



The Preparation and Use of Zinc Oxide Nanoparticles for Polyvinyl Chloride Photo-Stabilization

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Abstract

The prevailing study reports the successful green synthesis of zinc oxide (ZnO) nanoparticles (NPs) using orange peel extract and their application as polyvinyl chloride (PVC) photostabilizers. The method of creating ZnO NPs synthetically is both cost-effective, environmentally friendly and compliments the growing need for sustainable practices in science and industry. The ZnO NPs were synthesized using zinc nitrate and orange peel extract. The results show that the presence of orange peel extract significantly influences the morphology, size, and uniformity of the ZnO nanoparticles. Scanning electron microscopy showed the existence of agglomerated ZnO, NPs and energy-dispersive X-ray spectra, which revealed their composition as zinc and oxygen. Fourier transform infrared spectrum showed an absorption band, corresponding to Zn–O bonding, in the range of 400-600 cm⁻¹. The ZnO NPs' spectrum showed a band at 596 cm⁻¹ corresponding to the Zn–O stretching vibration, indicating the formation of ZnO. The potential use of different concentrations of ZnO NPs as photostabilizers for polyvinyl chloride (PVC) has been studied. Thin films of PVC were produced, followed by irradiation, and the changes that occurred in the polymeric chains were assessed. The molecular weight decrease, weight loss, generation of fragments containing alkene, carbonyl, and hydroxyl groups, and the morphological features of irradiated PVC's surface were assessed. The PVC films doped with ZnO NPs showed a lower degree of photodegradation compared to the undoped ones. The PVC film containing a ZnO NPs weight percentage of 0.05 was the most effective in decreasing the photodegradation of PVC.

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1. Introduction

Nanomaterials behave like enhanced atoms, displaying atom-like characteristics as a result of their expansive surface area and increased band gap between valence and conduction bands when scaled down to near atomic dimensions, leading to

heightened surface energy [1]. Advancements in nanotechnology are anticipated to transform various biomedical research fields, including medication delivery, cell imaging, and cancer therapy [2]. Among the many metal oxide NPs, zinc oxide (ZnO) stands out with its unique characteristics, such as

orientation, size of crystal, crystalline density, and morphology aspect ratio. It possesses a bandgap of 3.3 eV at an energy of 60 meV and room temperature (RT), making it a hot commodity in various scientific and technological applications [3–5]. ZnO NPs could absorb the UV-A and UV-B radiations, effectively providing broad-spectrum UV protection. Whereas TiO₂ primarily blocks UV-B radiation and also offers UV-A protection. In other words, ZnO NPs gives the edge in terms of protection and opaqueness. This also suggests that ZnO NPs may soon outshine nano TiO₂ [6]. The chemical synthesis of NPs can lead to the adsorption of toxic chemicals on their surface, potentially hindering medical applications. To combat this issue, there is a burgeoning interest in using eco-friendly methods for NPs synthesis, leading to a heightened awareness of green chemistry. Such an approach requires the utilization of environmentally friendly materials such as plant extracts, fungi, bacteria, and enzymes [7]. As an abundant source of therapeutic compounds and secondary metabolites, plants contribute to human health with minimal adverse effects. The simplicity, eco-friendliness, and broad activities of plant extracts make them particularly attractive for the synthesis of NPs [8,9]. Plants such as *Ocimum sanctum*, *Citrus limon*, and lemongrass have been harnessed to produce silver (Ag) and gold (Au) NPs [10, 11]. Moreover, the use of Aloe vera leaf extract in the fabrication of ZnO NPs has been documented. Alkaloids, saponins, terpenoids, steroids, flavonoids, tannins, and polysaccharides are crucial bioactive compounds found in plants that make a substantial contribution to different technological applications in therapeutic and traditional practices [12]. Zinc oxide nanoparticles (ZnO NPs) were generated utilizing Cassia fistula plant extract by the solution combustion technique, with polyphenols (11.0%) and flavonoids (12.5%) serving as reducing agents [13]. Additionally, 36 nm ZnO nanoparticles were effectively biosynthesized utilizing Sargassum myriocystum, a seaweed species from the Gulf of Mannar. These nanoparticles exhibited long-term stability, with no discernible alterations over six months. FTIR analysis verified that fucoidan-soluble pigments derived from microalgae promoted nanoparticles' reduction and stability [14]. Synthesis using *Solanum nigrum* leaf extract produced quasi-spherical-shaped ZnO NPs with a diameter of around 29.79 nm [15]. The proteins and carbonyl groups acted as both capping and reducing agents in the process. ZnO NPs formed from *Trifolium pratense* flower extract displayed consistent peaks in the UV-Vis spectra 24, 48, 72,

96, and 120 h after generation, indicating the stability of particles [16]. *Nyctanthes arbor-tristis* has also been used as the biological reduction agent in the generation of ZnO NPs [17]. *Rosa canina* fruit extract behaved as a stabilizing and reducing agent in ZnO NPs synthesis, as admitted by phytochemical investigations and associated with FTIR analysis. Bio-capping was performed using phenolic and carboxylic acids that existed in the fruit extract [18]. ZnO NPs have drawn much attention due to their potential for applications such as biological sensing, biological labeling, gene delivery, drug delivery, and nanomedicine. They also exhibit antibacterial, antifungal, acaricidal, pediculicide, larvicidal, and antidiabetic activities [19, 20]. Polyvinyl chloride (PVC) has numerous uses in modern society and is manufactured in various shapes and forms [21, 22]. However, it can undergo photodegradation, which shortens its lifespan and releases products that are harmful to the environment as well as human health. Thus, expanding the lifetime of PVC is of significant interest [19-22]. Possible approaches for protection against photodegradation include PVC modification or doping with photostabilizers [23–30]. In the present work, a green synthesis method using *Citrus x sinensis* peel extract has been employed to produce ZnO-NPs. The ZnO NPs, with their potential to stabilize PVC and act as antibacterial, antifungal, acaricidal, pediculicide, larvicidal, and antidiabetic agents, are promising candidates for various applications in the medical industry.

2. Materials and Methods

2.1. Materials and Plant Extract Preparation

Zinc nitrate dihydrate (Zn(NO₃)₂·2H₂O) and sodium hydroxide (NaOH) were obtained from Merck (New Delhi, India). PVC, with an average molecular weight of around 160,000, was purchased from Petkim Petrokimya (Istanbul, Turkey). Fresh *Citrus x sinensis* oranges were obtained from a local market (Baghdad, Iraq). The oranges were cleaned and peeled, and the peels were thoroughly washed in 2–3 rounds with tap water, followed by two rounds of rinsing with distilled water to remove impurities. The peels were dried at RT and ground in a pestle and mortar to get a fine powder. The ground dried peels (50 gm) were transferred into distilled water (400 ml) in a glass beaker (500 ml) and stirred at 60 °C for 10 min, during which a light yellow solution was obtained. Following cooling to RT, the solution was filtered using filter paper (Whatman No.1) and stored in a refrigerator.

