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Optimizing the UV Absorption and Suspension Stability of ZnO Nanostructures Using the Chemical Precipitation Method

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Abstract

This research addresses the long-standing challenge in the cosmetic industry by producing a chemically pure zinc oxide (ZnO) powder with an appropriate morphology and size, excellent ultraviolet (UV) absorption, and high suspension stability. Here, a zinc oxide nanostructure (ZnO-NS) was synthesized using a modified chemical precipitation method, varying parameters such as temperature (25°C and 80°C), stirring time (1 and 4 h), molar ratio of sodium hydroxide to zinc nitrate (4:1 and 1:1), the presence of ethylenediaminetetraacetic acid (EDTA) as a capping agent, and the different order of adding ingredients (addition route). Various characterization techniques, including XRD, FE-SEM, and UV-Vis spectroscopy, were employed. Morphologies observed were spherical, acicular, plate-like, and flower-like, with average dimensions ranging from 30 to 100 nm. It was found that, in the absence of a capping agent, the anisotropic flower-like structure with acicular petals provided the best suspension stability over 10 days, while plate-like morphology demonstrated the highest UV absorption. Notably, the

EDTA-free sample ON25(4)-1 exhibited a nanostructured, plate-like morphology, acceptable suspension stability after 10 days, and achieved 84% UV absorbance at 370 nm. This sample demonstrates strong potential to address the challenges in sunscreen products.

Keywords

ZnO; EDTA; Morphology; Nanostructure; UV-Vis

1. Introduction

Zinc oxide (ZnO) powder is widely used in various fields such as solar cells, photocatalysts, photodetectors, gas sensors, light-emitting diodes, field-effect transistors, ultraviolet lasers, water treatment [1, 2], and cosmetics [3, 4]. This is mainly due to their outstanding optoelectronic properties, which depend on their morphology and size [5]. For instance, ZnO has a wide band gap (E_g) of 3.37 eV [6] and a high exciton binding energy (60 meV) [7]. Additionally, Lautenschlager et al. [8] indicated that ZnO, used in local sunscreens, is safe and does not cause skin irritation or allergies. Therefore, in recent decades, numerous studies have focused on the unique properties of ZnO-NS, including their high refractive index, antibacterial properties, and UV protection [9]. Naturally, ZnO exists in the form of zincite and appears in a solid state as an odorless powder, and its color varies from white to pale yellow [10]. Its crystal structure is wurtzite, with lattice parameters $a = 3.25 \text{ \AA}$ and $c = 5.20 \text{ \AA}$ (JCPDS card No: 79-2205) [1, 11].

Because of the skin irritation caused by the chemicals in traditional sunblocks, it is

suggested to use nontoxic inorganic compounds in sunscreen formulations for optimal UV absorption, dispersion, and suspension stability based on ZnO's size and morphology. ZnO lotions offer an effective, broad-spectrum physical sunblock that is longer-lasting and non-irritating. However, large ZnO particles (over 100 nm) create a white, chalky barrier that is not esthetically pleasing [12, 13]. Also, the ZnO suspension stability is crucial for good cream quality [13]. Given the importance of ZnO in various applications, achieving nanostructured ZnO (ZnO-NS) with compatible morphology and nanostructure size, while preventing agglomeration of particles, has been a considerable challenge in this field for an extended period. Capping agents have garnered attention as a solution to these issues during the chemical synthesis of ZnO-NS [14]. However, adding capping agents (chemical materials) to sunscreen formulations should be limited and isn't ideal.

Electrostatic capping agents such as ethylenediaminetetraacetic acid (EDTA) and trisodium citrate (TSC) are mainly used to control the size and morphology of ZnO-NS. For instance, Duraimurugan et al. [2] studied the impact of EDTA and TSC on the morphology and size of ZnO. They found that EDTA causes irregular nanoflake ZnO, with dimensions ranging from 100 to 300 nm. In contrast, TSC-capped ZnO creates a solid microsphere with spikes pointing outward in all directions. Chandrasekaran et al. [15] discovered that capped ZnO exhibits a high absorption peak in the 365 to 370 nm range compared to uncapped ZnO, showing changes in morphology. Their TEM and HR-TEM results suggest that uncapped ZnO doesn't have a specific morphology, and the particles are highly agglomerated. Conversely, EDTA-capped ZnO particles are highly dispersed with a hexagonal morphology. Navaneethan et al. [16] suggested that adding

0.2M of zinc acetate, as a precursor, to a solution of 0.3M NaOH and 0.025M EDTA at room temperature can produce highly monodispersed hexagonal thin ZnO nanodisks. Saini et al. [17] showed that the absorption spectrum of EDTA-capped ZnO nanoparticles peaks at 370 nm and has a E_g of 4.0 eV. SEM micrographs also confirmed the creation of nanoclusters.

In line with the study's objectives, ZnO is synthesized in a wide variety of sizes and different morphologies, such as flakes, plates, hedgehogs, flowers, rods, belts, and wires [18-20]. Many techniques are applied to synthesize ZnO, including three general approaches: chemical synthesis, such as precipitation and hydrothermal methods, physical synthesis, such as laser ablation, and biological synthesis [21]. The chemical precipitation method is one of the most conventional techniques for synthesizing ZnO-NS. In this method, ZnO is precipitated from an aqueous solution of zinc salt such as $Zn(NO_3)_2$, $ZnSO_4$, $Zn(CH_3COO)_2$, $ZnCl_2$, etc., with the aid of precipitating agents such as NaOH, KOH, $(NH_4)_2CO_3$, etc. Finally, this precipitate is calcinated in a furnace [11, 22, 23]. Reaction factors such as the reactant concentration, pouring rate, and temperature can be controlled to achieve ZnO with a narrow size distribution and high specific surface area [24]. In comparison to other chemical methods, the chemical precipitation route is a simple yet efficient and cost-effective synthetic technique because the precursors are readily and economically available [25].

