properties of the synthesized nanoparticles with regards to bandgap energy variations. Crystallinity, defects and particle size also affect the bandgap energy of ZnO nanoparticles.

UV-Visible absorption characteristics of sample are shown in Figure (8 to 12) below. Energy band gap (E_g) has been calculated using following Tauc relationship,

$$ah\nu = A(h\nu - E_g)^n \quad (1)$$

$$\alpha = -\frac{\ln T}{d} \quad (2)$$

Here α is absorption coefficient, d is the film thickness, $h\nu$ is incident photon energy, A is constant and E_g is energy band gap corresponds to the particular transition in the material, n is an index having values $1/2, 3/2, 2$ and 3 depending on the nature of transition(1/2 for allowed direct, 2 for allowed indirect, 3/2 for forbidden direct, 3 for forbidden indirect transitions). Value of E_g was calculated from the graph between $(ah\nu)^{1/n}$ and $h\nu$ as shown in Figure (8,10, 12). By extra-polation of linear region at $\alpha = 0$, the intercept of the linear fit on x-axis gives E_g.

The bandgap of Glycine based ZnO slightly lower (~3.55 eV) than that of other ZnO powders, although the lowest bandgap (~3.5–3.51 eV) of that of the ZnO powders is caused by the structural imperfections and residual carbon content from the citric acid [18].

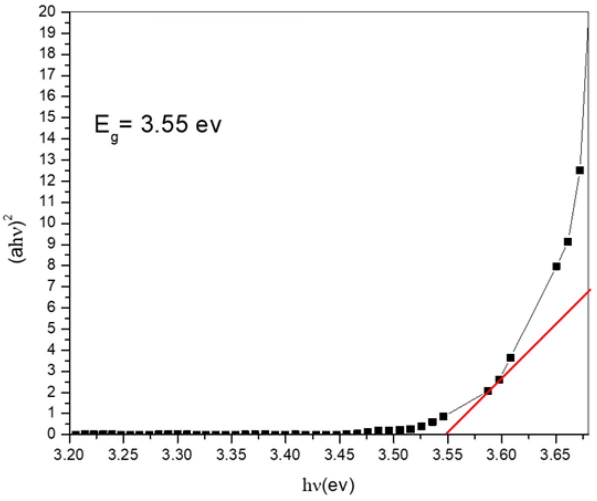


Figure 8 : Band gap energy for as synthesized ZnO sample with glycine as fuel (Best fit data).

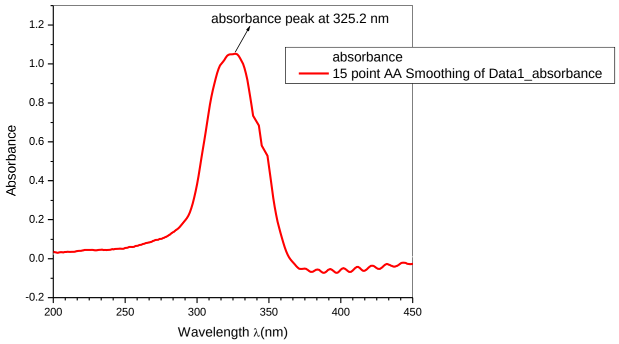


Figure 9 : Absorbance plot for as synthesized ZnO sample with glycine as fuel (Best fit data).

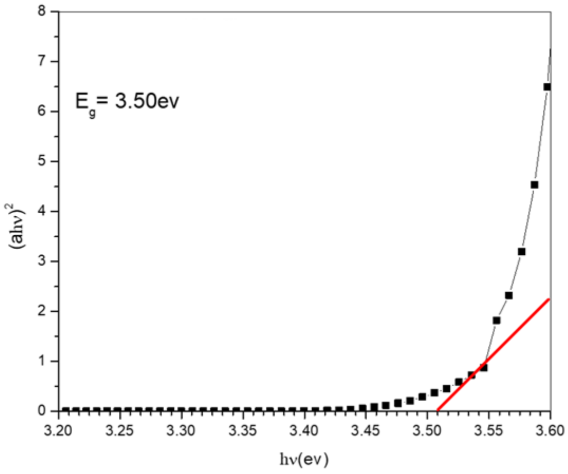


Figure 10: Band gap energy for as synthesized ZnO sample with citric acid as fuel (Best fit data).