2.2. Synthesis of ZnO NPs

ZnO Nps were synthesized utilizing the *Citrus x sinensis* peel extract. $\text{Zn}(\text{NO}_3)_2 \cdot 2\text{H}_2\text{O}$ (2 gm) was dissolved in distilled water (100 ml). The mixture was stirred for 5 minutes at room temperature before adding the peel extract. The extract serves multiple functions: as a reducing agent, stabilizer/capping agent, and size/shape controller. This green synthesis approach replaces toxic chemicals typically used in conventional methods, offering a safer and more sustainable alternative. The orange peel extract not only facilitates nanoparticle formation but also enhances biocompatibility, making the resulting ZnO nanoparticles particularly suitable for photostabilization, antimicrobial applications, and potential biomedical uses. Following extract addition, the pH of the mixture was adjusted to 12 using 1 M NaOH solution. The mixture was stirred at RT for 2 h, filtrated, and the solid was washed with distilled water several times. The solid obtained was allowed to dry in an oven at 80 °C for 6 h and calcined at 500 °C for 2 h before use.

2.3. Analytical methods

ZnO NPs were analyzed using energy dispersive X-ray (EDX), scanning electron microscopy (SEM), Fourier-transform infrared (FTIR) spectroscopy (400–4000 cm^{-1}), X-ray powder diffraction (XRD), and UV-Vis spectroscopy. The elemental composition of ZnO NPs was determined using EDX analysis. The FTIR spectra were obtained using an FTIR-8300 spectrometer from Shimadzu, Tokyo, Japan, and the UV-Vis spectra were monitored on a JASCO V650 spectrometer (JASCO, Tokyo, Japan). An Ostwald U-tube viscometer (Ambala, Haryana, India) was used to determine the viscosity of PVC in tetrahydrofuran (THF). The SEM images of ZnO NPs were captured on SIGMA 500 VP (Carl Zeiss Ltd, UK). The damage caused to the surface of PVC films due to irradiation was examined using a Veeco instrument from Veeco Instruments Inc., NY, USA, an Inspect S50 microscope from FEI Company, Czechia, Czech Republic, and Meiji Techno Microscope (Tokyo, Japan).

2.4. Preparation of PVC films doped with ZnO NPs

A 5 gm of PVC was filled into 100 ml THF to prepare a polymeric solution that was combined with ZnO nanoparticles (0.01–0.05 gm) and agitated at ambient temperature for 3 hours. The produced liquid was subsequently placed onto a glass plate including 15 holes, each with a thickness of 40 μm . The solvent was allowed to evaporate at ambient

temperature for 24 h, and the films were dried in an oven at 40°C under vacuum for 8 h.

2.5. UV-Vis irradiation of PVC films

The PVC films were irradiated (0–300 h) using a tester that utilized UV light with the highest wavelength (λ_{max}) 365 nm and intensity of 6.2×10^{-9} einstein $\text{dm}^{-3} \text{s}^{-1}$. The tester contains a stainless steel plate that has two holes on both the front and back sides. Fluorescent UV-B 365 lights, each rated at 40 watts, were positioned on either side of the tester. The PVC specimens were positioned vertically and situated 10 cm from the light source, aligned parallel to the lights. To guarantee constant exposure, the samples were systematically rotated, guaranteeing uniform irradiation from all angles.

2.6. FTIR spectrophotometry of PVC films

The photodegradation of the polymer results in the cleavage of C–C bonds, producing alcohols (with hydroxyl, –OH groups), ketones (with carbonyl, C=O groups), and unsaturated residues (with alkene, C=C bonds) [31,32]. To monitor these chemical changes, FTIR spectrometry was used to track the increasing intensity of absorption peaks at 3500 cm^{-1} (O–H), 1722 cm^{-1} (C=O), and 1602 cm^{-1} (C=C) during irradiation. The variations in these peaks were compared with the C–H bond (1328 cm^{-1}), which remained constant. The indices (I_s) for hydroxyl (I_{O-H}), carbonyl ($I_{C=O}$), and alkene ($I_{C=C}$) groups were determined applying Equation (1), where A_s and A_r correspond to the absorbance of the functional group and the C–H reference peak, respectively [33].

$$I_s = \frac{A_s}{A_r} \dots (1)$$

2.7. Weight loss of PVC films

PVC oxidative degradation results in undesirable alterations in color, the release of volatiles (e.g., HCl), and the creation of residues of small molecular weight. The process decreases polymer weight [34]. The PVC weight loss (%) was calculated from W_0 (PVC weight before irradiation) and W_t (weight of irradiated films) using Equation (2) [35].

$$\text{Weight loss (\%)} = \frac{W_0 - W_t}{W_0} \times 100 \dots (2)$$

2.8. Average molecular weight of PVC films

PVC undergoes chain fragmentation during photodegradation, resulting in a decrease in its average molecular weight (M_v). The intrinsic viscosity $[\eta]$, assessed in tetrahydrofuran (THF) for irradiated films, provides a reliable measure for estimating the molecular weight (M_v) of PVC through Equation (3) [36].

$$[\eta] = 1.63 \times 10^{-2} M_v^{0.766} \dots (3)$$

3. Results and Discussion

3.1. Examination of ZnO NPs

An environmentally friendly method has been used to produce ZnO NPs by utilizing *Citrus x sinensis* peel extract, as presented in Figure 1. Phytochemicals generated from plants act as reducing agents, converting metal precursors into metal nanoparticles (NPs). These chemicals stabilize the nanoparticles owing to their antioxidant and non-toxic properties [37]. The reduction process is mainly facilitated by vital phytochemicals, such as terpenoids, flavonoids, phenolic compounds, aldehydes, and alkaloids. The precise content and concentration of these reducing agents vary among

plant extracts. The synthesis, stabilization, and quantity of NPs produced are affected by factors such as contact time, temperature, metal salt concentration, pH, and the phytochemical profile of the plant extract [38]. It has been suggested that metal ions are stabilized through encapsulation with an organic covering in three stages after being reduced by plant extracts. 1) Activation phase: This included the reduction of metal ions and the reduced metal ions' nucleation. 2) Growth phase: This phase is involved in maintaining the stability of nanoparticles. 3) Termination phase: This phase determines the shape of the NPs formed [39]. The NPs were characterized using FTIR, SEM, XRD, and UV, and the specific details are explained in the following section.