In the present study, the effect of morphology and particle size on the suspension stability and optical properties of ZnO-NS was investigated. ZnO-NS was prepared through a chemical precipitation method using zinc nitrate, sodium hydroxide, and EDTA as the precursor of zinc, precipitating agent, and capping agent, respectively. The UV

absorption and suspension stability of the synthesized samples were optimized by exploring the effect of temperature, time, addition route, and capping agent on the morphology and particle size of the ZnO-NS, which have not been investigated recently. An EDTA-free sample has been successfully introduced, which is expected to have good potential to meet the needs of the cosmetic industry, which has not been reported so far.

2. Experimental

2.1. Preparation

The chemicals ($\geq 99\%$ purity) were obtained from Merck: zinc nitrate ($\text{Zn}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$), sodium hydroxide (NaOH), and EDTA. Deionized water (purchased from Zolal Teb Shimi) was utilized in all experiments as the synthesis medium. Using the conventional chemical precipitation method (Figure 1), a 0.5 M aqueous solution of zinc nitrate was prepared and mixed with a 2 M sodium hydroxide solution to form a milky white gel-like suspension. Then, the suspension was stirred for 1 h, filtered, and washed several times with deionized water to achieve zinc hydroxide ($\text{Zn}(\text{OH})_2$) creamy mud. Subsequently, this mud was calcinated in an atmospheric furnace at 200°C for 2 h, and then ZnO-NS was obtained.

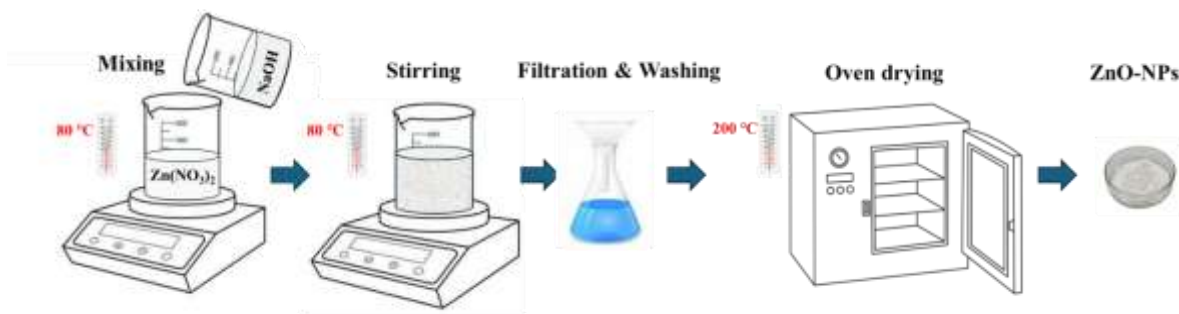


Figure 1. Overview of the chemical precipitation method used in this work. In this study, two levels for four main factors were considered: 25°C and 80°C for

temperature, 4:1 and 1:1 for the NaOH: $\text{Zn}(\text{NO}_3)_2$ molar ratio, NaOH in $\text{Zn}(\text{NO}_3)_2$ and $\text{Zn}(\text{NO}_3)_2$ in NaOH for the addition route, and 1 h and 4 h for the stirring time. All synthesis conditions are summarized in Table 1.

Table 1. Experimental conditions of ZnO samples

Sample	Temperature (°C)	$\frac{[\text{NaOH}]}{[\text{Zn}(\text{NO}_3)_2]}$	Addition route	Stirring Time (h)
ON80(4)-1	80	4	NaOH in $\text{Zn}(\text{NO}_3)_2$	1
NO80(4)-1	80	4	$\text{Zn}(\text{NO}_3)_2$ in NaOH	1
NO80(4)-4	80	4	$\text{Zn}(\text{NO}_3)_2$ in NaOH	4
NO25(4)-1	25	4	$\text{Zn}(\text{NO}_3)_2$ in NaOH	1
ON25(4)-1	25	4	NaOH in $\text{Zn}(\text{NO}_3)_2$	1
ON25(1)-1	25	1	NaOH in $\text{Zn}(\text{NO}_3)_2$	1

To see how the capping agent changed the properties of the ZnO-NS, the samples ON25(4)-1 and ON25(1)-1 were redesigned to EON25(1)-1 and EON25(4)-1 by adding a 0.25 M EDTA solution to a 2 M NaOH solution (Table 2). After stirring at 25°C, the EDTA-modified precipitating agent solution was added drop by drop into the as-prepared 0.5 M zinc nitrate solution to form a cloudy white suspension, and the rest of the steps were as mentioned earlier.

Table 2. The experimental conditions of the capping agent-modified ZnO samples

Capping agent	Sample	$\frac{[\text{NaOH}]}{[\text{Zn}(\text{NO}_3)_2]}$ (molar ratio)	Addition route
EDTA	EON25(4)-1	4	(EDTA + NaOH) in $\text{Zn}(\text{NO}_3)_2$
	EON25(1)-1	1	(EDTA + NaOH) in $\text{Zn}(\text{NO}_3)_2$

2.2. Characterization

The powdered samples were characterized using a Philips PW1730 X-ray diffractometer.

The hexagonal lattice parameters were found using Eq. 1 where h, k, and l represent the Miller indices, and d is the spacing between planes (hkl):

$$\frac{1}{d^2} = \frac{4}{3} \left(\frac{h^2 + hk + k^2}{a^2} \right) + \frac{l^2}{c^2} \quad (1)$$

With the first-order approximation (n = 1) and for the (100) and (002) orientations, lattice constants 'a' and 'c' were calculated by Eqs. 2 and 3.

$$a \text{ (Å)} = \frac{\lambda}{\sqrt{3} \sin \theta_{(100)}} \quad (2)$$

$$c \text{ (Å)} = \frac{\lambda}{\sin \theta_{(002)}} \quad (3)$$

Where $\lambda = 1.54056 \text{ Å}$ is CuK α radiation wavelength and $\theta_{(hkl)}$ is the Bragg angle for the (hkl) plane [11]. The 2θ positions of the peaks were obtained from the XRD pattern and converted to θ values. The bond length (L) of Zn-O is calculated from Eq. 4 [26].

$$L \text{ (Å)} = \sqrt{\frac{a^2}{3} + \left(\frac{1}{2} - \left(\frac{a^2}{3c^2} + \frac{1}{4} \right) \right)^2 \times c^2} \quad (2)$$

