RESEARCH PAPER

Valorization of Zahidi Date Palm Waste for Green Synthesis of ZnO Nanoparticles: Phytochemical-Driven Morphology Controlled

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ABSTRACT

It's a sustainable and environmentally friendly method for reducing agricultural waste, while in the meantime it helps for the production of additional valuables. The production of ZnO nanoparticles by using green method employing four different Zahidi date palm (*Phoenix dactylifera* L.) residue aqueous extracts such as kernels, spines, leaflets and fibers are reported in the present investigation. The phytochemical content analyses of the prepared extracts show a variation in secondary metabolites for each extract and are discussed to find its role in the formation of nanoparticles and morphology. Kernels extract exhibited the highest total phenolic and flavonoid contents, while leaflet extract showed the highest saponin contents, and spines extract contained the highest alkaloid content. The prepared biosynthesized ZnO nanoparticles were characterized using UV-visible, FTIR, XRD, FESEM, and EDX techniques.Distinct ZnO morphologies were obtained depending on the residues used during synthesis. Kernels extract produced flower-like nanostructures, spines extract generated spherical nanoparticles, leaflet extract formed sheet-like structure, and fiber extract resulted in dense irregular nanostructures. Since all synthesis conditions were maintained constant, the variation in ZnO morphology was mainly attributed to residue-dependent phytochemical differences.

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INTRODUCTION

Recently, environmental sustainability has become one of the most important areas of scientific research, particularly in the field related to material production and resource and waste management [1]. As agricultural activities continue to grow, large quantities of plant waste are generated that are often discarded by burning or abandonment, leading to negative environmental impacts and the loss of resources that can be exploited [2]. In this sense, agricultural waste is no longer seen only as an environmental burden, but has become a genuine opportunity to produce value-added from renewable sources. Converting waste products into usable materials following circular economy principles

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leads to improved resource efficiency and helps minimize environmental pollution while fostering sustainable growth. This is emphasized by Silva et al. [3].

Keeping this viewpoint in mind and fitting this global shift, nanotechnology emerges as a promising path for optimizing resource management. Nanomaterials are increasingly prominent due to their unique characteristics stemming from their microscopic dimensions and large surface area to volume ratio [4]. These characteristics make nanomaterials invaluable in numerous sectors, such as medicine, pollution control and agriculture [5]. In addition to the impact of their size, the significance of nanomaterials is heightened by our ability to manipulate their structural features and shapes, which allows for the tailoring of materials to perform specific roles in various applications [6]. Among various nanomaterials, zinc oxide nanoparticle has emerged as a multifunctional material due to their chemical stability, optical activity, surface activity, and biological properties, and make it a promising candidate for applications in environmental technology, biomedical fields, and agricultural practices [7].

Recently, the green approach has emerged as an environmentally friendly option for nanoparticles production, driven by growing environmental awareness and the development of sustainable approaches in the field of nanotechnology. This is because traditional chemical and physical methods often involve complex procedures, toxic chemicals, and high energy consumption [8]. Particularly, plant-mediated biosynthesis has revealed significant attention, as plant extracts can serve as reducing agents, stabilizers, and coating during the formation of nanoparticles [9]. These extracts are rich in bioactive compounds like phenolics, flavonoids, tannins, saponins, alkaloids carbohydrates, and organic acids. Which play an important role in the reduction of metal ions and the stabilization of nanoparticles [10]. This aspect could affect the resulting morphology, nucleation rate, rate of growth, as well as properties, otoxicity, cost-effectiveness and environmental impact. [11].

In this context, agricultural crop residues could also serve as a cheaper source of plant extracts for biological plant-mediated synthesis. In contrast to plants, it avoids taking the entire useful plant into waste, as crop residues have minimal economic uses for agriculture, which could otherwise create a substantial quantity of biodegradable waste [2]. The use of these crop residues to develop value - added materials, by making useful materials with sustainable and clean methodology, reduces soil degradation and accumulation of waste. In this context, date palm residue has attracted considerable attention, owing to its ready availability, high yield, cost - effectiveness, as well as high nutritional quality, with good potential to act as an ideal choice to prepare Ag nanomaterials via green approach [12].

This issue is particularly important in Iraq, where date palms are a strategic crop, and the Zahidi cultivar accounts for more than 40% of the number of trees and more than 50% of date production [13]. As a result, large quantities of agricultural residues associated with this variety, such as kernels, spines, leaflets and fibers, are generated. Although these wastes are available in large quantities, their investment in advanced applications is still limited. There is a need to develop innovative ways to convert these wastes into value-added materials, reducing the environmental impact and enhancing the use of local resources.

However, different waste residues from a single plant may not share the same bio-chemical constituents. Therefore, the amount of various bio-components like phenols, flavonoids, saponins, and/or alkaloids could vary, which might be directly reflected in a change of reduction ability, crystallization direction and rate and even shape of the produced nanoparticles [14].

However, most previous studies have focused on only one plant part, or used different synthesis conditions, making it difficult to understand the true impact of the extract's chemical composition on the properties of nanoparticles. Therefore, comparative studies using different parts of the same plant under similar synthesis conditions is essential to understand this effect more accurately.

Based on the above, this study aimed to synthesize zinc oxide nanoparticles using aqueous extracts of four different residues of date palm variety, namely seeds, spines, leaflets and fibers, as reducing and stabilizing agents. This work also aimed to analyze the phytochemical composition of date palm residues and relate this analysis to the physical (compositional, optical and morphological) and chemical properties of the resultant synthesized nanoparticles. Thus, this work may not be beneficial to the sustainable production of environmentally friendly nanoparticles but to gain clearer insight into variation in chemical compounds in plants influencing morphology control. Furthermore, date palm residues should be able to be a sustainable source to obtain high-value nanomaterials. The novelty of this work lies in the direct comparative green synthesis of ZnO nanoparticles using four parts (kernels, spines, leaflets and fibers) of a single dominate date palm variety under controlled laboratory settings and using all four under exactly the same environmental condition. Previous works did focus on green synthesis of ZnO nanoparticles from a variety of sources or different residue types. But in contrast, to these previous works, the present study selected kernels, spines, leaflets and fibers of a single common date palm to be utilized as reducing and stabilizing agent for green fabrication of ZnO nanoparticles all in one study and under identical experiment conditions, allowing the dependence of the nature of phytochemical contents on controlled nanoparticle synthesis to be more accurately evaluated and to provide better specific insight into phytochemical-influenced control on the morphology of ZnO nanostructures.

MATERIALS AND METHODS

Materials

Zinc acetate dihydrate Zn $(CH_3COO)_2 \cdot 2H_2O$ with 99% purity, BDH, England was used as the zinc precursor for the synthesis of zinc oxide nanoparticles. Deionized water, and ethanol were used during the extract preparation, nanoparticles synthesis, washing, and solution preparation processes. The plant materials used in this study were date kernels, leaflets, fibers, and palm spines, which were collected from an orchard in Babylon Province, Iraq.