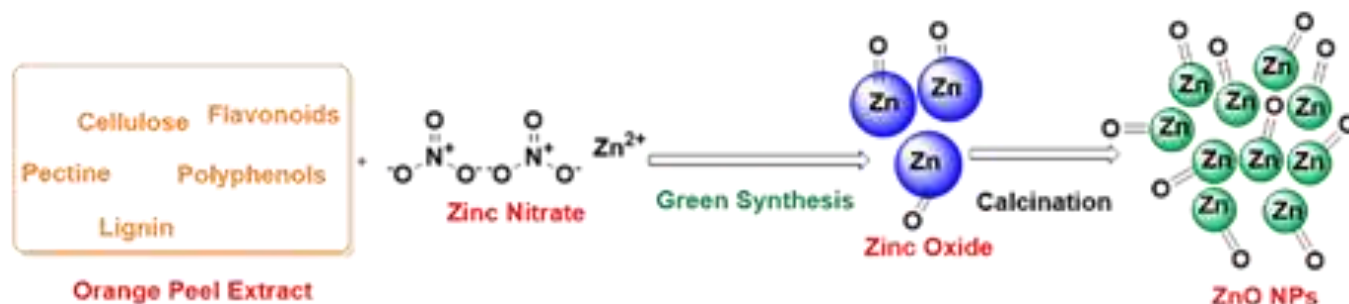


Figure 1. Green synthesis of ZnO NPs.

3.2. FTIR Spectroscopy

FTIR analysis of desiccated orange peels reveals characteristic spectral bands linked to cellulose and lignin [40]. The dominant peak in the high-energy region originates from hydroxyl groups found in carbohydrates and lignin. The strong band at 1027 cm^{-1} corresponds to C–O–H or C–O–R bonds, signifying the presence of alcohols or esters. A peak at 2921 cm^{-1} is attributed to C–H stretching vibrations, while the bending vibrations at 1421 cm^{-1} indicate aliphatic chains ($-\text{CH}_2-$ and $-\text{CH}_3-$), which are fundamental to lignocellulosic materials

[41]. Additionally, a peak at 1741 cm^{-1} confirms the presence of carbonyl functional groups, including esters.

The ZnO NPs' spectrum showed a band at 596 cm^{-1} corresponding to the Zn–O stretching vibration, indicating the formation of ZnO. A broad band at 3263 cm^{-1} was attributed to O–H stretching vibrations, possibly coming from H_2O that was absorbed on the surface of the products, as shown in Figs 2 and 3.

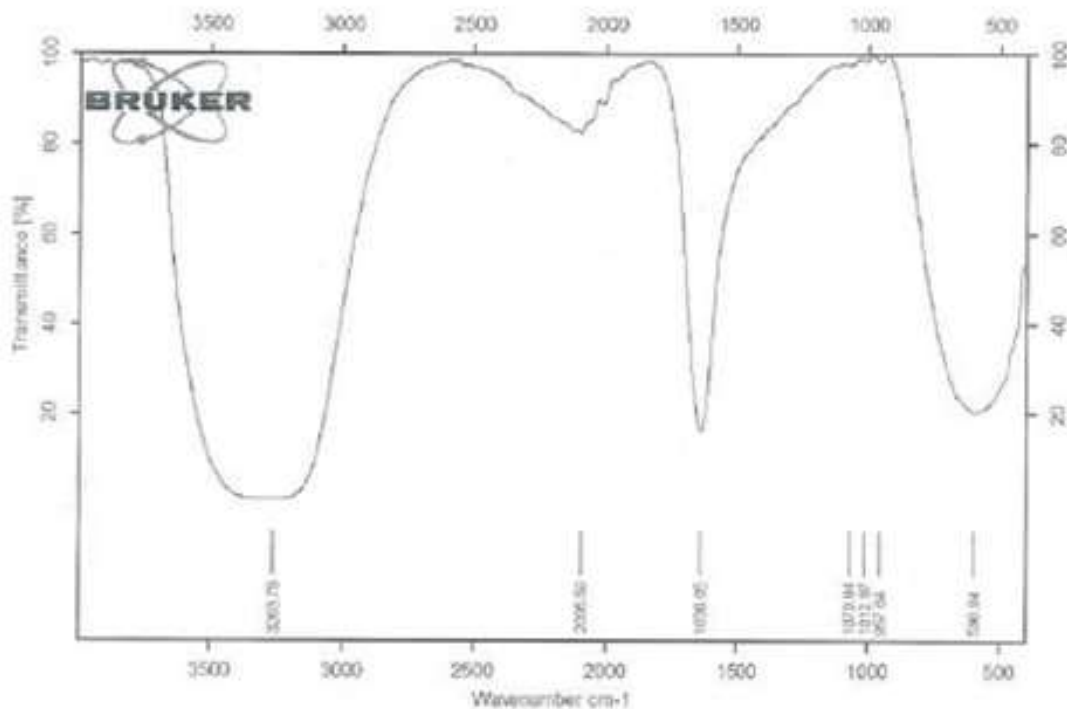


Figure 2. FTIR spectrum of dried orange peels.

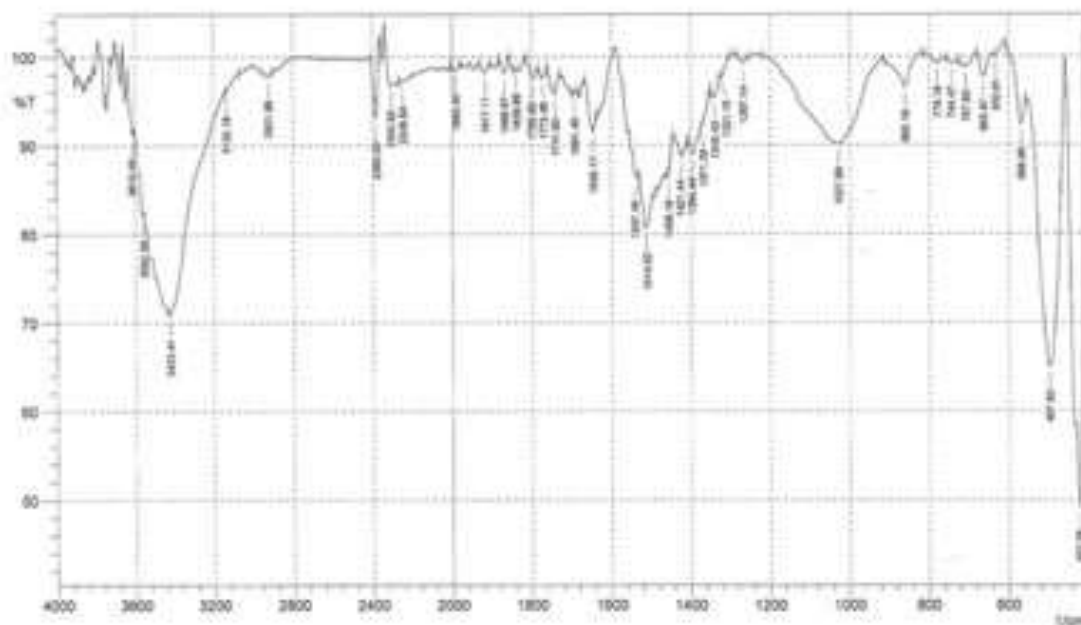


Figure 3. FTIR spectrum of ZnO NPs prepared using orange peel extracts.

