

Research Article

EFFECT OF pH AND PRECURSOR TYPE ON GREEN-SYNTHESISED ZINC OXIDE PARTICLES USING MANGO SEED EXTRACT

Rabiatul Adawiyah Abdol Aziz^{1,✉}, Nur Arfa Zulkifli¹, Siti Fatma Abd Karim¹,
Nurul Asyikin Md Zaki¹, and Habsah Alwi¹

¹Faculty of Chemical Engineering, Universiti Teknologi MARA, 40450 Selangor, Malaysia

✉Corresponding author: Rabiatul Adawiyah Abdol Aziz ; E-mail: rabia1338@uitm.edu.my ;
ORCID: 0009-0008-2189-1283

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Abstract

Zinc oxide (ZnO) possesses optical and antimicrobial characteristics relevant to functional material applications. Plant-assisted synthesis provides an alternative to conventional ZnO synthesis routes that may involve chemical-intensive and energy-demanding processing. In this study, mango (*Mangifera indica*) seed extract (MSE) was used as a plant-derived synthesis medium to investigate the effects of pH and precursor type on ZnO characteristics. Zinc acetate dihydrate (ZA) and zinc nitrate hexahydrate (ZN) were separately mixed with MSE, adjusted to pH 5, 7, 8, 10, 12 or 14, subjected to controlled thermal and agitation treatments and subsequently recovered as dried ZnO products. The synthesised products were characterised using dynamic light scattering (DLS), zeta-potential analysis, scanning electron microscopy–energy-dispersive X-ray spectroscopy (SEM–EDX), Fourier-transform infrared spectroscopy (FTIR), X-ray diffraction (XRD) and ultraviolet–visible (UV–Vis) spectroscopy. ZA at pH 12 exhibited the most negative measured zeta potential (–25 mV) and the smallest DLS-derived hydrodynamic size of approximately 649 nm. SEM–EDX showed that all samples contain Zn and O elements and revealed predominantly spherical-to-irregular particle features for ZA, whereas ZN at pH 12 produced distinctive flower-like bundles. XRD confirmed the characteristic hexagonal wurtzite ZnO phase, with Scherrer-derived apparent crystallite sizes of approximately 17–39 nm. The larger DLS-derived hydrodynamic sizes relative to the XRD-derived apparent crystallite sizes reflected the different physical characteristics measured by the two techniques. FTIR showed Zn–O-associated absorption within approximately 400–600 cm^{–1}, while UV–Vis analysis showed pronounced absorption within approximately 250–300 nm, with the highest measured absorbance within the ZA series observed at pH 8. Overall, pH and precursor chemistry produced property-dependent responses, and no single synthesis condition provided the most favourable response across all evaluated characteristics.

1. Introduction

Zinc oxide (ZnO) is a multifunctional inorganic material with optical and antimicrobial characteristics that support its use in a range of functional material systems. Its optical behaviour enables effective interaction with ultraviolet radiation, while ZnO nanomaterials have also been widely investigated for antimicrobial functions (Irede et al., 2024). Conventional physical and chemical ZnO synthesis routes may involve hazardous reagents and substantial energy consumption, contributing to increasing interest in plant-assisted approaches that use naturally derived constituents during particle formation (Mutukwa et al., 2022).

Plant extracts contain phytochemical constituents that can participate in nanoparticle formation and act as capping or stabilising agents during green synthesis (Villagrán et al., 2024). Mango (*Mangifera indica*) seed is an agro-industrial by-product rich in bioactive compounds, including polyphenols, flavonoids and tannins (Cárdenas-Hernández et al., 2024). Aqueous mango seed extract has also been previously used as a plant-derived medium for ZnO synthesis (Rajeshkumar et al., 2023). These findings support the use of mango seed extract (MSE) as a plant-derived synthesis medium.

Reaction pH is an important synthesis variable because changes in alkalinity alter hydroxide availability and the chemical environment governing ZnO growth (Abdulrahman et al., 2021). Recent ZnO studies have demonstrated pH-dependent differences in particle morphology, crystal characteristics and optical behaviour, although the magnitude and direction of these responses vary among synthesis systems (Mechai et al., 2024). The common finding across these studies is therefore the sensitivity of ZnO formation to reaction pH rather than a universal response to increasing alkalinity. This variability suggests that pH should be interpreted together with the surrounding chemical environment rather than as an isolated determinant of the resulting ZnO characteristics.

Precursor chemistry represents another component of the synthesis environment

because different zinc salts have been shown to produce differences in ZnO morphology, crystallite size and particle-size distribution under comparable preparation conditions (Gatou et al., 2022). Plant-assisted systems introduce an additional chemical environment because phytochemicals derived from plant extracts can participate in nanoparticle formation and stabilisation (Jeevanandam et al., 2022). This is particularly relevant to MSE-assisted synthesis, in which interactions between Zn-containing species and plant-derived constituents may contribute to the resulting particle characteristics. Systematic comparison of zinc acetate and zinc nitrate across a broad pH range within the same MSE-assisted framework remains limited. The novelty of the present study therefore lies in evaluating both variables under a common synthesis environment and determining whether their effects remain consistent across colloidal, morphological, structural and optical characteristics.