Preparation of plant residues extracts

Four plant residues of *Phoenix dactylifera* L. var Zahidi were shade-dried at room temperature for seven days and then subsequently ground into fine powder using Super Crest electric grinder 2000 W. To prepare the aqueous extracts, 5 g of each powdered sample was separately mixed with 100 mL of Deionized water. The mixtures were heated at 50-60 °C for 45 min under continuous stirring to aid the extraction of the bioactive compounds. The resulting solutions were then left to cool to room temperature and filtered to obtain a clear aqueous extract, which were used in the subsequent biosynthesis process [15].

Characterization of plant extracts

Phytochemical analysis of plant residues extracts

The aqueous extracts were analyzed to assess their phytochemical composition and to evaluate the possible relationship between extract chemistry and nanoparticle formation. Total phenol content (TPC) was determined using Folin-Ciocalteu method and total flavonoid content (TFC) was measured using colorimetric aluminum chloride complex method according to [16] with some modifications. Total tannin content (TTC) was measured according to [17] with minor adjustments. Total alkaloids content (TAC) was determined according to [18] with some modification. Total Saponins content (TSC) was assessed according to [19] with some modifications. All measurements were performed in triplicate for each plant extract.

Spectroscopic and structural characterization of plant extracts

The aqueous extracts of date palm residues were characterized using several techniques. UV-Visible spectroscopy was used to assessed the absorption spectra of bioactive compounds. FTIR analysis was performed to determine the major functional groups present in the extracts. XRD analysis was conducted to examine the structural characteristics of the plants extracts and to know the crystalline or non-crystalline phases present in the extracts.

Biosynthesis of ZnO nanoparticles

A 0.02M of zinc acetate was prepared by dissolving 2.195 g of zinc acetate dihydrate in 500 mL of Deionized water. The solution was heated at 50-60 °C and magnetically stirred for 30 minutes to achieve homogeneity. Subsequently, 25 ml of plant residue extracts were added separately and gradually to the zinc acetate solution under continuous stirring. A few drops of NaOH were then added to adjust the PH of mixture to 12. The reaction was allowed to continue until a visible suspension and precipitate formed as shown in (Fig. 1), indicating the formation of ZnO nanoparticles [20].

Purification and drying of nanoparticles

Following precipitate formation, the obtained product was collected by filtration and washed several times with deionized water and ethanol to remove residual impurities and excess organic

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constituents. Finally, the washed precipitate was then dried in an oven at 70–80°C to obtain a dry ZnO nanoparticles powder [21].

Characterization of ZnO nanoparticles

The synthesized ZnO nanoparticles were characterized using several analytical techniques. X-ray diffraction (XRD) was used to determine the crystalline phase and estimate crystal size of the obtained nanoparticles. FTIR was performed to detect the functional groups found in the synthesized material, the role of which can be played by plant components during the formation of nanoparticles, whereas, the UV - Visible spectrophotometer was used to assess the optical properties of the produced nanoparticles. SEM was employed to investigate the surface morphology of ZnO nanoparticles and EDX analysis confirmed the presence of elements that compose ZnO nanoparticles. ZnO nanoparticle synthesis with plant extracts is depicted in Fig. 1.

Experimental design and comparison

A comparative experiment was conducted in this study with four plant residues derived from the same date palm cv. Zahidi: the kernels, spines, leaflets and fibers. All experiments were performed with identical reaction conditions including the concentration of the zinc precursor, the volume of extract, reaction temperature, pH, reaction duration, incubation period, centrifugation step and drying procedure to examine how differences in phytochemical compounds in plant residues influence ZnO nanoparticle synthesis, crystallinity and Morphology.

Statistical analysis

Statistical analysis was performed using SPSS statistics software (version 26.00) according to [22] with minor modification. All phytochemical analyses of plant residue extracts were performed

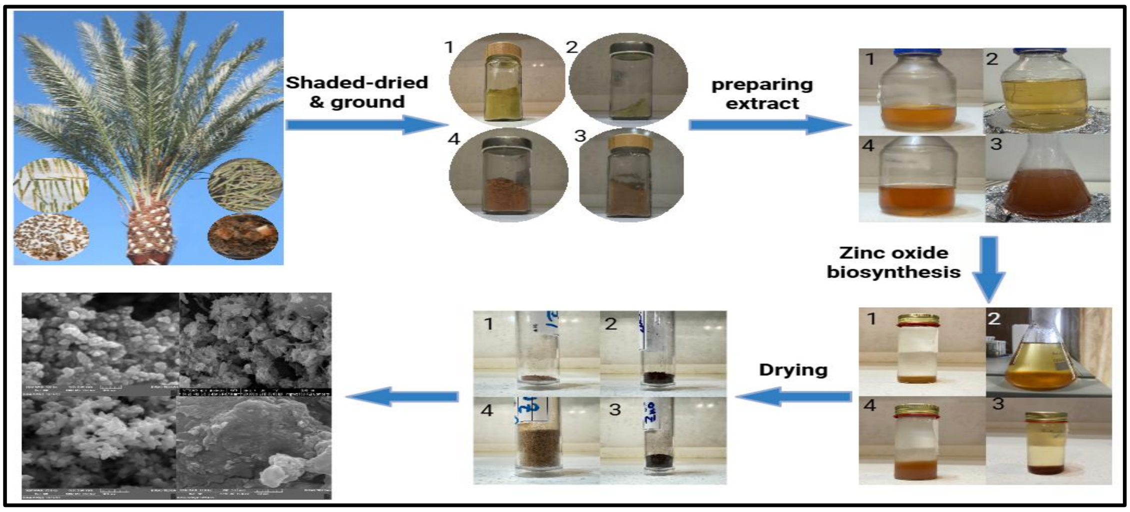

Fig. 1. Preparation stages of ZnO-NPS using four date palm residue extracts: (1) Spines (2) Leaflets (3) Kernels (4) Fibers.

Table 1. Phytochemical composition of aqueous extracts obtained from date palm residues. Values expressed as mean ± standard deviation (n=3).

Plant residues	Phenolics TPC mg GAE/g	Flavonoids TFC mg QE/g	Tannins TTC mg TAE/g	Saponins TSC mg DE/g	Alkaloids TAC mg AE/g
Kernels	21.26 ±1.09^{a}	18.90 ±0.38^{a}	7.64 ±0.61^{a}	18.35 ±0.94^{b}	18.03 ±3.01^{b}
Spines	13.62 ±0.22^{b}	15.11 ±0.25^{b}	5.22 ±2.1^{ab}	16.39 ±1.13^{b}	33.05 ±2.01^{a}
Leaflets	16.36 ±0.49^{c}	8.06 ±1.22^{c}	3.35 ±0.69^{b}	26.37 ±1.84^{a}	11.66 ±2.13^{c}
Fibers	4.82 ±0.35^{d}	6.01 ±0.64^{d}	7.52 ±2.23^{a}	11.64 ±1.9^{c}	21.18 ±1.00^{bc}

Different letter within the same column indicates significant differences (p<0.05) based on Tukey's HSD test.

in triplicate, and the obtained values were expressed as mean ± standard deviation (mean ± SD). One-way analysis of variance (ANOVA) was used to evaluate the differences among the studied groups. When significant differences were detected, the multiple comparisons of bioactive compounds between plant residues extracts were performed using Tukey's HSD post hoc at a significance level of $p < 0.05$.