3.3. XRD analysis

Figure 4 presents the XRD results for ZnO NPs prepared using green chemistry with orange peel extract. The analysis was conducted on the sample after calcination at 500 °C for 2 h. The sharp peaks in the XRD pattern indicate that ZnO NPs are highly crystalline. In addition, the distinct

fingerprint of ZnO revealed the high purity of the prepared NPs, as no impurities were detected. Diffraction peaks at 31.75, 34.25, 36.25, 47.45, 56.55, 62.85, 67.95, and 68.85 match the well-documented wurtzite pattern (JCPDC files No. 36-1451), confirming the specific crystalline structure of the ZnO NPs [42]. All the peaks from ZnO NPs

match the standard diffraction pattern of the hexagonal crystal structure.

3.4. SEM and EDX analysis

Figure 5 shows SEM images of various scales of the ZnO NPs' topography and surface morphology fabricated using green methods. The images reveal the diverse agglomeration of the morphology and features of the produced ZnO NPs. Generally, the synthesized ZnO NPs tend to be homogenous and agglomerated with no other dominating phases [43].

The EDX analysis provides information about the chemical composition of ZnO NPs (Figure 6). Zn and O atoms generate the most prominent peaks, whereas N, C, Al, and Ca contribute to weaker peaks, likely resulting from X-ray emissions of macromolecules like alcohols or phenolic compounds (Figure 7) [44].

3.5. AFM analysis

The 2D and 3D AFM images of ZnO NPs confirm that the particle sizes are in the nano range. The particle size, as determined from XRD data, closely aligns with the results obtained from AFM (Figure 8). The dispersion of ZnO NPs is clearly relatively uniform.

The average size of the ZnO NPs was determined to be 50 nanometers (Figure 9). These particles were evenly distributed in the sample, with an average roughness of 13.3 nm.

3.6. UV-VIS diffuse reflectance spectra

The UV-Vis diffuse reflectance analysis was performed over a wavelength range of 200 to 800 nm on the ZnO NPs derived using orange peel extract. The results were compared to the reflectance spectra of the ZnO blank (without using extract) as a reference. Figure 10 shows a sudden decrease in the reflectance spectra for both samples, which is attributed to the presence of band gap energy. The reflectance spectra showed distinct absorption edges at 570 nm for blank calcined ZnO and 566 nm for the orange peel extract-derived ZnO. This 4 nm blue shift to a shorter wavelength demonstrates a quantum confinement effect, confirming that the biologically synthesized ZnO nanoparticles possess smaller crystallite sizes compared to the conventionally prepared material [45]. The blue shift was ascribed to the size quantization phenomena and could be attributed to the extract acting as a capping agent.

The calculated band gap energy (E_g) for the calcined ZnO NPs was 3.74 eV, which was higher than that of the blank ZnO material (non-calcined), which was 3.62 eV (Figure 11). The blue shift was ascribed to the size quantization phenomena and is attributed to the extract acting as a capping agent.

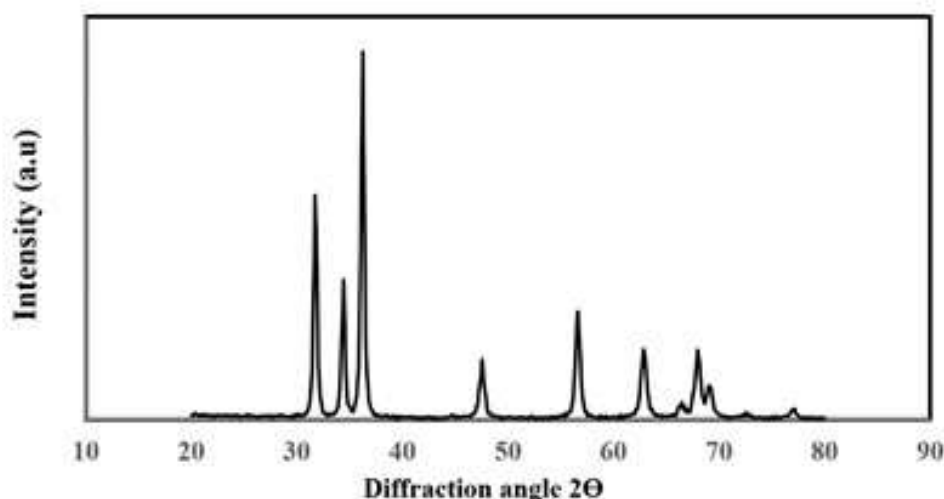


Figure 4. PXRD pattern of ZnO NPs.