The average crystallite size (D) of the ZnO-NS was calculated using Debye-Scherrer's formula after appropriate corrections to the XRD patterns (Eq. 5):

$$D \text{ (nm)} = \frac{0.9\lambda}{\beta \cos \theta} \quad (3)$$

Where β is the full width at half maximum (FWHM) of the broadened diffraction line at the 2θ position in radians. FE-SEM images of the samples were taken using a TESCAN-MIRA3 scanning electron microscope. For the sedimentation experiment, ZnO-NS stock suspensions at a final concentration of 0.008 wt.% were prepared and sonicated for 15 min in deionized water (pH $\approx$ 7) before use. The Ultraviolet-Visible (UV-Vis) absorption spectra of the prepared suspensions were recorded in the wavelength range of 200 to 700

nm using a Bloor Azma specphoto UV-VIS-NIR. The data were expressed as apparent absorbance to represent the overall attenuation of transmitted light, including absorption by ZnO, scattering caused by particles or agglomerates, and any sedimentation over time. Assuming a direct allowed transition, the E_g (eV) for each sample was calculated using Tauc's method (Eq. 6) [27].

$$(\alpha h\nu)^2 = A(h\nu - E_g) \quad (4)$$

In this equation, α is the absorption coefficient (cm^{-1}) h is Planck's constant (6.626×10^{-34} J.s) and ν is frequency (s^{-1}).

3. Results and Discussion

3.1. Effect of the main factors

For all samples, the average size of the smallest dimension was between 30 and 100 nm, as shown in Figure 2. Different temperatures, stirring times, reactant molar ratios, and addition routes led to diverse morphologies, such as spherical, plate-like, acicular, and flower-like structures Table 3. The plate-like morphology of sample ON25(4)-1 (Figure 2a) was converted to a flower-like (platelet petals) morphology in sample NO25(4)-1 (Figure 2b) by simply changing the addition route. In addition, by changing the level of this factor at a temperature of 80°C , the polyhedral and plate-like shape of the sample NO80(4)-1 (Figure 2d) transformed into acicular-shaped particles of the sample ON80(4)-1 (Figure 2(e)). Increasing the molar ratio of NaOH to $\text{Zn}(\text{NO}_3)_2$, which raises the hydroxide ion (OH^-) concentration, resulted in a more plate-like morphology instead of a flower-like (acicular petals) morphology, as shown in Figure 2a and Figure 2c. Varying temperatures also resulted in different morphologies. When the NaOH solution

was added to $\text{Zn}(\text{NO}_3)_2$ solution, increasing the temperature from 25°C to 80°C caused a change in the morphology from plate-like particles (Figure 2a) to acicular particles (Figure 2e). However, in the reverse addition route, the increase in temperature transformed the flower-like structure into a polyhedral and plate-like structure (Figure 2b to Figure 2d). By giving the samples more time to grow, the polyhedral and plate-like shapes changed into flower-like (Dahlia) structures (Figure 2d and f).

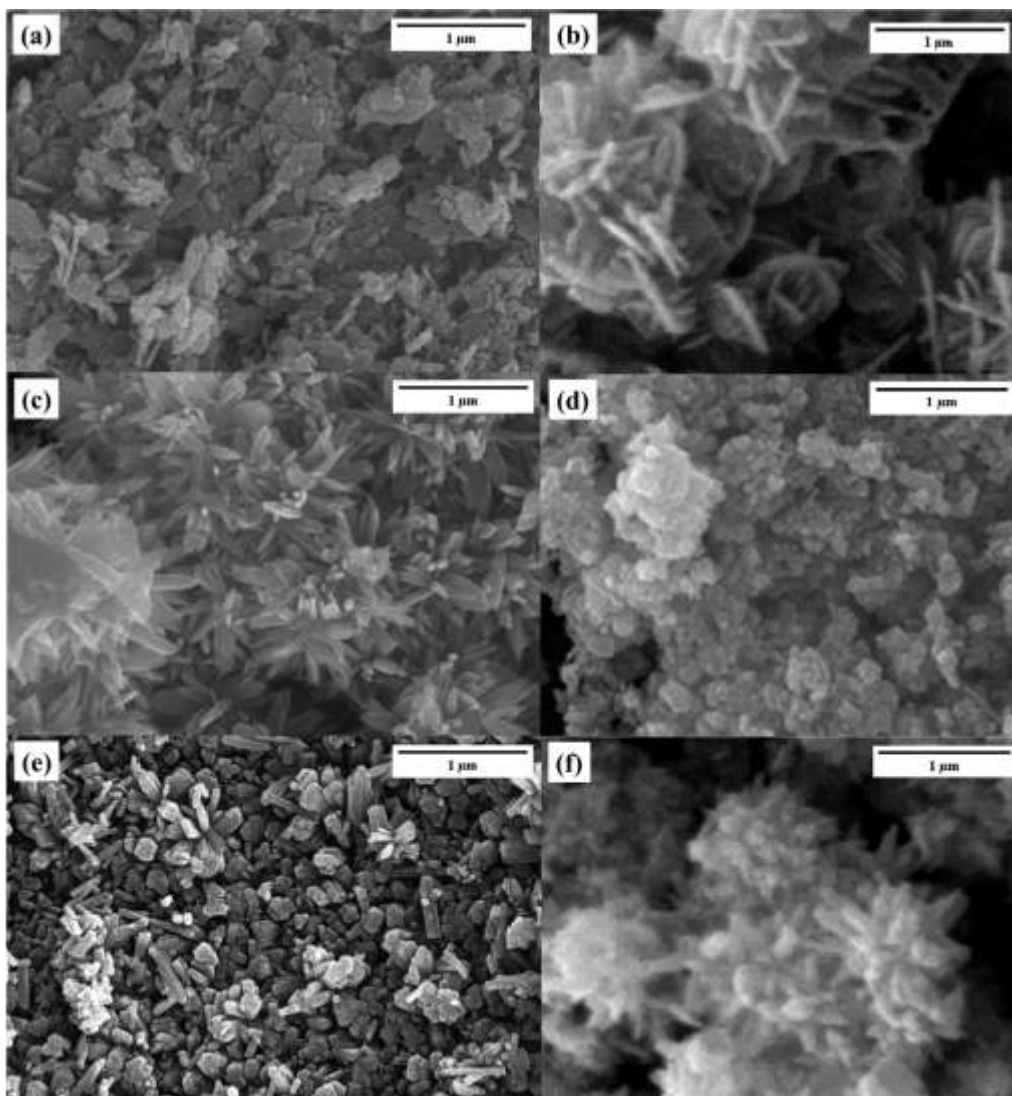


Figure 2. FE-SEM image of samples (a) ON25(4)-1 (b) NO25(4)-1 (c) ON25(1)-1 (d) NO80(4)-1 (e) ON80(4)-1 (f) NO80(4)-4.