RESULT AND DISCUSSION

Characterization of plant extracts

Phytochemical analysis of plant extracts

The phytochemical composition of the aqueous extracts obtained from different residues of date palm Zahidi as in Table 1. The different plant parts varied from each other about each of the determined phytoconstituents ($p<0.05$). The kernels extract resulted in the highest amount of total phenolics content (21.26 ±1.09 mg GAE/g) and total flavonoids content (18.90 ±0.38 mg QE/g) followed by leaflet extract. The least amounts of phenolics and flavonoids were found in the fiber extract, which might've resulted in a weaker reducing capacity toward metal ions. Saponin content was the highest (26.37 ±1.84 mg DE/g) in Leaflet, where the highest total alkaloids content (33.05 ±2.01 mg AE/g) was noticed in the Spines and kernels extract obtained highest total tannins (7.64 ±0.61 mg TAE/g). These findings showed that these plant parts have different phytoconstituent profiles which were likely affect the reduction of metal ions and to stabilize the formed nanostructure particles that also determine their nanostructure shape [23].

X Spectroscopic and structural characterization of plant extracts

UV-Visible of plant residues extract

The UV-Visible spectra of aqueous extracts obtained from various Zahidi date palm residue parts are presented in Fig. 2. The spectra revealed distinct peaks within the absorption range of 285 to 307 nm. Such peaks indicate the presence of phytochemicals that are capable of reducing zinc ions [24]. The kernels' extract achieved the greatest absorption peaks at 307 nm, yielding an absorption intensity of 1.8, whereas the spines', leaflet's and fiber's extracts respectively showed absorption peaks at 285, 289 and 292 nm and absorption intensities at 0.95, 2.2 and 1.4. These absorption bands correspond to the π-π* and n-π* electronic transitions typical of phenolic and flavonoid compounds. The slightly larger

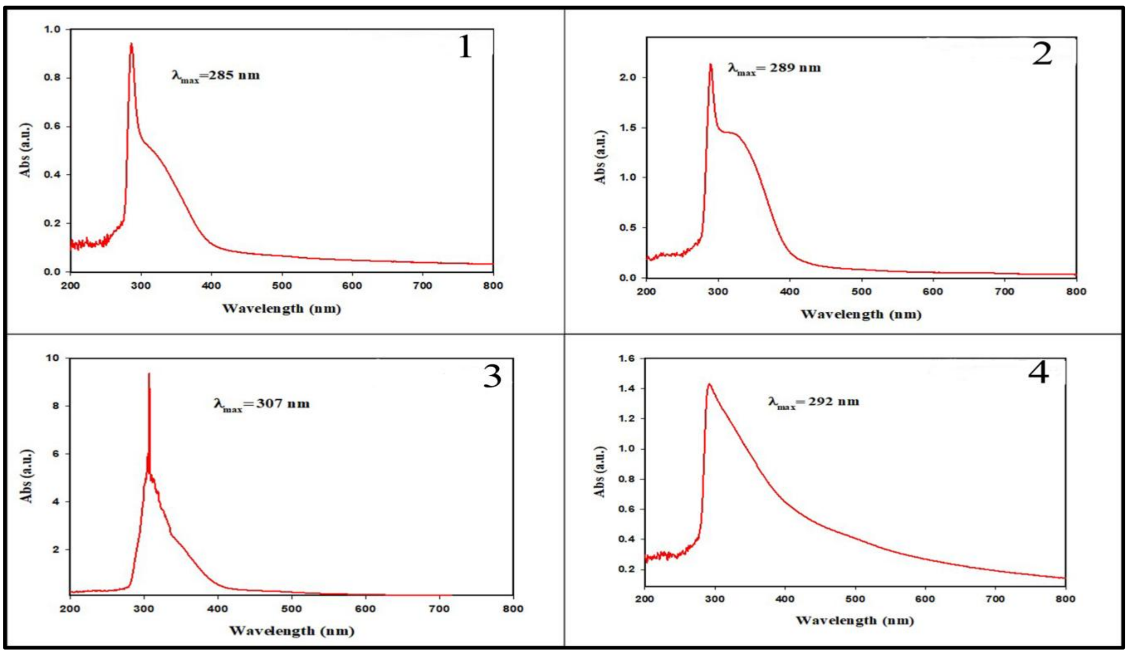

Fig. 2. UV-Visible analysis of date palm residue extracts.

wavelength observed for the kernels' extract suggests its phytochemical makeup may be richer or more conjugated than the other parts. This observation aligns well with the kernels' reported higher phenolic and flavonoid content [25].

FTIR analysis of plant extracts

The FTIR analysis of the aqueous extracts obtained from different Zahidi date palm residues are presented in Fig. 3. FT-IR analysis revealed the presence of several functional groups in all extracts, indicating their potential role in ZnO nanoparticle synthesis. Broad spectrum bands in the region of 3190-3558 cm^{-1} were attributed to O-H stretching vibrations, suggesting the presence of hydroxyl-containing compounds such as phenolics and flavonoids and/or N-H vibrations corresponding to amines and amides. The bands within range 2862-2920 cm^{-1} corresponded to aliphatic C-H stretching corresponded to methyl and aldehyde, while peaks around 1631-1732 cm^{-1} were assigned to carbonyl and/or aromatic C=C vibrations agreed with aromatic groups, proteins. The bands in the range of 1020-1328 cm^{-1} were associated with C-O, C-N, C-O-C stretching vibrations corresponding with phenols and carbohydrates [26]. These results confirm the presence of functional groups capable of metal ion binding, reduction, and stabilization during green synthesis [27].

When comparing the spectra of extracts from kernels, spines, leaflets, and fibers, all exhibit the presence of active groups responsible for reduction and bio stabilization. However, their density and clarity differ. Extracts from spines and kernels are characterized by more pronounced hydroxyl peaks, indicating higher reducing capacity and better stability of the nanoparticles [28]. In contrast, aliphatic components predominate in palm leaflets and fibers, making them more suitable as stabilizing agents [29]. Therefore, extracts from spines and kernels are considered the best for preparing small-sized, highly stable