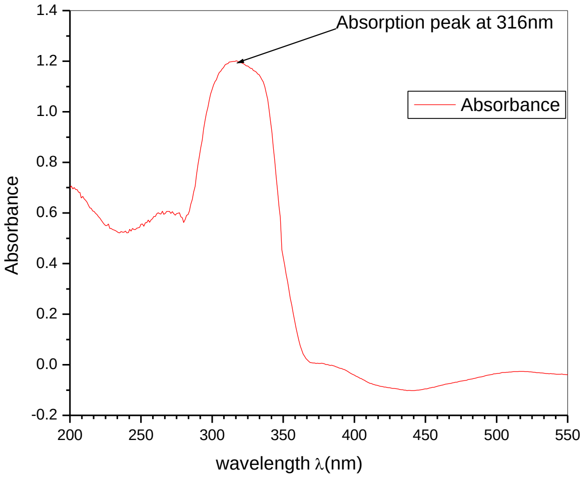


Figure 11: Absorbance plot for as synthesized ZnO sample with citric acid as fuel (Best fit data).

These results underscore the crucial role of fuel selection in tailoring nanoparticle properties for specific applications. A balanced approach using glycine enables the synthesis of ZnO nanoparticles with moderate particle size and good crystallinity, making them suitable for use in electronic and biomedical fields. On the other hand, citric acid offers the advantage of increased porosity, which is beneficial for adsorption and catalysis; however, improvements in material stability and optical properties are necessary for broader applicability.

The observed differences in combustion behavior, structural integrity, and optical characteristics clearly illustrate how fuel type influences the SCS process. Glycine facilitates controlled combustion and crystallite growth, while citric acid promotes porosity but compromises crystallinity. Understanding these fuel-specific effects is essential for optimizing SCS conditions to engineer ZnO nanoparticles with targeted properties for diverse industrial and technological uses.

5.4 Thermal Stability and Surface Properties

Thermal stability is a key parameter in evaluating the suitability of nanoparticles for various high-performance applications. Therefore, understanding and enhancing their thermal behavior is essential. Experimental findings reveal that ZnO nanoparticles synthesized at an optimized fuel-to-oxidizer ratio exhibit thermal stability more than three times higher than non-optimized samples, with minimal weight loss even beyond 500°C. This indicates effective removal of volatile organic compounds during combustion, resulting in products suitable for high-temperature applications such as catalysis and electronics.

Another critical factor is the optimization of surface properties, which plays a pivotal role in enhancing surface reactivity for applications like photocatalysis and adsorption [19]. While increased porosity contributes to higher surface area and reactivity, it may also pose a disadvantage in mechanical applications, where excessive porosity can compromise structural integrity.

Careful adjustment of the fuel-to-oxidizer ratio allows for fine-tuning of nanoparticle characteristics—achieving a balance between porosity and mechanical strength—to suit specific functional requirements. By systematically controlling these synthesis parameters, high-quality zinc-based nanometal oxides with enhanced crystallinity, thermal stability, and uniform nanoscale dispersion can be reliably produced for a wide range of industrial and technological applications.

Conclusions:

This study presents the application of solving a system of differential equations involving functional and parametric variations to address the problem of synthesizing zinc-based nanometal oxides via the Solution Combustion Synthesis (SCS) method. The investigation systematically explores the influence of fuel efficiency parameters, particularly the fuel-to-oxidizer ratio and the type of fuel, on the properties of the synthesized nanoparticles.

Experimental results demonstrate that the structural and morphological characteristics of the nanoparticles are highly sensitive to these parameters. The optimal results—including highest phase purity, enhanced crystallinity, uniform morphology, and minimal secondary phases—were obtained at the stoichiometric fuel-to-oxidizer ratio ($\phi = 1$). In contrast, samples synthesized under oxidizer-deficient conditions ($\phi > 1$) showed signs of incomplete combustion, leading to unreacted precursors and lower phase purity. Conversely, fuel-rich conditions ($\phi > 1$) led to the formation of carbonaceous residues, resulting in increased porosity and reduced crystallinity, which may be beneficial for applications such as catalysis and adsorption [20].

The type of fuel also plays a crucial role in determining combustion temperature, reaction dynamics, and nanoparticle properties. Glycine, due to its dual function as a fuel and a chelating agent, facilitated controlled combustion and promoted better crystallinity and compositional homogeneity. In contrast, citric acid, though effective at increasing porosity through lower combustion temperatures, required post-synthesis thermal treatment to achieve phase-pure crystalline products.

X-ray Diffraction (XRD) analysis confirmed that stoichiometrically synthesized ZnO samples displayed narrower peaks, indicative of superior crystalline structure. Scanning Electron Microscopy (SEM) revealed increased porosity in ZnO particles derived from citric acid. Additionally, UV–Vis spectroscopy showed that synthesis parameters affect optical bandgap values, influencing the material's potential for photocatalytic and optoelectronic applications.

Overall, the study establishes that fuel-rich conditions enhance surface area, making them advantageous for catalytic processes, while stoichiometric synthesis yields high-crystallinity ZnO suitable for electronic and optical uses. These insights demonstrate how precise tuning of SCS parameters can optimize nanoparticle properties for targeted technological applications.

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