Table 3. Morphology comparison of ZnO samples at a glance

Sample	Morphology	Schematic	Figure No.
ON25(4)-1	Plate-like		Figure 2(a)
NO25(4)-1	Flower-like (platelet petals)		Figure 2(b)
ON25(1)-1	Flower-like (acicular petals)		Figure 2(c)
NO80(4)-1	Polyhedral and plate-like		Figure 2(d)
ON80(4)-1	Acicular		Figure 2(e)
NO80(4)-4	Flower-like (Dahlia)		Figure 2(f)
Note: The schematic illustrations were generated with the assistance of AI tools to visually represent the observed morphologies based on experimental FE-SEM results.			

These changes in the size and morphology of ZnO-NS led to differences in the aqueous suspension stability. These responses were monitored at 1 and 10 days after the initial dispersion (Figure 3).



Figure 3. Nanostructure stability in water after (a) 1st day, and (b) 10th day.

The ZnO suspension has a point of zero charge around 9. Therefore, it isn't electrostatically stable in the tested aquatic environment ($\text{pH} \approx 7$) because the colloidal ZnO particles dissolve and release a high concentration of Zn^{2+} [28-30]. Besides dissolving, nanosized ZnO particles are more likely to adsorb to each other in an aqueous environment, rapidly growing to the micron scale and forming aggregates. This is because well-dispersed nanoparticles have larger diffusion coefficients, faster particle collisions, stronger van der Waals adsorption, greater surface hydrophobicity, higher surface energy, and experience water bridging [31, 32].

However, sample ON25(1)-1 notably exhibited the best suspension stability without

visible sedimentation or dissolution after 10 days. In this sample, the anisotropic flower-like morphology with acicular-shaped petals gives it a high surface area-to-volume ratio. This increased surface area enhances the interaction between the particles and the aqueous medium and overcomes the hydrophobicity of the ZnO particles, contributing to their suspension stability [33]. On the other hand, it is predicted that the plates and rods morphology have greater van der Waals attraction, which reduces the energy barrier for agglomeration [34]. This might seem contradictory, but according to the Derjaguin–Landau–Verwey–Overbeek (DLVO) theory, colloidal stability is the result of a balance between van der Waals attraction and electrostatic repulsion [35]. Therefore, the acicular petals of ON25(1)-1 contribute to enhanced surface charge accumulation, which induces electrostatic repulsion and counteracts the attraction between particles. This prevents agglomeration and keeps the particles dispersed in the aqueous medium. Consequently, the remarkable suspension stability of ON25(1)-1 highlights the critical role of morphology beyond the size effect alone in determining the colloidal performance of ZnO-NS in aqueous medium. The UV absorption spectrum (Figure 4) serves as a valuable tool for assessing the optical properties of ZnO-NS.

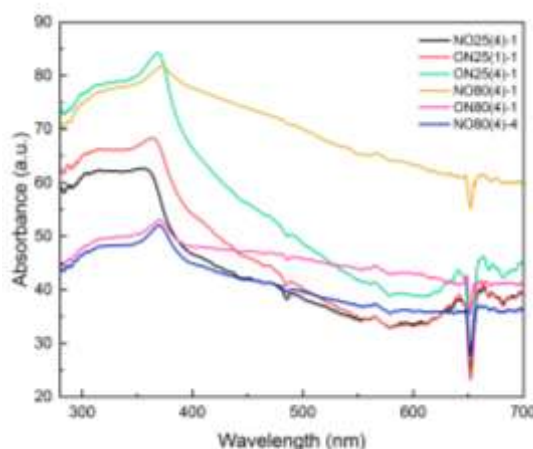


Figure 4. Diagram of the UV absorption at room temperature for samples without capping agents.

Based on this spectrum, the absorbance values at a specific wavelength of 370 nm are reported in Figure 5. Sample ON25(4)-1 demonstrated a notable 84% absorbance at this wavelength. This is because the plate-like morphology has a larger optical cross-section than acicular and flower-like morphologies, facilitating the reflection and scattering of UV radiation [20, 27, 36, 37].

It is worth noting that the UV absorbance intensity is closely dependent on the particle size. Specifically, in the same morphologies, as the particle size increases within the range of 40 to 70 nm, there is a corresponding increase in the UV absorption [38]. However, once the particles surpass the 70 nm threshold, they become essentially opaque to UV radiation, resulting in a decrease in absorption. This phenomenon was observed in samples NO25(4)-1, NO80(4)-4, and ON25(1)-1 with a flower-like morphology. In this way, the growth process of the UV absorbance continued from sample NO25(4)-1 to ON25(1)-1, but in sample NO80(4)-4, it stopped because the average diameter of the petals exceeded 70 nm.