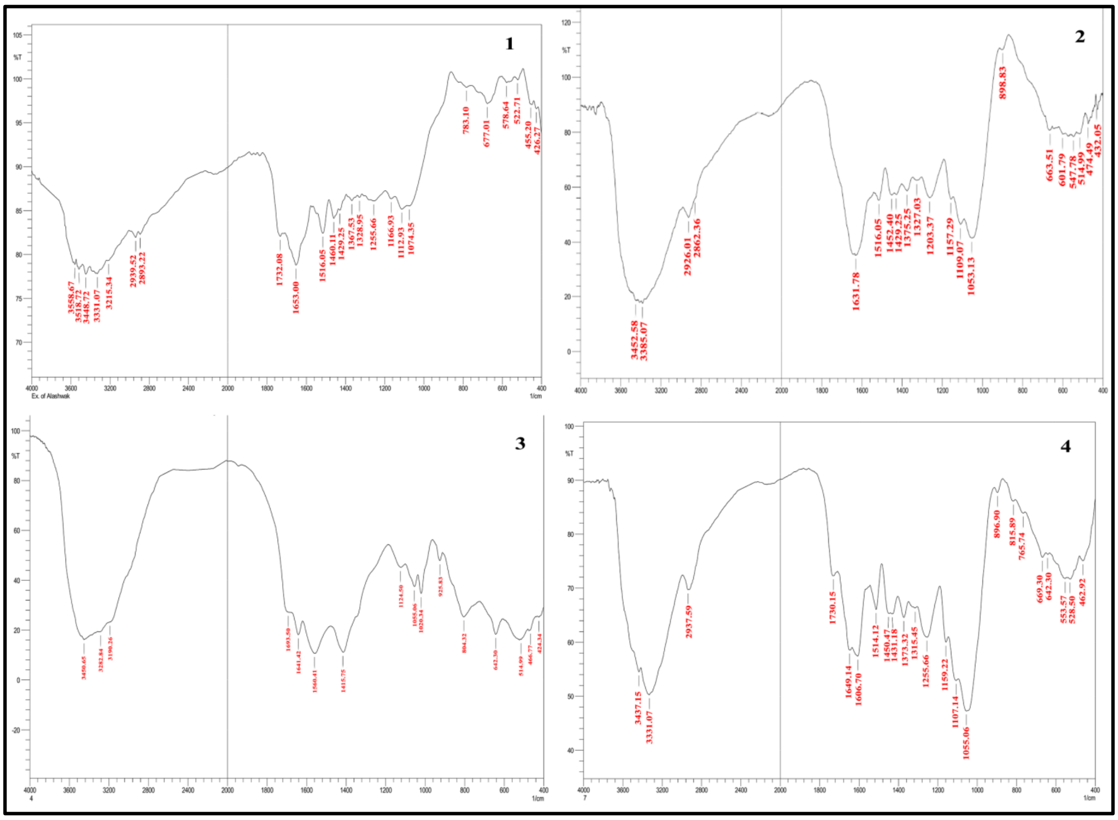

Fig. 3. FTIR spectra of date palm residue extracts: (1) Spines (2) Leaflets (3) Kernels (4) Fibers.

nanoparticles.

XRD analysis of plant extracts

XRD analysis of Zahidi date palm residue extracts exhibited a sharp absorption peak around the degree 2 THETA= 20-25°, and varying absorption intensity among the extracts within a range 140-285 as shown in Fig. 4. The kernels extract showed a major peak near 22° and an absorption intensity at 240, while the spines extract showed a sharp peak near 23° and an absorption intensity exceeding 250. The leaflets extract exhibited a peak at ~23° with an absorption intensity at 140, while the fibers extract showed a sharp peak around 21° and an absorption intensity at 285. Based on the obtained results, the extract wasn't homogeneous and contained a mixture of compounds with diverse compositions, thus differing in their efficiency in nanoparticle biosynthesis. Similar to the compounds, it also had a combination of amorphous and crystalline phases, but a considerable amount of it was found to be amorphous due to broad peaks, indicating no order over a large range of atomic arrangements, confirming organic matter composing the extract. After the primary peak, intensity decreased gradually due to the multiple groups of organics found without the characteristic peak widths of any metal's crystalline phase.

This pattern suggests the potential use of these extracts as reducing and stabilizing agents in the green manufacturing of nanoparticles, as amorphous organic compounds are the most effective at binding metal ions and stabilizing nanoparticles [30].

Characterization of ZnO nanoparticles

UV-Visible analysis of ZnO nanoparticles

The UV-Vis spectra of the synthesized ZnO NPs are presented in Fig. 5. As compared with the UV-Visible analysis of Zahidi date palm extracts, the synthesized ZnO exhibited characteristic absorption peaks. Kernels-derived ZnO showed absorption peak at 310 and 355 nm, with the major peak at 355 nm. Spines-derived ZnO exhibited peaks at 300 and 360 nm, with the major peak at 300 nm. Leaflets-derived ZnO showed peaks at 300 and 360 nm, whereas fiber-derived ZnO showed peaks at 295 and 350 nm. The absorbance results at wavelengths between 350-360 nm are indicator of ZnO nanoparticles formation and their association with the energy gap due to electron transfer from the valence band to the conduction band [31]. The peaks absorbance of

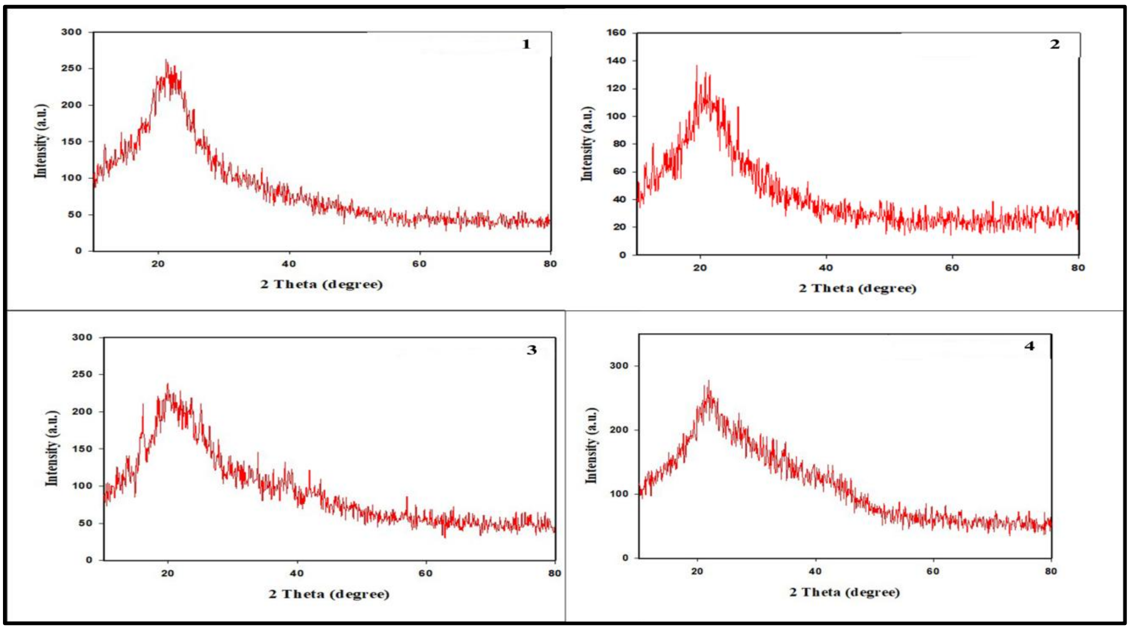

Fig. 4. XRD spectra of date palm residue extracts: (1) Spines (2) Leaflets (3) Kernels (4) Fibers.

zinc oxide nanoparticles at wavelength between 295 and 310 nm may explain either by the persistence of phenolic compounds attached to the nanoparticles and their role as stabilizing and capping agents [32], or by the displacement of zinc oxide nanoparticles with dimensions less than 10 nm due to quantum confinement and the restriction of electron movement within the nanostructure [33].