Accordingly, this study investigated the effects of pH 5–14 and precursor type, namely zinc acetate dihydrate (ZA) and zinc nitrate hexahydrate (ZN), on MSE-assisted ZnO synthesis. The resulting products were evaluated in terms of DLS-derived hydrodynamic size, zeta potential, particle morphology and elemental composition, functional groups, XRD-derived apparent crystallite size and optical absorption behaviour. The objective was to determine how pH and precursor type influenced these physicochemical characteristics and whether a common synthesis condition produced favourable responses across the measured properties or whether the preferred condition was property dependent.

2. Materials and Methods

2.1. Materials

Mango (*Mangifera indica*) seeds were obtained from a local fruit-processing facility in Shah Alam, Selangor, Malaysia. Zinc acetate dihydrate ($\text{Zn}(\text{CH}_3\text{COO})_2 \cdot 2\text{H}_2\text{O}$) and zinc nitrate hexahydrate ($\text{Zn}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$) from Sigma-Aldrich® were used as Zn^{2+} precursor salts. Sodium hydroxide (NaOH), distilled water and ethanol were used for pH adjustment,

solution preparation, washing and sample preparation.

2.2. Preparation of Mango Seed Extract (MSE)

The mango seeds were cleaned, washed with tap and distilled water and finally rinsed with diluted ethanol with dilution ratio of 1:4. The seeds were oven-dried at 60 °C until constant mass, ground and sieved before storage at 4 °C.

For extraction, 1 g of mango seed powder was dispersed in 100 mL of distilled water (1:100, w/v) and stirred at 500 rpm at 70 °C for 1 h. These extraction conditions were adapted from a previously reported aqueous mango-seed-extraction approach used for plant-assisted ZnO synthesis (Rajeshkumar et al., 2023). The mixture was subsequently cooled to room temperature and filtered through Whatman No. 1 filter paper. The resulting MSE was collected and stored at 4 °C in amber glass bottles until use.

2.3. Green Synthesis of ZnO

ZA and ZN solutions were separately prepared at 0.05 M. For each synthesis condition, 10 mL of MSE was mixed with 75 mL of zinc precursor solution under magnetic stirring at 500 rpm. The pH of each mixture was adjusted to 5, 7, 8, 10, 12 or 14 by the dropwise addition of 0.1 M NaOH under continuous stirring. The mixtures were maintained at 70 °C for 1 h, followed by orbital shaking at 40 °C and 200 rpm for 1 h. These thermal and agitation conditions were adapted from a previously reported MSE-assisted ZnO synthesis procedure and were maintained consistently across all pH and precursor treatments to permit direct comparison of the two investigated synthesis variables (Kamalia et al., 2025). After standing undisturbed at room temperature for 1 h, the precipitates were recovered by filtration, washed three times with distilled water, rinsed with diluted ethanol and dried at 60 °C for 24 h. The dried products were gently ground and stored in a desiccator before characterisation.

2.4. Characterisation of Synthesised ZnO

2.4.1. Hydrodynamic Size and Zeta Potential

Hydrodynamic size and zeta potential were measured using a ZN3600 Zetasizer (Malvern Instruments Ltd., UK). Prior to measurement, 0.025 g of dried ZnO powder was dispersed in 10 mL of distilled water and ultrasonicated for 30 min. Measurements were conducted at 25 °C. The refractive index of ZnO was set to 2.0, while that of distilled water was approximately 1.333. DLS was used to determine the hydrodynamic size of redispersed particle entities, whereas folded capillary cells were used for zeta-potential measurements. Accordingly, the DLS-derived hydrodynamic size was not interpreted as the physical diameter of individual ZnO crystallites, and the measured zeta potential was not treated as a direct measurement of colloidal stability during the original synthesis reaction.

2.4.2. SEM–EDX Analysis

Surface morphology and elemental composition were examined using SEM–EDX (SU3500, Hitachi High-Technologies Corporation, Tokyo, Japan). Samples were mounted on carbon stubs, gold-coated and examined at 15–20 kV. SEM was used for qualitative comparison of external particle morphology and visible particle association. Quantitative SEM-derived particle-size distributions were not generated because image-based particle segmentation was not performed. EDX provides local elemental information from the analysed region and, particularly when standardless quantification is used, should be interpreted cautiously as qualitative or semi-quantitative compositional information rather than as definitive bulk composition (Hodoroaba, 2020).