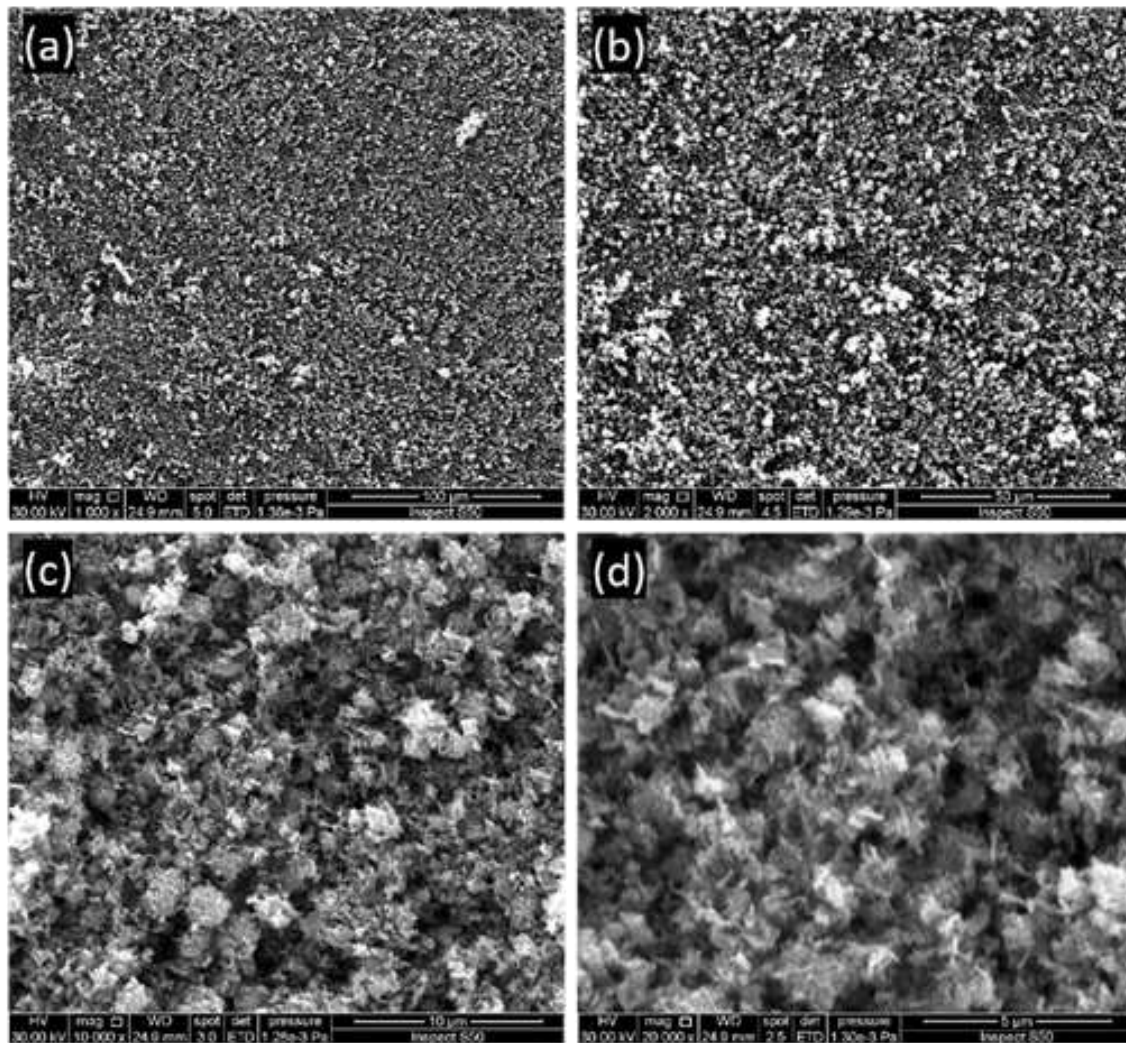


Figure 5. SEM images of ZnO NPs at different scales: (a) 100 μm , (b) 50 μm , (c) 10 μm , and (d) 5 μm .

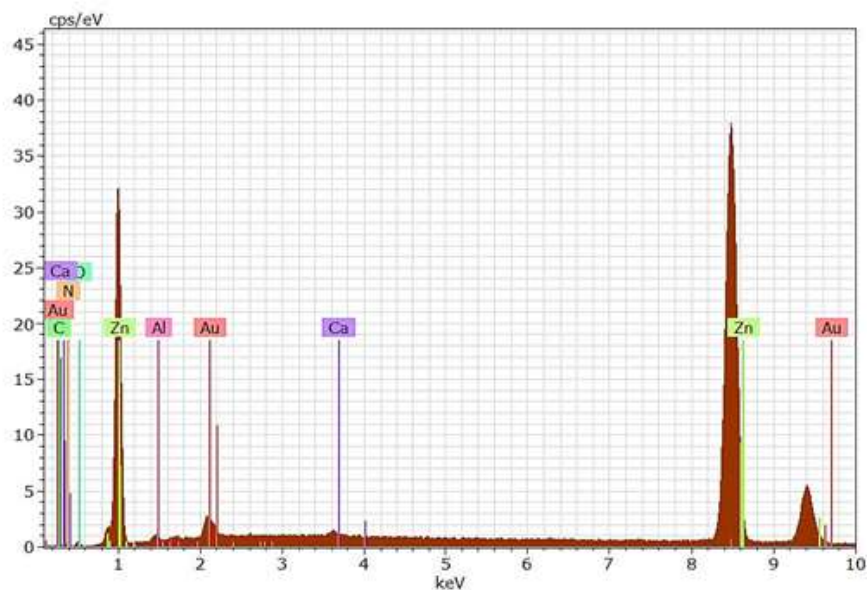


Figure 6. EDX spectrum of ZnO NPs.

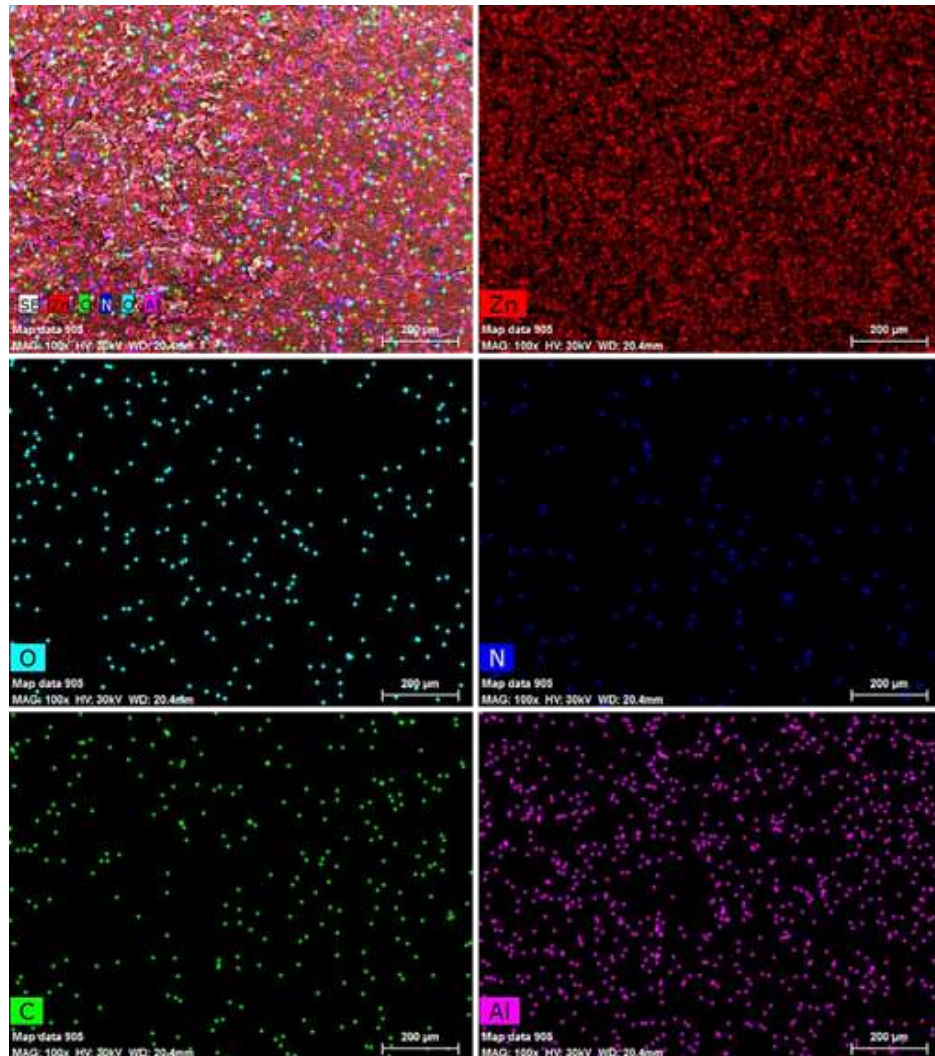


Figure 7. Elemental mapping images of ZnO NPs.