These finding indicate that extracts of date palm residues are rich sources of bioactive compounds, which gives them importance in agricultural, pharmaceutical and food applications, and makes them suitable options in green synthesis of nanoparticles, due to their ability to reduce and stabilize nanoparticles in an environmentally friendly way.

FTIR analysis of ZnO nanoparticles

The FTIR spectra of the synthesized ZnO nanoparticles as shown in Fig. 6 confirmed the absorption spectra of the nanoparticles showed a complete or partial difference in the number and location of peaks as compared with the spectra of the residue's extracts. This comparison revealed the appearance of new peaks in the low-absorption region within the range of 416 – 644.22 cm^{-1}. These peaks are the most important indicator confirming the vibrations of the zinc nanoparticles [34]. Furthermore, the shifting of some peaks and the disappearance of others to varying degrees among the extracts were observed, depending on their contribution to biosynthesis. Many studies have shown that functional groups such as hydroxides, carboxyl groups, and carbonyl groups play a key role in stabilizing and reducing metal ions, and that metabolic compounds such as polyphenols, flavonoids, carbohydrates, proteins, and organic acids contribute directly to the biosynthesis of nanoparticles [35].

When comparing the spectra of extracts from kernels, spines, leaflets, and fibers, all exhibit the presence of active groups responsible for reduction and bio stabilization. However, their density and clarity differ. Extracts from spines and kernels are less characterized by more pronounced hydroxyl peaks, indicating higher reducing capacity and better stability of the nanoparticles. In contrast, aliphatic components predominate in palm leaves and fibers, making them more suitable as stabilizing agents. Therefore, extracts from spines and kernels are considered the best for preparing

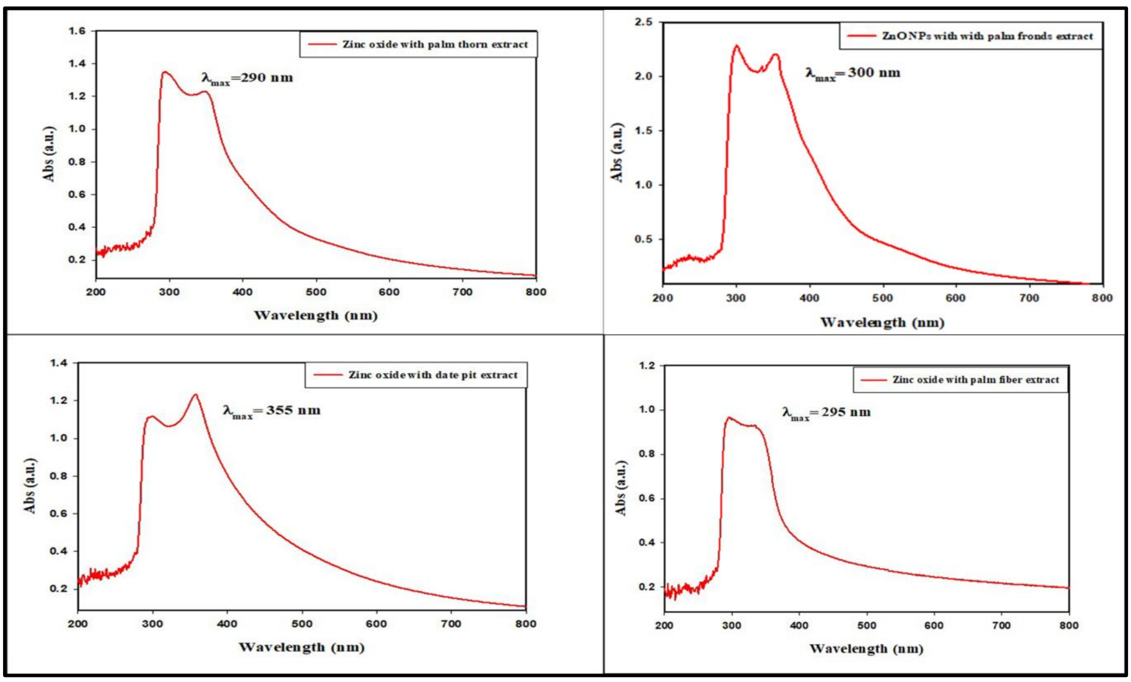

Fig. 5. UV-Visible spectra of synthesized ZnO nanoparticles: (1) Spines (2) Leaflets (3) Kernels (4) Fibers.

small-sized, highly stable nanoparticles.

XRD analysis of ZnO nanoparticles

The XRD patterns of the synthesized ZnO nanoparticles are presented in Fig. 7. The XRD patterns showed the crystalline nature of the all-synthesized nanoparticles prepared by plant extracts (kernels, spines, leaflets, fibers)

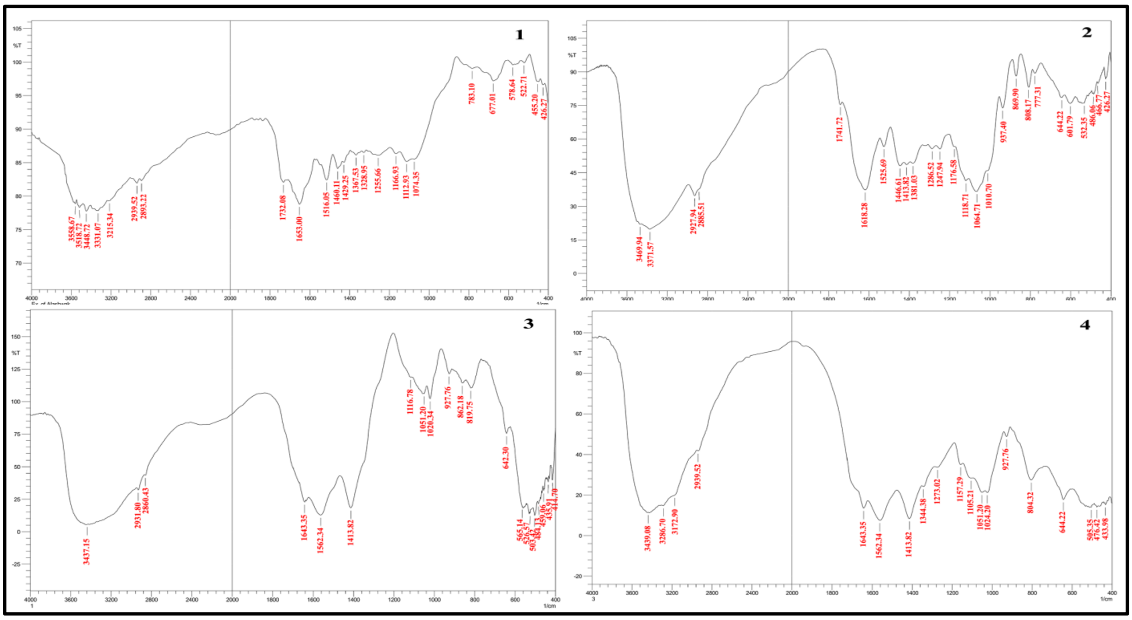

Fig. 6. FTIR spectra of synthesized ZnO nanoparticles: (1) Spines (2) Leaflets (3) Kernels (4) Fibers.