2.4.3. FTIR Analysis

FTIR spectra were obtained using a PerkinElmer spectrometer over 4000–400 cm^{-1} at a resolution of 4 cm^{-1} and evaluated for Zn–O-associated absorption and residual surface-associated functional groups. FTIR is commonly used in plant-mediated ZnO characterisation to identify surface-associated functional groups, with Zn–O-related vibrations typically occurring in the lower-wavenumber region of approximately 400–600 cm^{-1} (Fagier, 2021).

2.4.4. XRD Analysis

XRD analysis was performed using a D/MAX-2000/PC diffractometer (Rigaku Corporation, Tokyo, Japan) equipped with Cu K α radiation ($\lambda = 1.5406 \text{ \AA}$) over $20\text{--}80^\circ 2\theta$. Diffraction patterns were compared with JCPDS No. 36-1451 for hexagonal wurtzite ZnO.

Apparent crystallite size (D) was estimated from the (101) reflection using the Scherrer equation (Hassanzadeh-Tabrizi, 2023):

$$D = \frac{k\lambda}{\beta \cos\theta} \quad (1)$$

where K is the shape factor (0.9), λ is the X-ray wavelength ($1.5406 \text{ \AA}$), β is the full width at half maximum (FWHM) of the selected diffraction reflection expressed in radians, and θ is the corresponding Bragg angle. The Scherrer-derived values represent the size of coherently diffracting crystalline domains and were therefore reported as apparent crystallite sizes rather than particle sizes.

2.4.5. UV-Vis Analysis

Optical absorption was evaluated using a UV-1900i UV-visible spectrophotometer (Shimadzu) over $200\text{--}800 \text{ nm}$, and the spectra were compared among pH and precursor conditions. UV-Vis spectroscopy is commonly used to evaluate the optical response of biosynthesised ZnO, including changes in ultraviolet absorption associated with different synthesis conditions (Suciyati et al., 2024). The resulting spectra were compared among pH and precursor conditions.

2.5. Data Analysis

All synthesis conditions were prepared using three independent synthesis replicates, and

instrumental analyses were conducted using three technical replicates for each independent synthesis replicate. Quantitative data for which replicate measurements were available were summarised as mean $\pm$ standard deviation. Comparisons among pH conditions and between the ZA and ZN precursor systems were performed descriptively. No inferential statistical tests were conducted; therefore, differences among synthesis conditions were interpreted as observed trends and were not described as statistically significant. Technical replicates were used to assess measurement repeatability and were not treated as independent experimental units.

3. Results and Discussion

3.1. Physical Observation

Visible precipitation varied with synthesis pH and precursor system (Fig. 1). Only a small amount of precipitate was observed at pH 5, whereas greater white precipitate formation occurred under more alkaline conditions, particularly between pH 8 and 12. Increasing alkalinity (OH^-) modifies the $\text{Zn}^{2+}/\text{OH}^-$ chemical environment and can promote zinc hydrolysis, supersaturation and subsequent nucleation and crystal development (Mechai et al., 2024). However, intermediate zinc species, supersaturation and nucleation rates were not measured directly in the present study. The visual observations therefore demonstrate pH-dependent precipitation behaviour but do not independently establish the reaction pathway responsible for ZnO formation. The composition and crystalline characteristics of the recovered products were subsequently evaluated using EDX, FTIR and XRD.

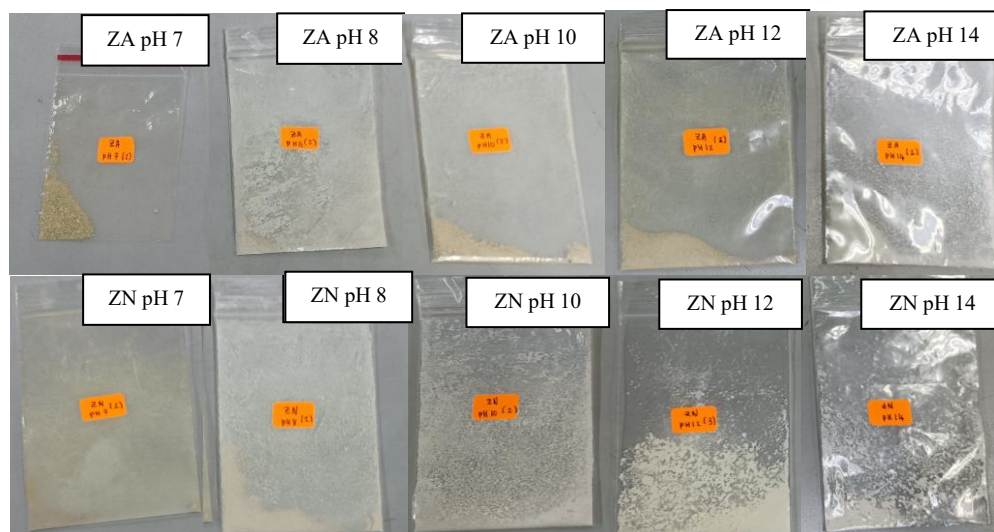


Figure 1. ZnO products synthesised using MSE at different pH conditions and precursor types.