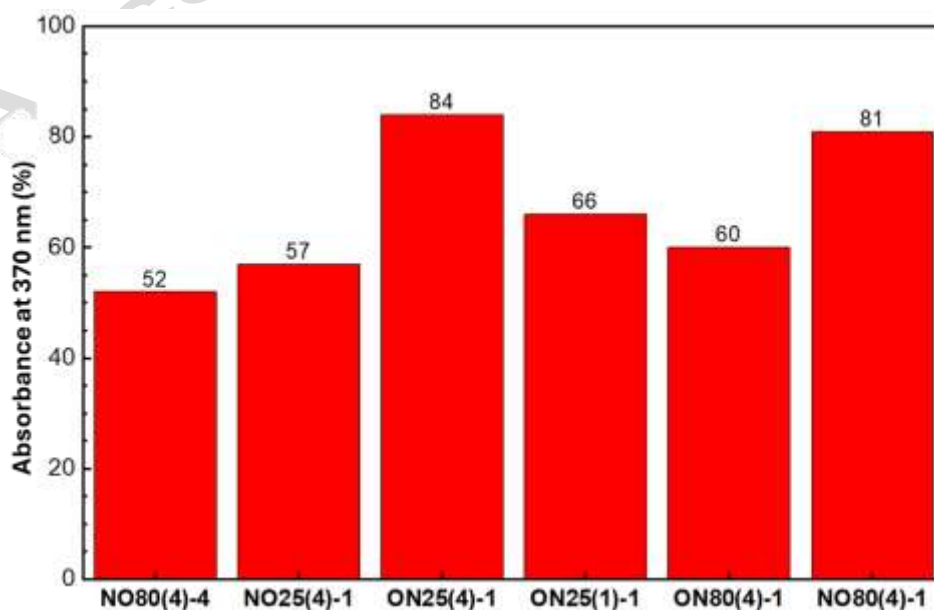


Figure 5. The UV absorbance value at 370 nm for samples without capping agents.

The E_g values for the ZnO samples were calculated using Tauc's plots and (4). For each sample, $(\alpha h\nu)^2$ was plotted versus $h\nu$ and then by linear extrapolating the linear region of the plot to $(\alpha h\nu)^2=0$ the E_g was estimated (Figure 6).

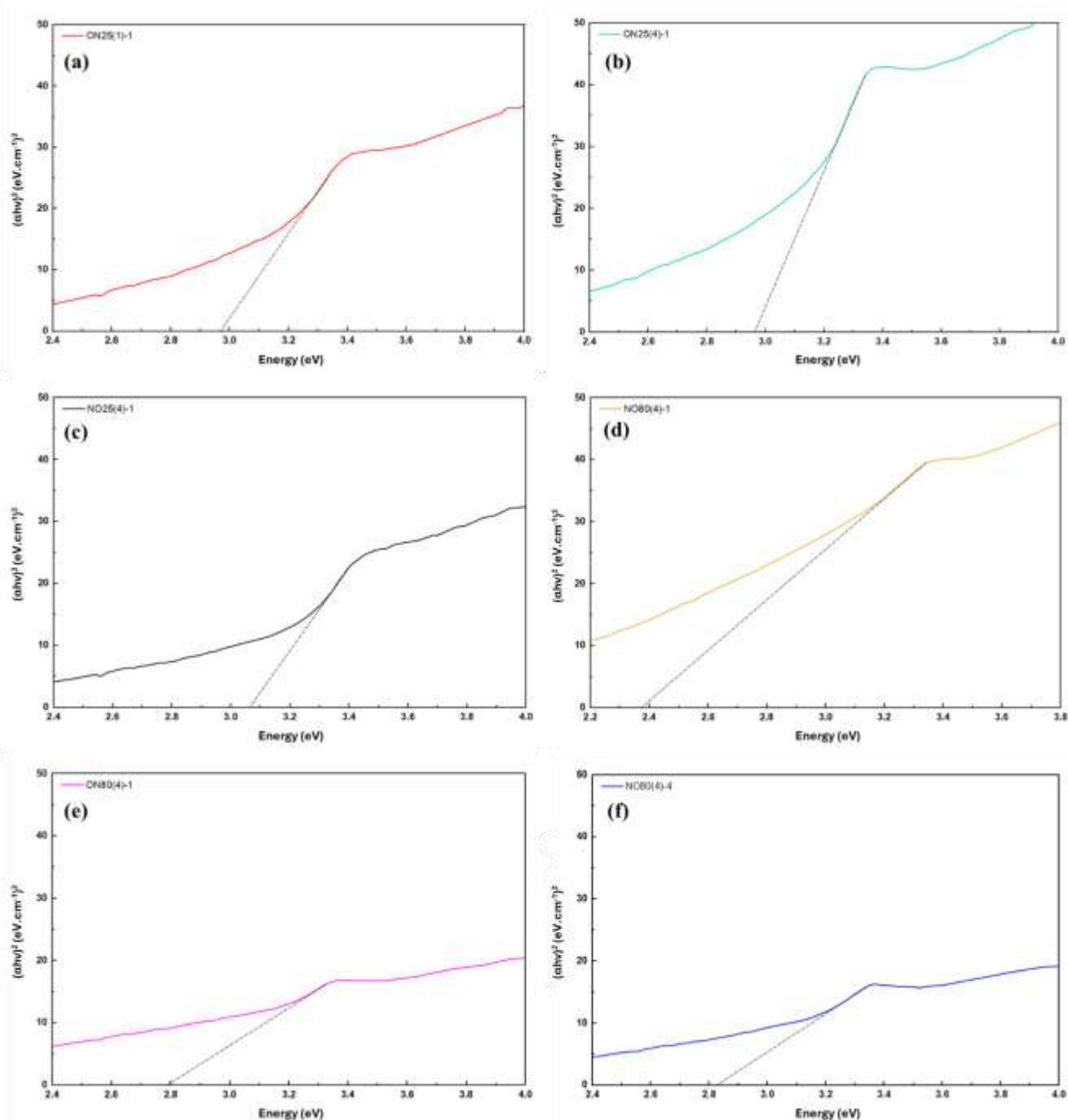


Figure 6. Tauc's plot of samples (a) ON25(1)-1 (b) ON25(4)-1 (c) NO25(4)-1 (d) NO80(4)-1 (e) ON80(4)-1 (f) NO80(4)-4.