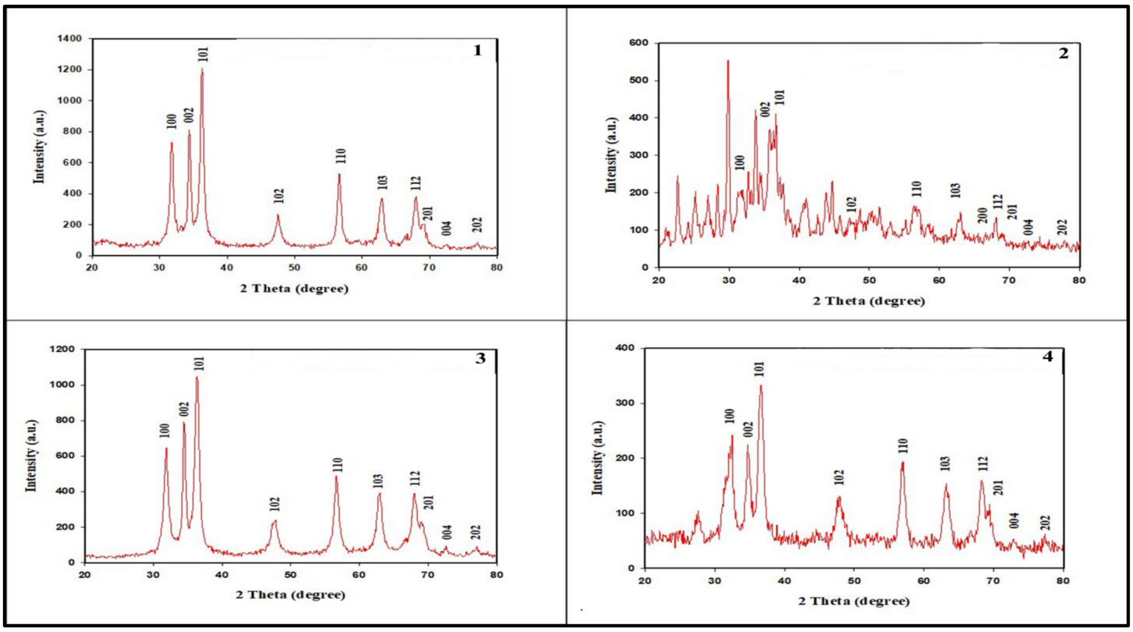

Fig. 7. XRD patterns of synthesized ZnO nanoparticles: (1) Spines (2) Leaflets (3) Kernels (4) Fibers.

correspond to the known crystalline levels of hexagonal zinc oxide nanoparticles (Wurtzite) in different degrees. The nanoparticles prepared by kernels and spines showed clear diffraction peaks in the range of 31.7-77°, indicating good crystallinity and the absence of undesirable phases or clear crystalline impurities [36]. The nanoparticles prepared by leaflets and fiber extracts showed a large number of peaks within a wide angular range of 21.69-77.84°, which can be explained by the formation of a sophisticated and multidirectional crystalline structure [37].

The average crystallite size values calculated from the XRD using the Scherrer equation. The calculated crystallite sizes showed clear variation among the synthesized ZnO nanoparticles and reflect the effect of each extract. Kernels-derived ZnO exhibited 11-23 nm with an average crystallite size of approximately 15 nm, spines-derived ZnO about 13-29 nm with average 17 nm, leaflets-derived ZnO about 9-50 nm with average 26 nm, and fibers-derived ZnO about 5-47 nm with average 20 nm. The ZnO nanoparticles mediated-kernels and spines samples exhibited a more regular and stable structure and a highly reactive active surface [38]. In contrast, the zinc oxide