3.2. Zeta Potential and Hydrodynamic Size

Zeta potential and DLS revealed descriptive differences between precursor and pH conditions (Table 1). ZA at pH 12 exhibited the most negative measured zeta potential (-25 mV) and the smallest hydrodynamic size of

approximately 649 nm. Zeta-potential magnitudes within approximately the ± 20 to ± 30 mV range are commonly associated with appreciable electrostatic stabilisation, although they do not necessarily indicate complete colloidal stability (Sultan et al., 2024).

Table 1. Zeta potential and DLS-derived hydrodynamic size of ZnO synthesised using zinc acetate dihydrate (ZA) and zinc nitrate hexahydrate (ZN) at different pH values.

ZA					ZN				
pH	Zeta potential (mV)	SD	Hydrodynamic size (nm)	SD	pH	Zeta potential (mV)	SD	Hydrodynamic size (nm)	SD
7	-4.99	0.71	4218.00	845.99	7	-4.61	0.22	1923.33	264.23
8	-21.07	0.38	1143.33	87.80	8	-15.40	2.63	1618.33	189.47
10	-8.17	0.46	3440.00	972.12	10	-13.50	0.10	1610.33	237.39
12	-25.00	0.10	649.20	40.63	12	-6.39	1.14	2156.67	408.16
14	4.01	0.24	2426.33	485.15	14	-18.00	0.62	2252.33	200.24

Note: Values are presented as mean $\pm$ standard deviation from three independent synthesis replicates, with instrumental measurements conducted in triplicate. No inferential statistical comparisons were performed; therefore, differences among conditions are interpreted descriptively.

The most negative measured zeta potential and smallest hydrodynamic size within the ZA series were both observed at pH 12. This coincidence is consistent with greater electrostatic repulsion and reduced association of the redispersed particle entities under the measurement conditions. However, the present descriptive dataset does not establish a statistically significant relationship or a direct causal relationship between zeta potential and hydrodynamic size. Particle morphology, surface chemistry and dispersion history may

also contribute to the measured hydrodynamic response. The response also differed between precursor systems. ZN-derived products exhibited zeta potentials of approximately -4 to -18 mV and predominantly micrometre-scale hydrodynamic dimensions, whereas ZA showed a broader response and reached approximately 649 nm at pH 12. Precursor-dependent differences in DLS-derived size, morphology and other physicochemical characteristics have similarly been reported for ZnO synthesised from different zinc salts (Gatou et al., 2022).

Therefore agreement lies in the sensitivity of ZnO particle behaviour to precursor chemistry rather than in reproduction of an identical precursor-specific size response. Since the present measurements were performed after dried ZnO had been redispersed in water, the results describe the hydrodynamic behaviour of the redispersed products rather than particle dimensions or colloidal stability during the original synthesis reaction.

3.3. Surface Morphology and Elemental Composition

SEM showed predominantly spherical-to-irregular associated particle structures, with visible clustering under several synthesis conditions (Fig. 2). The most evident precursor-dependent difference occurred at pH 12, at

which ZA exhibited predominantly spherical-to-irregular features whereas ZN formed distinctive flower-like bundles despite both being processed at the same nominal pH and Zn^{2+} concentration. Previous work comparing zinc acetate- and zinc nitrate-containing ZnO synthesis systems has likewise demonstrated that precursor composition can modify ZnO microstructure, aggregation and morphology (Kaenphakdee et al., 2022). However, the specific morphologies reported in that study were not identical to those observed in the present MSE-assisted system. This comparison indicates that precursor chemistry can influence ZnO morphology, but the resulting morphology also depends on the surrounding synthesis environment rather than being determined solely by the identity of the zinc salt.