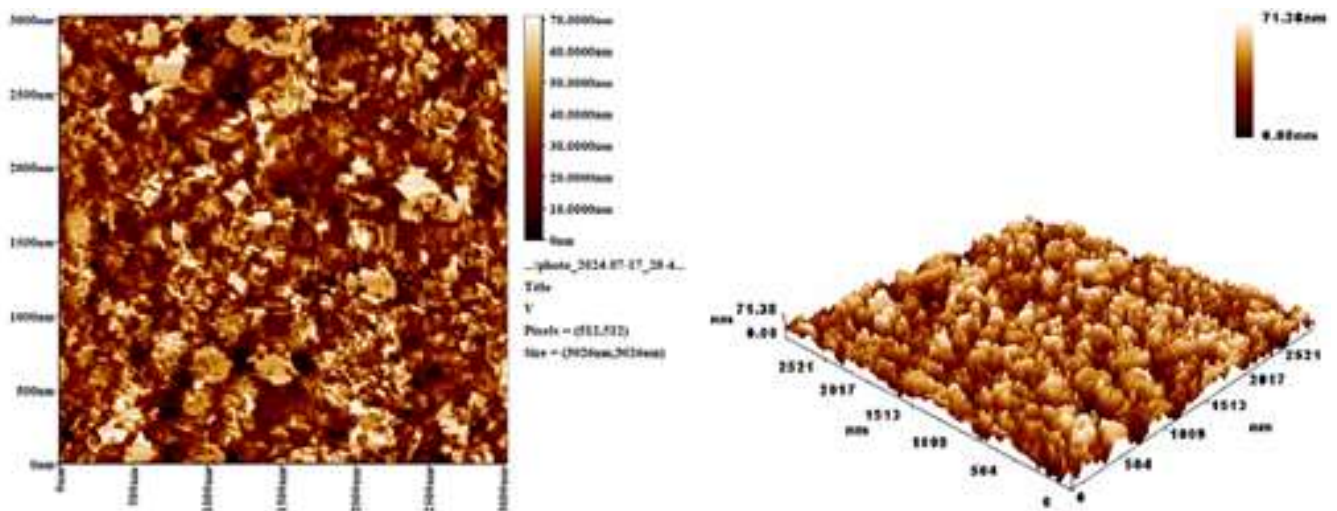


Figure 8. AFM images of ZnO NPs.

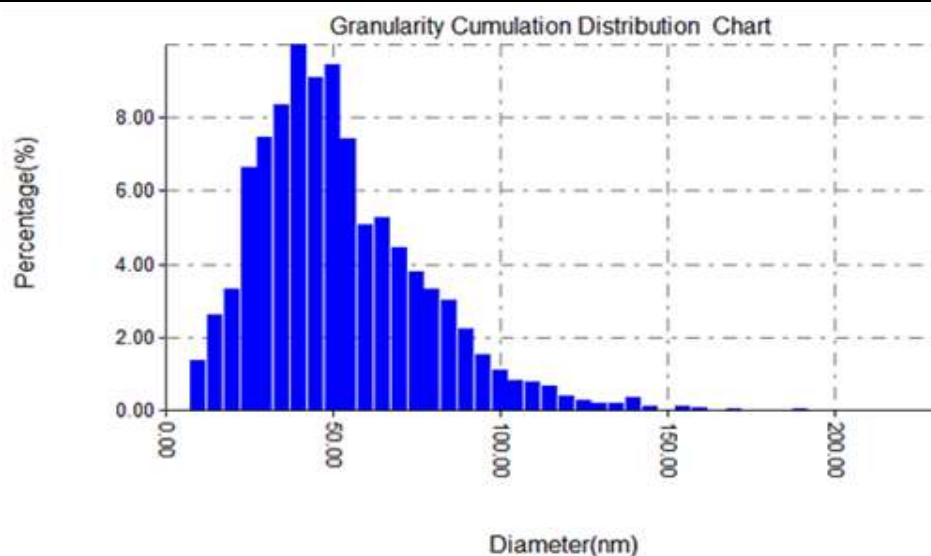


Figure 9. Histogram of average grain size of ZnO NPs.

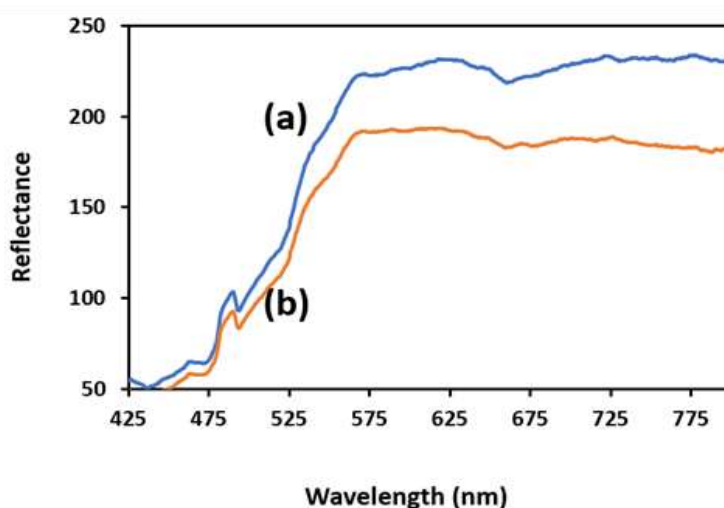


Figure 10. UV-Vis diffuse reflectance spectra for (a) the calcined blank ZnO and (b) the calcined ZnO NPs derived using orange peel extract.

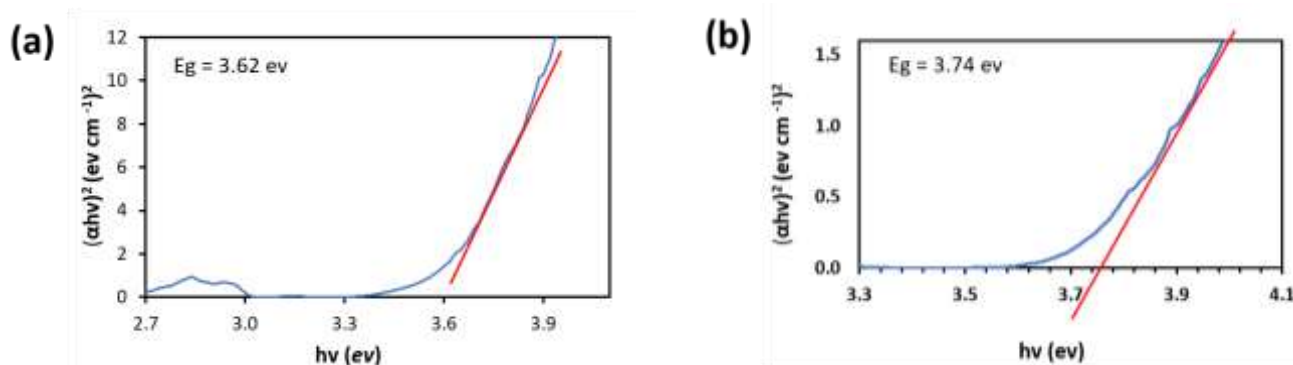


Figure 11. The band gap energy of a) the calcined blank ZnO and (b) the calcined ZnO NPs derived from orange peel.