The E_g value for all samples (Table 4) was lower than that of the ZnO bulk ($E_g=3.37$ eV) and showed bandgap narrowing, which was accompanied by the formation of an Urbach tail and a red shift to longer wavelengths. This phenomenon is mainly due to oxygen vacancies and zinc interstitials [27, 39]. However, for NO80(4)-1, which had the lowest E_g value and the second-highest apparent absorbance at 370 nm, Mie scattering appears to be the primary factor influencing absorption behavior. This sample with polyhedral and plate-like morphology displayed a broad absorption range in both UV and visible regions and showed the worst suspension stability due to rapid growth to the micron scale and aggregation within 1 day (Figure 3) [40,41].

Table 4. The bandgap values of the samples without capping agents

Sample name	E_g (eV)
ON25(1)-1	2.97
ON25(4)-1	2.96
NO25(4)-1	3.06
NO80(4)-1	2.37
ON80(4)-1	2.79
NO80(4)-4	2.82

So far in the research, sample ON25(1)-1 exhibits superior aqueous suspension stability, while sample ON25(4)-1 demonstrates the highest level of UV absorbance.

3.2. The capping agent effect

In this section, the goal is to assess the impact of EDTA on both the suspension stability and UV absorption of ON25(1)-1 and ON25(4)-1 and to leverage potential enhancements in these key properties. As shown in Figure 7, EDTA changed the flower-like and plate-like shapes of both samples ON25(1)-1 and ON25(4)-1 into a spherical morphology. Also, the smallest dimension of the EDTA-capped samples averaged 85 to 100 nm.

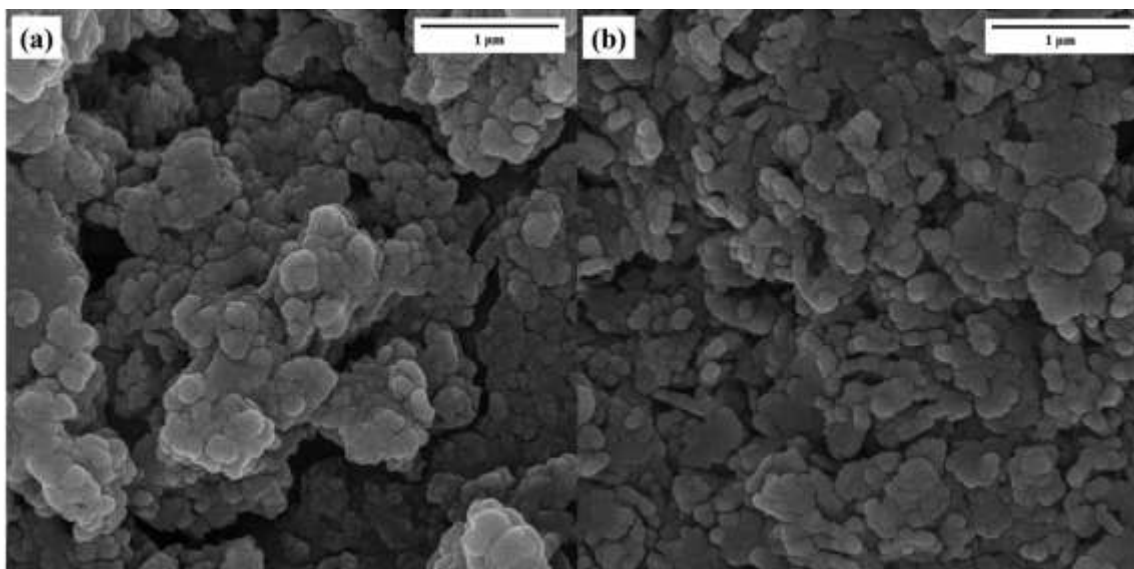


Figure 7. FE-SEM image of samples (a) EON25(1)-1 and (b) EON25(4)-1.

In the next step, the effect of adding a capping agent on the suspension stability of both samples was investigated. Contrary to expectations, sample EON25(1)-1 exhibited a significant reduction in stability, as shown in Figure 8.

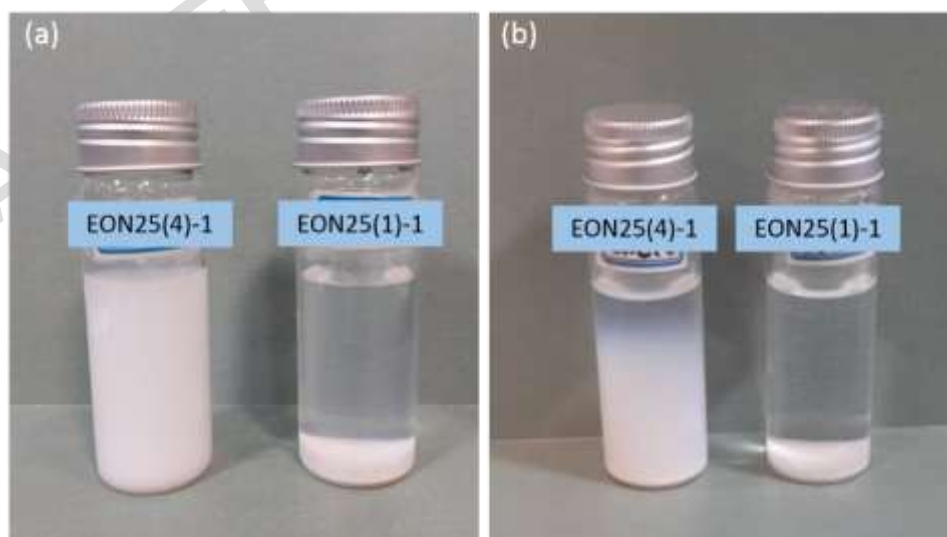


Figure 8. Nanostructure stability in water after (a) 1st day, and (b) 10th day.

In other words, EON25(1)-1 exhibited a higher degree of aggregation, leading to the

formation of larger particles. This behavior is attributed to the weaker interactions between ZnO-NS and the capping molecules, likely due to the lower NaOH: Zn(NO₃)₂ molar ratio and consequently lower OH⁻ concentration in EON25(1)-1. In this situation, the deprotonation of EDTA is expected to decrease from fully deprotonated form (Y⁴⁻). Therefore, this can slow down or interfere with the capping mechanism [42], leading to heterogeneous particles that are likely to fully agglomerate within just 1 day. The addition of capping agent was expected to affect the UV absorption. Results showed that the EON25(1)-1 and EON25(4)-1 samples exhibited 64% and 98% absorbance levels at the 370 nm wavelength, as depicted in Figure 9.