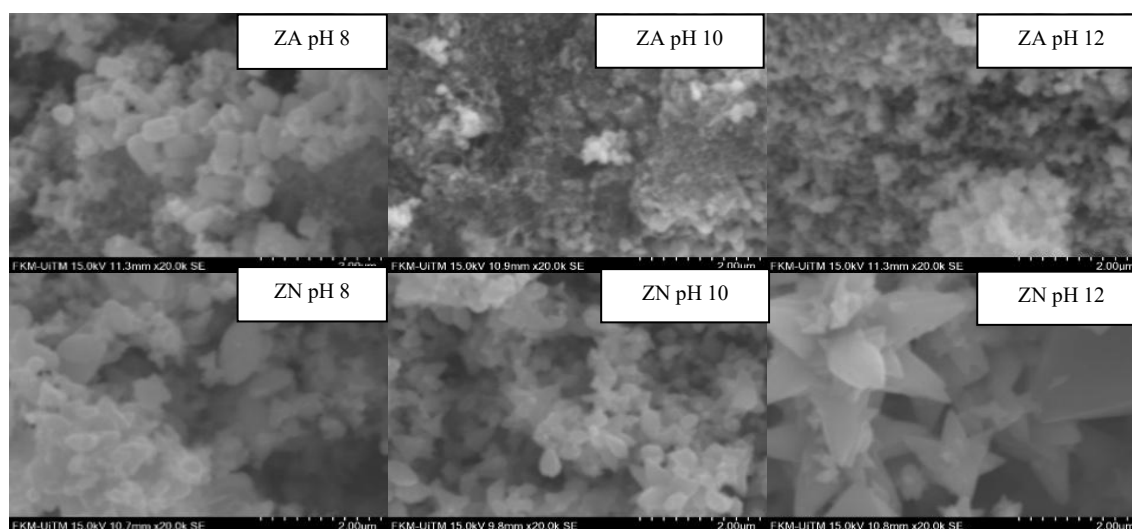


Figure 2. SEM micrographs of ZnO synthesised at different pH conditions using ZA and ZN at 20,000× magnification.

A plausible interpretation is that precursor chemistry modified the ionic and coordination environment surrounding Zn-containing species during nucleation and subsequent particle development. However, precursor-specific Zn^{2+} complexation, intermediate hydroxo species and crystallographic growth rates were not measured directly. The SEM evidence therefore demonstrates a precursor-dependent morphological response but does not establish the molecular mechanism responsible for that response. Quantitative image segmentation was

not performed; therefore, numerical SEM-derived particle-size distributions were not generated. SEM was consequently used to compare external particle morphology and visible particle association rather than to quantify particle diameter. These observations were interpreted together with the DLS-derived hydrodynamic sizes and XRD-derived apparent crystallite sizes because the three techniques describe different levels of particle organisation.

EDX spectra were dominated by Zn and O, with local semi-quantitative compositions of

approximately 86–89 wt% Zn and 11–13 wt% O. These elemental signals complement the Zn–O-associated FTIR absorption and wurtzite reflections observed by XRD. EDX provides spatially localised elemental information and its quantitative interpretation for nanoparticles is subject to analytical and sampling limitations. Therefore, EDX commonly used as qualitative

or semi-quantitative compositional evidence rather than as an automatic measure of bulk composition (Hodoroaba, 2020). Accordingly, the measured compositions were interpreted as evidence for the local presence of Zn and O rather than as quantitative confirmation of bulk chemical purity.

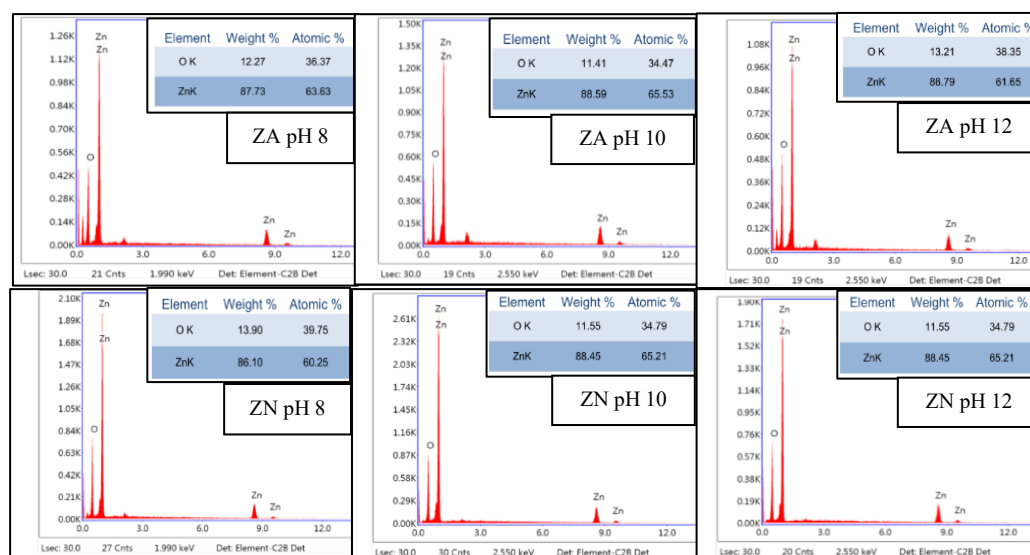


Figure 3. EDX spectra of ZnO synthesised at different pH conditions using ZA and ZN.

3.4. Functional Group Analysis

As shown in Fig. 4, FTIR spectra showed broad O–H-associated absorption within approximately 3200–3600 cm^{-1} and organic-associated bands within approximately 2800–3000 and 1400–1650 cm^{-1} . Their persistence after particle recovery and washing is consistent with residual MSE-derived constituents remaining associated with the recovered material. Plant-mediated ZnO systems commonly exhibit FTIR bands associated with hydroxyl- and other organic functional groups originating from plant-derived constituents, which may participate in interactions with Zn-containing species during synthesis (Fagier, 2021).