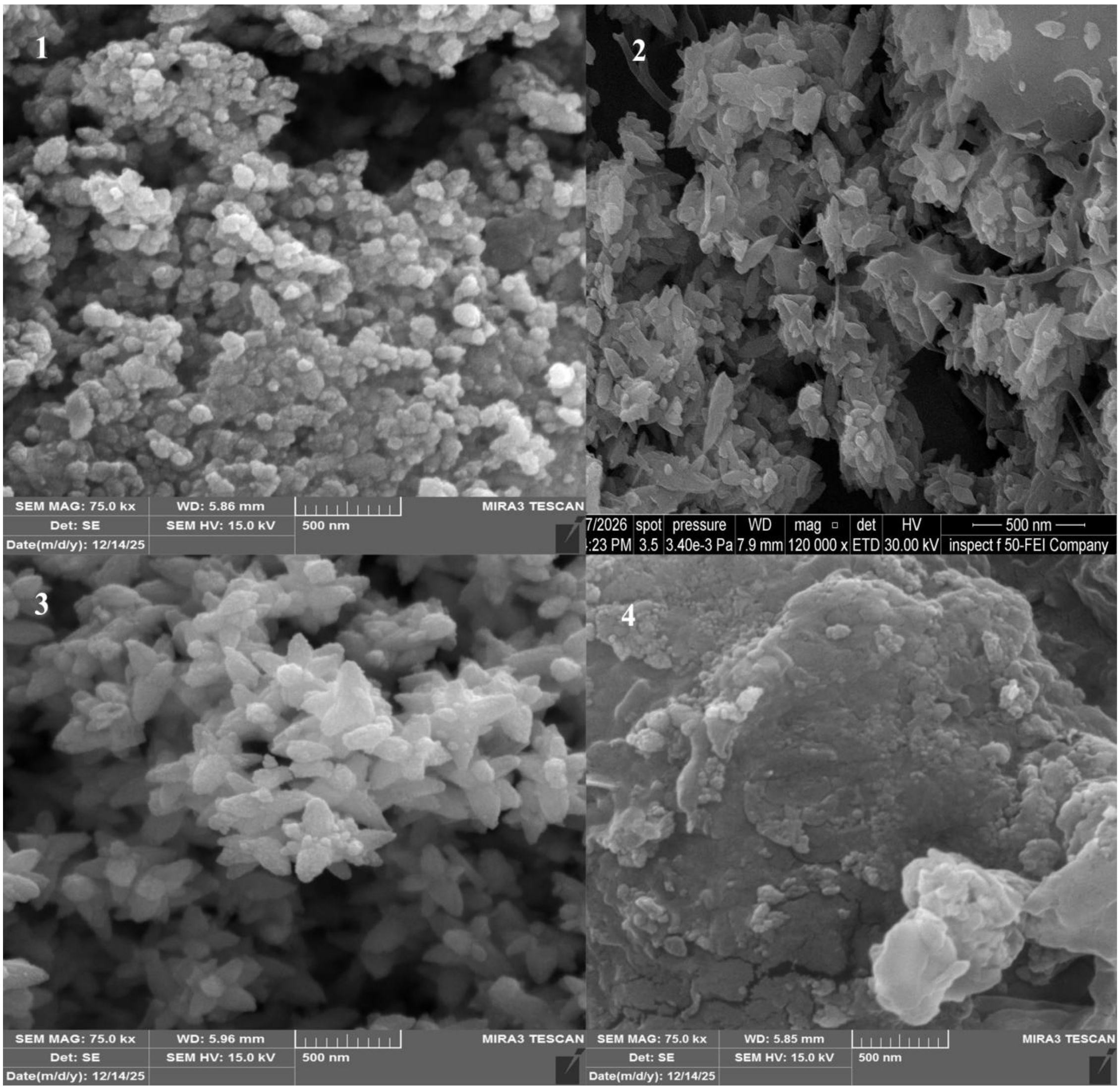

Fig. 8. FESEM mircograph of synthesized ZnO nanoparticles (1) Spines (2) Leaflets (3) Kernels (4) Fibers.

nanoparticle samples prepared using leaflets and fibers extracts showed considerable variation in crystal size, indicating relatively irregular crystal growth [39].

FESEM analysis and morphology

The morphology of the synthesized ZnO nanoparticles was examined using FESEM, and the corresponding micrograph as shown in Fig. 8. FESEM images revealed distinct morphologies depending on the residue's extracts used during synthesis. Kernels-derived ZnO showed flower-like nanostructure with petal dimension in the range 15-20 nm, Spines-derived ZnO exhibited predominantly spherical particles with size 14-20 nm. Leaflets-derived ZnO formed sheet-like structure ranging from 29-81 nm, whereas fiber-derived ZnO showed dense irregular nanostructure

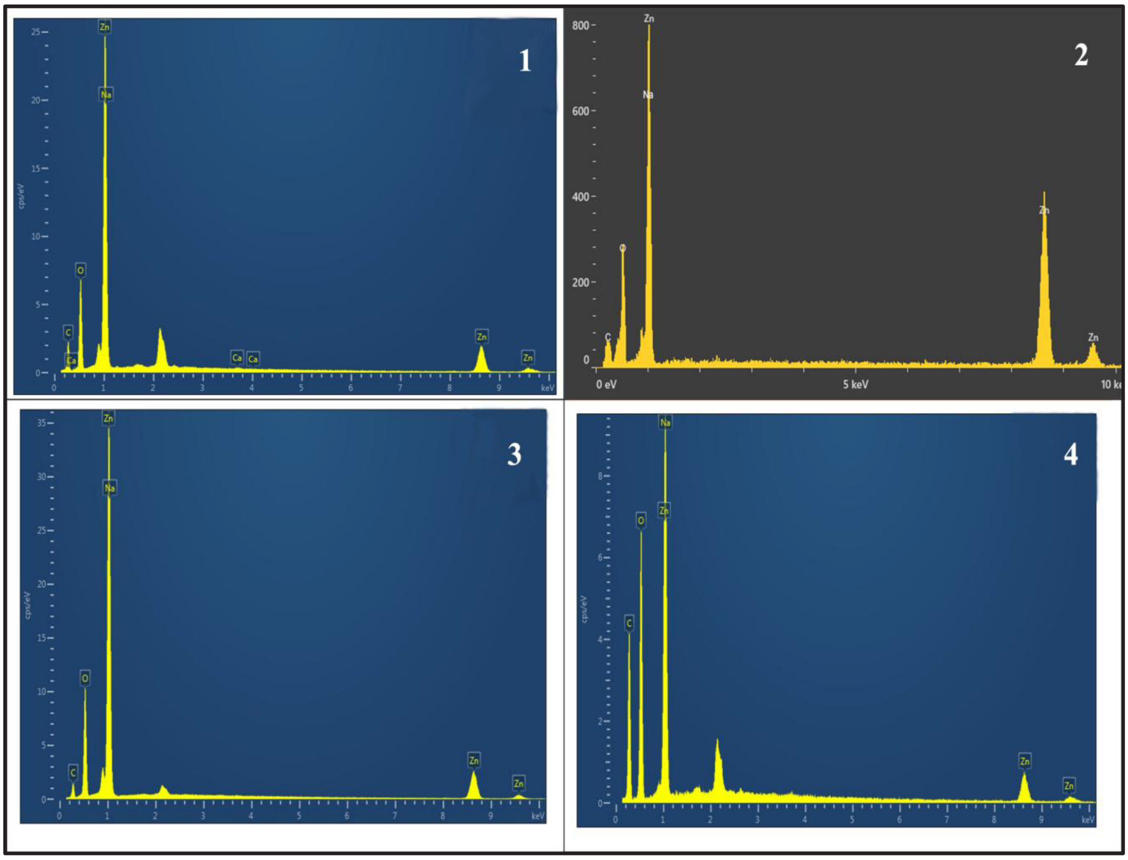

Fig. 9. EDX analysis of synthesized ZnO nanoparticles: (1) Spines (2) Leaflets (3) Kernels (4) Fibers.

Table 2. Proposed relationship between phytochemical composition of Zahidi date palm residues and the morphology of the synthesized ZnO nanoparticles.

Date palm residue	Dominant phytochemical	ZnO morphology	Proposed role in nanoparticle formation
Kernels	High total phenol and flavonoid contents	Flower-like	Strong reducing ability and multidirectional crystal growth
Spines	High alkaloid content	spherical	Uniform nucleation and isotropic growth
Leaflets	High saponin content	Sheet-like	Structure-directing effect and anisotropic growth
Fibers	Lower levels of major reducing phytochemicals	Dense irregular	Weak control over reduction, growth, and aggregation

with particle size around 17-21 nm. The result indicates thar the plant extracts play decisive role in directing nanoparticle growth and the final morphology [40].

EDX analysis

The elemental composition of the synthesized ZnO nanoparticles was confirmed by EDX analysis, as shown in Fig. 9. EDX spectra confirmed the presence of zinc and oxygen as the major elements in all synthesized samples, supporting the successful formation of ZnO nanoparticles [41]. The absence or low intensity of additional signals indicates that the prepared nanoparticles were relatively pure, with only minor contributions from residual plant-derived materials or sample preparation effects [42].