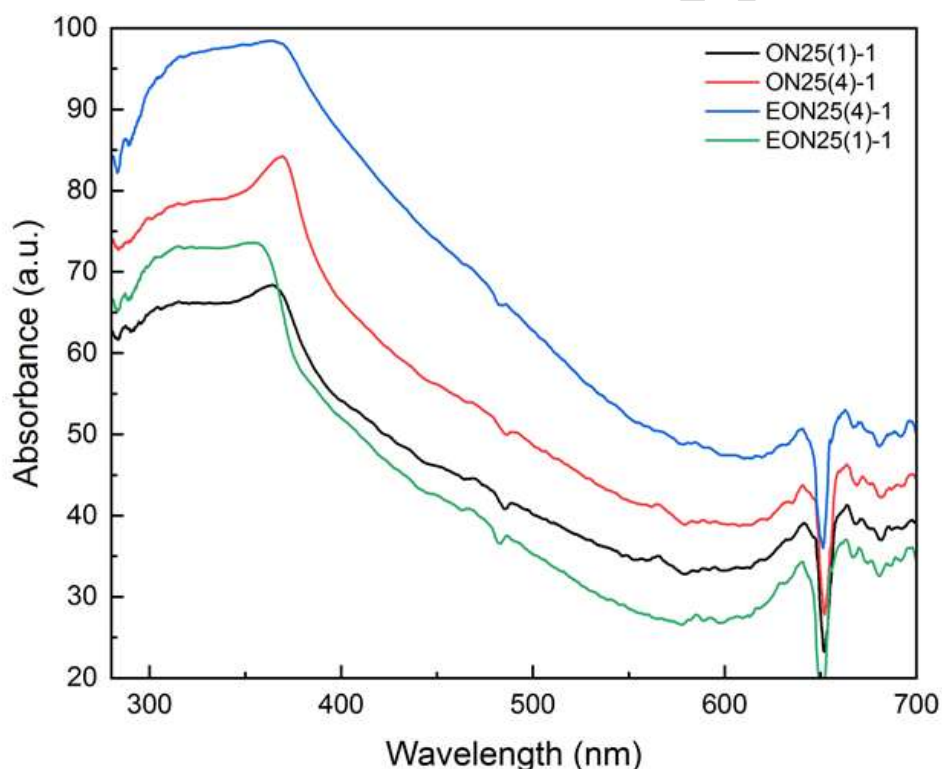


Figure 9. Analysis of UV absorption with and without capping agents.

The results of the comparative analysis between the EON25(4)-1 and ON25(4)-1 samples aligned with our initial predictions. The higher apparent absorbance of EON25(4)-1

observed in both UV and visible regions is due to increased Mie scattering effects. Based on visual assessment of turbidity in Figure 3 and Figure 8, the EON25(4)-1 exhibits slightly higher stability in water compared to the ON25(4)-1. This indicates that the EON25(4)-1, which has a spherical morphology and slightly larger dimensions, scatters more light than the ON25(4)-1 [43]. But no significant change in absorbance was observed from ON25(1)-1 to EON25(1)-1. This may be due to a compromise between four factors: particle agglomeration, reduction in particle number, increased sedimentation rate, and change in morphology, resulting in no change in UV-interacting surfaces per unit volume [27]. For the EON25(4)-1 ($E_g=2.65$ eV) and EON25(1)-1 ($E_g=3.15$ eV), the E_g value was lower than that of the ZnO bulk ($E_g=3.37$ eV) (Figure 10). The low E_g in EON25(4)-1 is caused by EDTA-induced changes in surface chemistry, particle morphology, and particle size. Residual EDTA-derived species, along with the spherical morphology and slightly larger dimensions, promote band-edge disorder and defect-related localized states, which enhance sub-bandgap absorption [44,45]. The extended Urbach tail supports this explanation observed for EON25(4)-1 in Figure 10a [46].

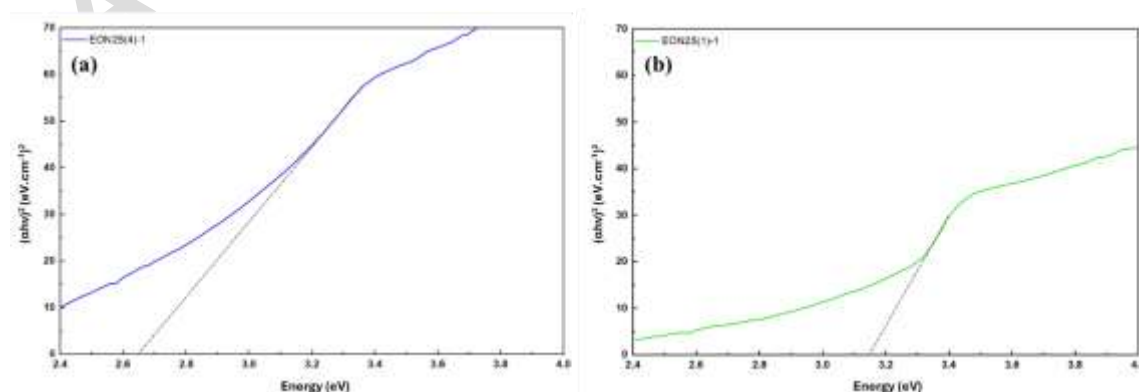


Figure 10. Tauc's plot of samples (a) EON25(4)-1 and (b) EON25(1)-1.

3.3. Phase and Structural Analysis

X-ray diffraction analysis was used to investigate the phase and crystal structure within a 2θ range of 20° to 80° (Figure 11).