Hydroxyl- and carbonyl-containing groups have been proposed to participate in Zn^{2+} coordination and surface stabilisation during plant-assisted ZnO synthesis. In the present study, however, FTIR did not identify the

individual phytochemical compounds responsible for these bands or directly demonstrate their role during nucleation. Their involvement should therefore be regarded as a mechanistically plausible interpretation rather than evidence of a specific synthesis pathway.

Zn–O-associated absorption was observed within approximately 400–600 cm^{-1} . Zn–O stretching vibrations in plant-mediated ZnO are commonly reported within this lower-wavenumber region (Fagier, 2021). FTIR alone does not demonstrate crystalline ZnO formation; consequently, these bands were interpreted together with the local Zn and O signals detected by EDX and the characteristic wurtzite reflections identified by XRD. Convergence of the three independent characterisation techniques provides stronger evidence for ZnO formation than interpretation based on any single measurement.

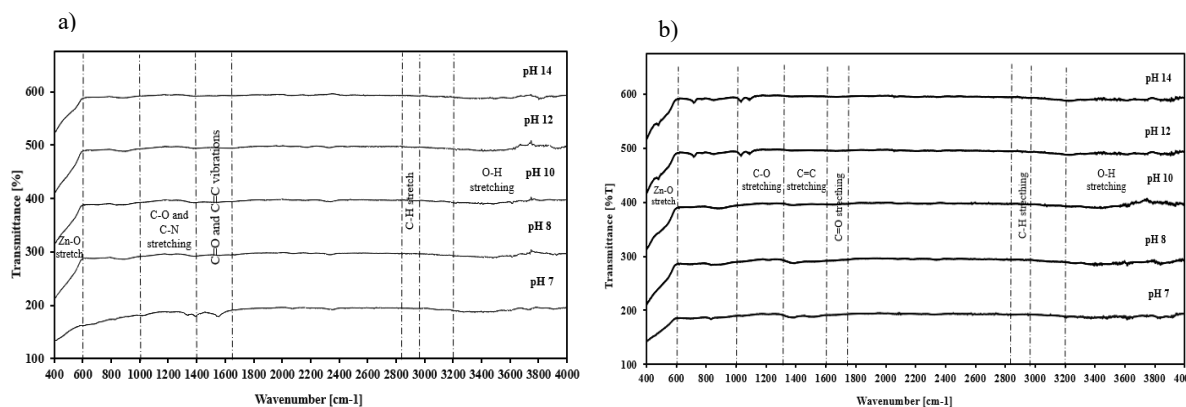


Figure 4. FTIR spectra of ZnO synthesised using MSE at different pH conditions with (a) zinc acetate dihydrate and (b) zinc nitrate hexahydrate.

3.5. Structural Characterisation

XRD patterns exhibited characteristic reflections at approximately 31.5° , 34.1° , 36.0° , 47.2° , 56.2° , 62.5° , 66.0° , 67.6° and 68.8° 2θ , corresponding to the principal crystallographic planes of hexagonal wurtzite ZnO (Fig. 5). Comparable ZnO reflections at approximately 31.7° , 34.3° , 36.2° , 47.5° , 56.5° , 62.8° and 67.9° 2θ have been reported for mango-assisted ZnO and assigned to the characteristic hexagonal

wurtzite structure (Endah et al., 2023). Importantly, both ZA- and ZN-derived products retained the same principal wurtzite phase despite the precursor-dependent morphological differences observed by SEM. Thus, precursor chemistry affected particle development without producing an observable change in the principal ZnO crystalline phase under the investigated conditions.