3.7. Assessment of PVC photodegradation using FTIR spectrophotometry

FTIR spectroscopy was used in assessing the effect of doping PVC with different concentrations of the synthesized ZnO NPs on its photodegradation. The PVC (5 G) was mixed with ZnO NPs (0.01, 0.03, and 0.05 G), and films were made. The PVC films were exposed to oxidative photodegradation for up to 300

h at a wavelength of 365 nm. Photodegradation of PVC results in the formation of undesired polymeric fragments containing polyene (C=C; carbon-carbon double bond residues), carbonyl (C=O; acids and ketones), and hydroxyl groups [25]. Figure 12 presents the FTIR spectra of the undoped PVC sheet prior to and after irradiation, showing the changes in the peak intensities.

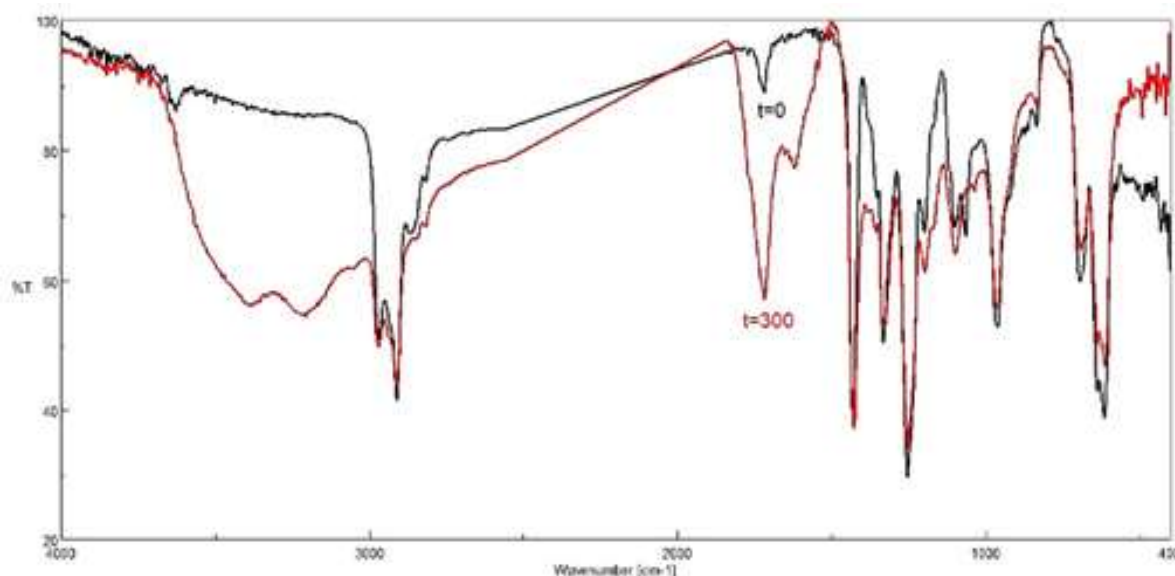


Figure 12. FTIR spectra of the plain PVC sheet (a) before (red) and after (black) irradiation.

The changes in the peak intensities for O–H, C=O, and C=C where at 3500 cm^{-1} , 1722 cm^{-1} , and 1602 cm^{-1} were sharp in the first 50 h and then gradually increased at the end of the exposure period. The irradiated blank (undoped) PVC film showed a considerable enhancement in the functional groups' intensities of the peaks to the unirradiated sample. The intensities of those peaks were compared to the one at 1328 cm^{-1} due to the C–H group as an internal reference. The PVC films doped with ZnO NPs show greater resistance to irradiation, with the indices of the main functional groups, calculated using Equation 1, being lower compared to the

irradiated virgin sheet. The PVC films doped with 0.05 weight % of ZnO NPs were the most photostabilized. The indices of the functional groups are graphed against time in 50 h time intervals and shown in Figures 13–15. These results shows that the green-synthesized ZnO NPs reduces the impact of UV light relative to the more severely damaged blank PVC specimen. For example, the $I_{\text{C=C}}$ at the end of the irradiation processes (300 h) was 0.41, 0.29, 0.25, and 0.22 for the blank PVC, PVC/0.01 ZnO NPs, PVC/0.03 ZnO NPs, and PVC/0.05 ZnO NPs, respectively. Similar patterns are observed for both $I_{\text{C=O}}$ and $I_{\text{O-H}}$.

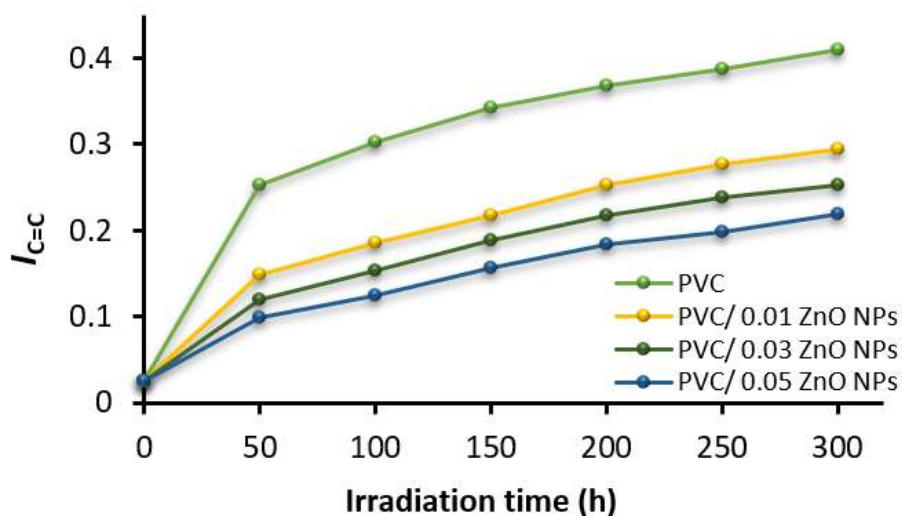


Figure 13. The difference in the $I_{C=C}$ index of the irradiated PVC films.