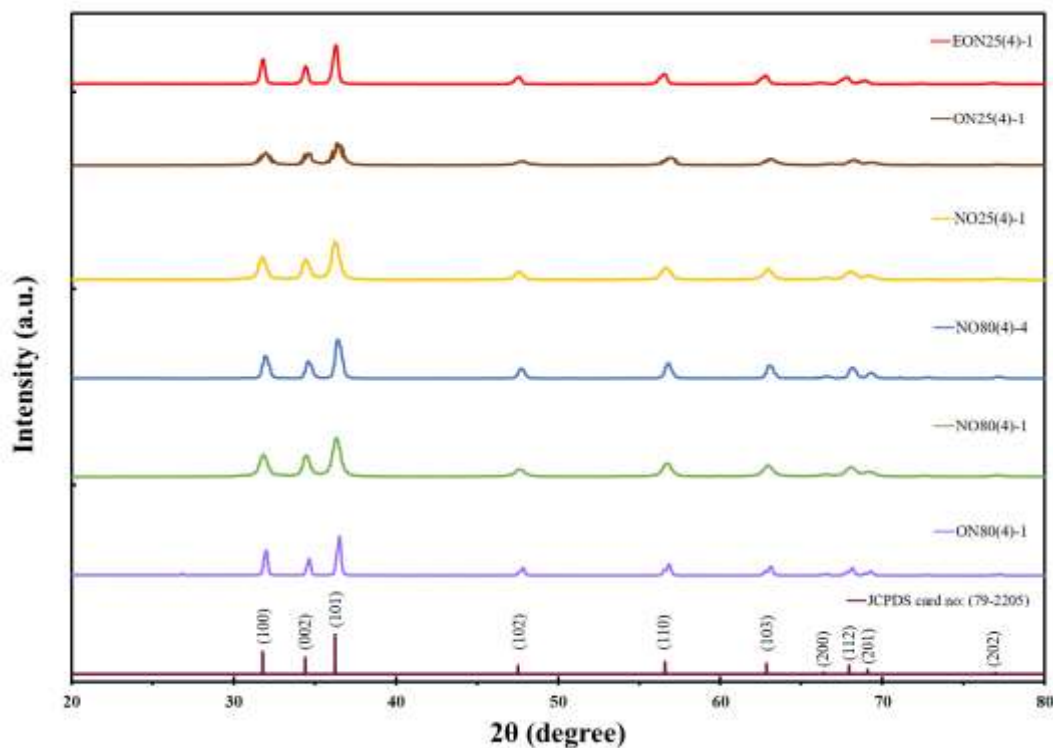


Figure 11. The XRD pattern of the synthesized ZnO-NS samples.

The diffraction pattern with peaks corresponding to the (100), (002), (101), (102), (110), (103), (200), (112), and (201) planes revealed that the synthesized ZnO-NS was pure and exhibited a hexagonal wurtzite structure (space group $p6_3mc$, JCPDS data card no. 79-2205) [11]. Using the results obtained from XRD, the hexagonal lattice parameters ‘a’ and ‘c’ were determined with Eqs. 2 and 3. The variable ‘L’ was calculated using Eq. 4, and ‘D’ was obtained with Eq. 5.

All values are given in Table 5. It is noteworthy that ‘D’ was calculated based on the average crystallite size for the first four peaks, which were at a lower 2θ and had significant intensity.

Table 5. XRD-related values of the samples

Sample name	a (Å)	c (Å)	L (Å)	D (nm)
ON80(4)-1	3.22	5.17	1.96	30
NO80(4)-1	3.24	5.20	1.97	18
NO80(4)-4	3.23	5.18	1.97	23
NO25(4)-1	3.25	5.20	1.98	18
ON25(4)-1	3.23	5.19	1.97	11
EON25(4)-1	3.24	5.20	1.97	28

Using a t-test, it was found that the values of 'a', 'c', and 'L' were very similar to the values for the JCPDS reference sample at a 95% confidence level. Therefore, changing the synthesis parameters didn't result in the formation of any new phases beyond pure ZnO. However, the one-way ANOVA indicated that the increase in 'D' values is statistically significant at the 95% confidence level due to the use of a capping agent, higher temperature, and longer stirring time. However, no definitive conclusion can be made about the change in the addition route. At 80°C, changing from ON80(4)-1 to NO80(4)-1 decreased 'D', whereas at room temperature, changing from ON25(4)-1 to NO25(4)-1 increased it. Furthermore, the increase in 'D' from 11 to 28 nm for ON25(4)-1 and EON25(4)-1 suggests that the capping agent promotes crystal growth [47]. Considering this change and previous observations, the optical cross-section might have been affected, leading to increased UV absorption [48, 49]. Although the size of 'D' varied, all values were under 100 nm. This confirms the nanostructure of the synthesized samples.

4. Conclusions

In this study, a simple and cost-effective chemical precipitation method was used to synthesize ZnO-NS. The results showed that all the synthesized ZnO-NS had a hexagonal wurtzite crystal structure with 'D' below 30 nm. The study highlighted how the main

synthesis factors influence the ZnO-NS morphology, resulting in shapes such as spherical, acicular, plate-like, and flower-like structures, with the smallest dimensions averaging 30-100 nm. The sample ON25(1)-1 had the best suspension stability over 1 to 10 days, while the sample ON25(4)-1 showed the highest UV absorbance without a capping agent. In ON25(1)-1, the anisotropic flower-like morphology with acicular-shaped petals promotes surface charge accumulation and makes it easier for particles to interact with the aqueous medium, leading to electrostatic repulsion. In ON25(4)-1, the plate-like shape provides a larger surface area, which helps in reflecting and scattering UV radiation more effectively. Adding EDTA as a capping agent caused significant agglomeration in ON25(1)-1 and increased the UV absorption in ON25(4)-1. In EON25(1)-1, a lower NaOH:Zn(NO₃)₂ molar ratio reduced EDTA deprotonation, which slowed down or even disrupted the capping process. As a result, the particles became heterogeneous and fully agglomerated within just 1 day. The most notable finding is the synthesis of the ON25(4)-1 sample, which is characterized by its plate-like structure. This EDTA-free sample demonstrated excellent suspension stability and an impressive UV absorbance of 84% at 370 nm. This sample shows great promise for helping to solve the challenges in the sunscreen industry.

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