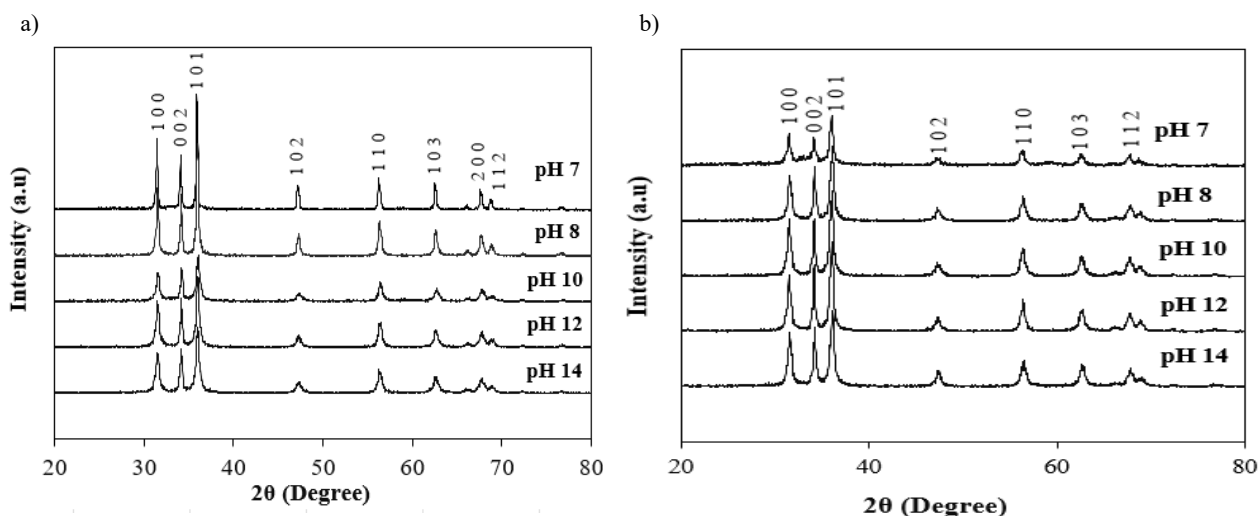


Figure 5. XRD patterns of ZnO synthesised using MSE at pH 7–14 with (a) zinc acetate dihydrate and (b) zinc nitrate hexahydrate.

Apparent crystallite sizes varied descriptively with both pH and precursor type (Table 2). For ZA, the apparent crystallite size decreased from 38.517 nm at pH 7 to 18.488 nm at pH 14, although the response was non-monotonic, with an increase from 18.995 nm at

pH 10 to 21.333 nm at pH 12. The ZN series showed a narrower range from 20.676 nm at pH 7 to 16.706 nm at pH 14, also with intermediate fluctuations. Changes in alkaline synthesis conditions and NaOH concentration have previously been shown to modify ZnO crystal

development and apparent crystallite dimensions in biosynthesis systems (Suciyati et al., 2024). Increased OH^- availability may therefore contribute to altered supersaturation and nucleation behaviour, providing a plausible explanation for the generally smaller coherent crystalline domains observed at higher pH.

However, because neither nucleation density nor crystal-growth kinetics was directly measured, the present XRD data demonstrate variation in apparent crystallite sizes but do not establish the kinetic mechanism responsible for that variation.

Table 2. Apparent crystallite sizes of ZnO synthesised under different pH conditions using zinc acetate dihydrate and zinc nitrate hexahydrate, estimated from the (101) reflection using the Scherrer equation

Precursor	pH	Apparent crystallite size (nm)	Precursor	pH	Apparent crystallite size (nm)
Zinc acetate dihydrate	7	38.517	Zinc nitrate hexahydrate	7	20.676
	8	30.814		8	17.552
	10	18.995		10	18.008
	12	21.333		12	19.809
	14	18.488		14	16.706

The comparison between ZA and ZN further demonstrates that precursor effects were not constant across the pH range. At pH 7, the apparent crystallite sizes were 38.517 nm for ZA and 20.676 nm for ZN, whereas at pH 14 the corresponding values were 18.488 and 16.706 nm. The difference between the two precursor systems therefore narrowed under the more alkaline condition. Independent comparison of zinc acetate and zinc nitrate has also demonstrated precursor-dependent differences in ZnO morphology and crystallite size (Limón-rocha et al., 2022). Taken together, the studies agree that precursor chemistry influences crystal development, but the specific magnitude and direction of the response depend on the surrounding synthesis environment. The present results therefore do not support the assumption that either ZA or ZN inherently produces smaller ZnO crystallites independent of pH.

The XRD-derived apparent crystallite sizes of approximately 17–39 nm were substantially smaller than the DLS-derived hydrodynamic sizes of approximately 649–4218 nm. This difference does not represent disagreement between the techniques because they quantify different physical characteristics. The Scherrer equation estimates the size of a coherently diffracting crystalline domain, whereas DLS

determines the hydrodynamic behaviour of dispersed entities that may contain multiple associated crystallites, surface-associated species and the surrounding solvation layer. SEM independently showed visible particle association under several synthesis conditions. Taken together, the evidence supports the interpretation that nanoscale ZnO crystalline domains occurred within larger associated particulate structures following redispersion. XRD, DLS and SEM were therefore interpreted as complementary assessments of apparent crystallite size, hydrodynamic association and external morphology, respectively, rather than as interchangeable particle-size measurements.

3.6. Optical Properties

All investigated ZnO products exhibited pronounced UV absorption within approximately 250–300 nm (Fig. 6). Strong ultraviolet absorption is characteristic of ZnO materials, while the exact absorption position and intensity can vary with synthesis route and resulting physicochemical characteristics; green-synthesised ZnO systems have likewise shown synthesis-dependent UV–Vis absorption responses (Aalami et al., 2024). The agreement therefore lies in the presence of a pronounced

UV response rather than in an identical absorbance trend across synthesis systems.