Correlation between phytochemical composition and ZnO morphology

There is a positive correlation between the phytochemical makeup of the date palm residues and the produced ZnO nanoparticles shape as in Table 2. About kernel residue (the richest in phenols and flavonoids), flower - shaped ZnO nanoparticles were synthesized due to strong reducing capability, as well as capable binding tendency, by such compounds enabling rapid nucleation and simultaneous 3D (multidimensional) crystal development as well as hierarchical arrangement [43, 44]. Alkaloid was dominant in spine residues, leading to the synthesis of spherical ZnO nanoparticles, hinting that such rich alkaloids may favor balanced nucleation along with uniform development. Saponin, a surface - active compound abundant in leaflets residue, assisted sheet - like ZnO nanostructures by acting as the directing molecule of crystal growth along preferred orientations and causing anisotropic development [45, 46]. Fiber residues with the lowest level of reducing phytochemicals synthesized dense irregularly shaped ZnO structures as a result of the weak inhibition in the reduction, stabilization and aggregation activities. Other reaction variables (concentrations of zinc precursor, extracts volume ratio to zinc precursor, temperature, pH, time and method of drying) were constant for all syntheses

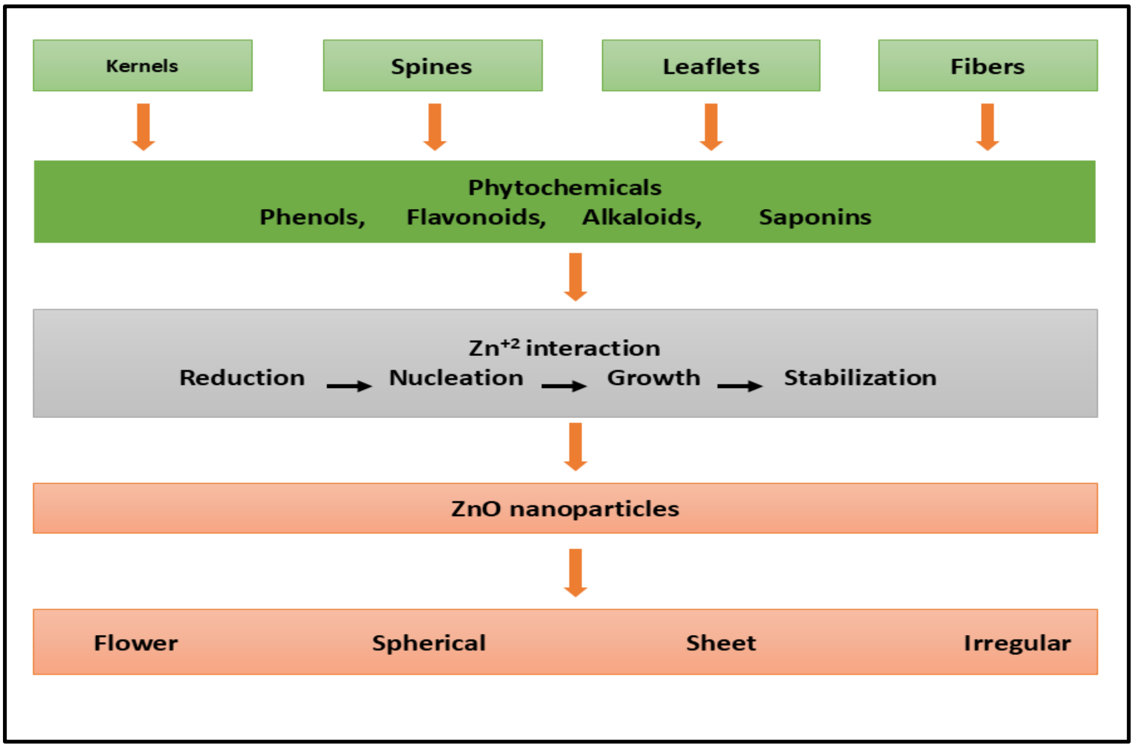

Fig. 10: Proposed mechanism of phytochemical-mediated green synthesis and morphology control of ZnO nanoparticles using different Zahidi date palm.

of ZnO nanoparticles. Therefore, the observed morphological variety among ZnO nanostructures primarily resulted from variation in secondary metabolite accumulation. Therefore, such results emphasize that while the plant residue plays the main role of the green reducing and stabilizing agent during nanoparticle synthesis, it acts as an architect directing the final shape. Hence, the importance of utilizing and investigating various plant residue types has become evident in the field of green nanoparticle synthesis [47].

Proposed mechanism

Based on the phytochemical, spectroscopic, structural, and morphological results, a possible mechanism can be proposed for the green synthesis and morphology control of ZnO nanoparticles using different Zahidi date palm residues. Phytochemicals present in the aqueous extracts initially interact with zinc ions through reactive functional groups such as hydroxyl and carbonyl are proposed as Fig. 10. These groups may facilitate zinc ion complexation and contribute to the formation of intermediate species in the reaction medium [48, 49]. Upon PH adjustment and under continuous heating and stirring, nucleation of Zn-containing species occurs, followed by crystal growth and conversion into ZnO nanostructures [50]. At the same time, residual phytochemicals in FTIR results may indicate adsorbed on the surface of the growing particles, acting as stabilizing and capping agents that limit uncontrolled aggregation.

The type and abundance of phytochemicals appear to influence the pathway of nanoparticle growth. Extracts rich in phenolic and flavonoid compounds, such as kernels extract, may enhance reduction efficiency and promote multidirectional crystal growth, leading to flower-like nanostructures. In contrast, alkaloid-rich spines extract may support more uniform nucleation and relatively isotropic growth, resulting in spherical nanoparticles. Leaflets extract, characterized by its high saponin content, may exert a structure-directing effect through its surface-active nature, thereby favoring anisotropic growth and sheet-like ZnO formation [51, 52]. On the other hand, the lower abundance of major reducing phytochemical in fiber extract may provide weaker control over nucleation, growth, and stabilization, leading to dense irregular nanostructures.

Since all synthesis parameters were maintained constant, including precursor concentration, extract volume, temperature, pH, reaction time, and dying conditions, the differences observed in ZnO morphology can be mainly attributed to residue-dependent phytochemical effects. Therefore, the proposed mechanism highlights the role of extract chemistry not only in nanoparticle formation but also in directing nanostructure morphology during green synthesis [48, 49].

CONCLUSION

Green synthesis of ZnO nanoparticles by employing aqueous extracts derived from Kernels, spines, leaflets and fibers of Zahidi date palm (*Phoenix dactylifera* L.) residues was investigated. ZnO nanoparticles produced using Kernels, spines, leaflets and fibers exhibit morphological resemblance to flower, sphere, sheet and dense irregular nanostructure respectively, confirming phytochemical composition affects ZnO nanoparticle morphology, even under the same reaction temperature, pH, concentration of ions, reaction time and the same amount of plant material. Accordingly, physicochemical property such as type of phytoconstituents, degree of functional groups of the secondary metabolites such as Phenols, Flavonoids, Saponins, Flavonoids, Tannins and Terpenoids has a great influence on ZnO structure control under green synthesis process. Consequently, the use of Zahidi date palm waste, characterized as renewable and low - cost, to produce novel functional ZnO nanoparticles will promote the field of green nanotechnology and encourage a sustainable route to use agro-industrial waste valorization.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this manuscript.

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