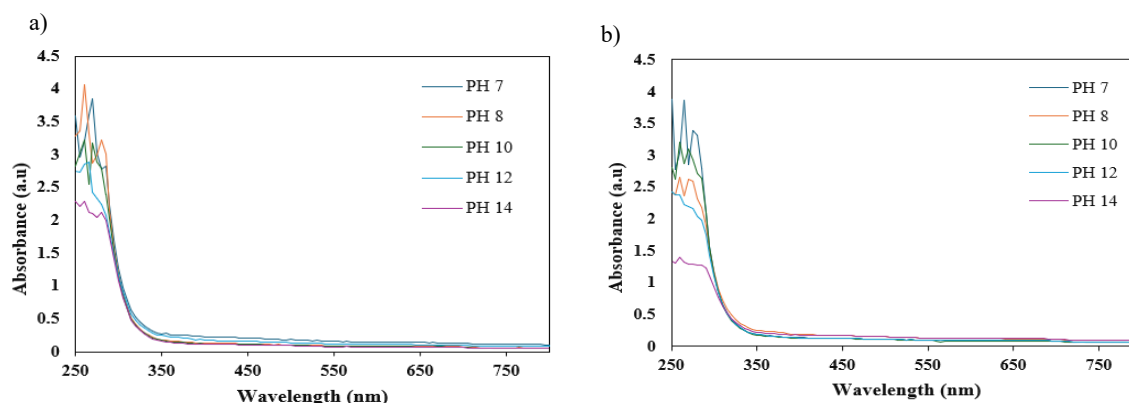


Figure 6. UV–Vis absorption spectra of ZnO synthesised using MSE at pH 7–14 with (a) zinc acetate dihydrate and (b) zinc nitrate hexahydrate.

Within the ZA series, the highest measured absorbance occurred at pH 8, whereas pH 14 produced the lowest response. In contrast, the ZN series showed its highest absorbance at pH 7 and generally lower responses at increasing pH. The differing trends between ZA and ZN under the same investigated pH range indicate that increasing alkalinity did not produce a common optical response for both precursor systems. Particle morphology, degree of association and crystalline characteristics can influence ZnO optical behaviour, although their individual contributions cannot be separated from absorbance measurements alone. Accordingly, their individual contributions could not be resolved quantitatively in the present study.

Importantly, the condition associated with the most favourable measured colloidal response was not the same condition associated with the highest measured optical response. ZA at pH 12 exhibited the most negative zeta potential and smallest hydrodynamic size, whereas ZA at pH 8 produced the highest measured absorbance within the ZA series. ZN at pH 12 additionally exhibited a distinctive flower-like morphology while retaining the principal wurtzite phase. These cross-characterisation differences provide direct evidence that the effects of pH and precursor chemistry were property dependent. Consequently, no single pH–precursor condition

can be designated as universally optimal from the present dataset.

4. Conclusion

MSE-assisted ZnO synthesis produced pH- and precursor-dependent differences across the measured physicochemical characteristics. ZA at pH 12 exhibited the most negative measured zeta potential of -25 mV and the smallest DLS-derived hydrodynamic size of approximately 649 nm, whereas ZN at pH 12 exhibited distinctive flower-like particle structures. XRD confirmed the characteristic hexagonal wurtzite ZnO phase with apparent crystallite sizes of approximately 17–39 nm. The substantially larger DLS-derived hydrodynamic sizes relative to the XRD-derived apparent crystallite sizes, together with visible particle association observed by SEM, support the interpretation that nanoscale crystalline domains occurred within larger associated particulate structures following redispersion. UV–Vis analysis showed pronounced absorption within approximately 250–300 nm, with the highest measured absorbance within the ZA series observed at pH 8.

The principal finding was that the favourable synthesis condition depended on the physicochemical characteristic being considered. ZA at pH 12 provided the most favourable measured colloidal response, ZA at

pH 8 produced the highest measured absorbance within the ZA series, and ZN at pH 12 exhibited a distinctive precursor-dependent morphology. Because the comparisons were descriptive and no inferential statistical tests were conducted, these differences should be interpreted as observed trends rather than statistically demonstrated treatment effects. Nevertheless, the combined DLS, SEM–EDX, FTIR, XRD and UV–Vis evidence indicates that pH and precursor chemistry were associated with non-identical responses across the evaluated characteristics.

The present study did not determine intermediate zinc species, quantitative surface chemistry, antimicrobial activity, safety or functional behaviour following incorporation into a polymer matrix. The powder-level findings therefore provide a basis for selecting ZnO conditions for subsequent property-specific validation rather than evidence of direct food-packaging or biomedical performance. Future research should evaluate antimicrobial activity, safety, polymer-matrix compatibility and whether the physicochemical differences observed among the ZnO products are retained following incorporation into biodegradable films.

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