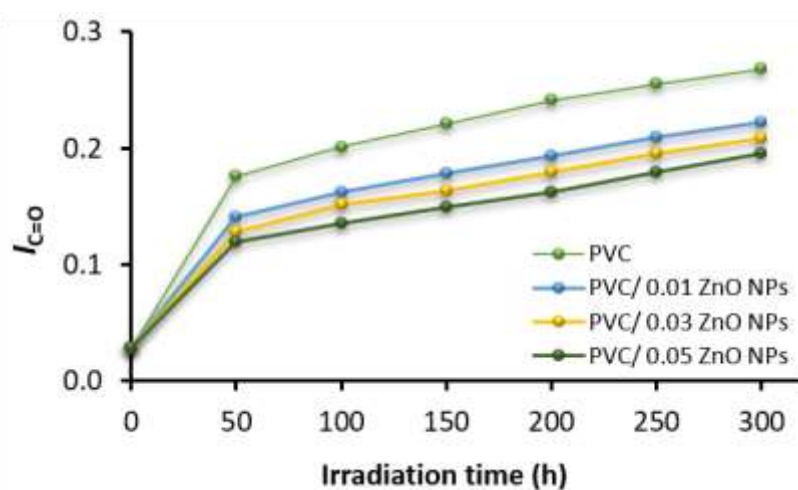


Figure 14. The difference in the $I_{C=O}$ index of the irradiated PVC sheets.

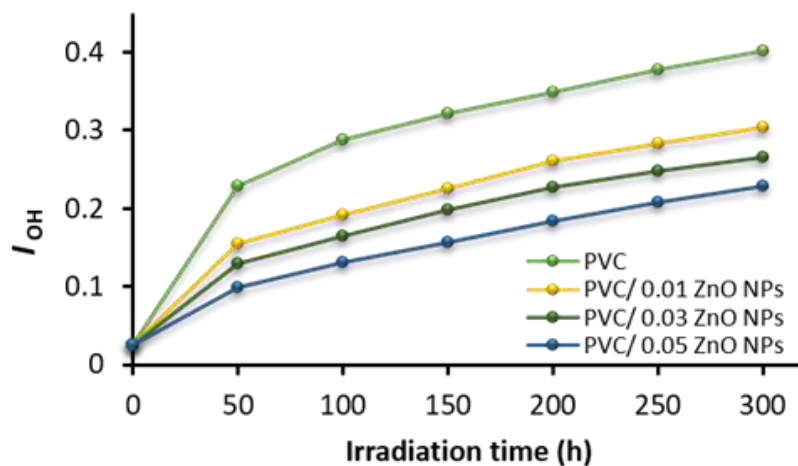


Figure 15. The difference in the I_{OH} index of the irradiated PVC sheets.

3.8. Assessment of PVC photodegradation using weight loss

Polymers typically undergo degradation when exposed to UV irradiation, causing them to lose some fragments. PVC experiences photooxidation, leading to dehydrochlorination (the removal of HCl) and the release of volatile organic residues, which in turn causes weight loss [46,47]. The PVC weight loss (%) due to irradiation was evaluated by

applying Equation 2. The impact of UV light on PVC films is illustrated in Figure 16. The outcomes showed that the PVC with the synthesized ZnO NPs had a lower weight loss (%) compared with the blank film. The weight loss (%) after 300 h was 0.43, 0.33, 0.29, and 0.26 for the blank PVC, PVC/0.01 ZnO NPs, PVC/0.03 ZnO NPs, and PVC/0.05 ZnO NPs, respectively.

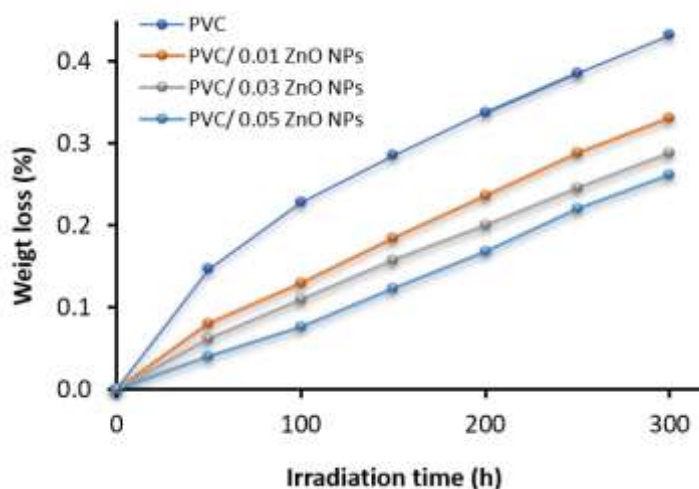


Figure 16. The difference in weight loss (%) of the irradiated PVC films.

3.9. Assessment of PVC photodegradation using average molecular weight

When PVC is exposed to light, it breaks down into smaller pieces, causing a decrease in its molecular weight (M_v). This decrease is mainly due to the polymeric chains either cross-linking or breaking. As a result, the intrinsic viscosity $[\eta]$, which M_v

strongly influences, is expected to decrease for solutions of PVC films after exposure to light [48]. For the PVC under investigation, the irradiated PVC films were dissolved in THF, and their $[\eta]$ was determined. Equation 3 was used to obtain the results shown in Figure 17.

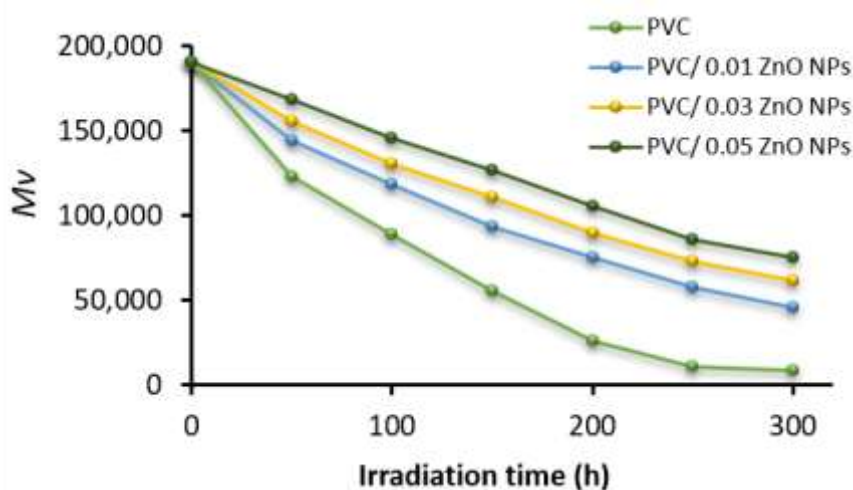


Figure 17. Changes in the M_v of the irradiated PVC films.

Some polymeric residues were not soluble, which indicates chain branching and cross-linking during the irradiation process. The decrease in the M_v was sharp at the beginning of the irradiation process, and the M_v of the blank PVC decreased from 190,000 to only 25,775 after 200 h of irradiation, compared with 104,881 for the film doped with 0.05 ZnO NPs. At the end of the irradiation process, the M_v was 8,099, 45,631, 61,386, and 75,234 for the blank PVC, PVC/0.01 ZnO NPs, PVC/0.03 ZnO NPs, and PVC/0.05 ZnO NPs, respectively.

3.10. Assessment of PVC photodegradation using surface analysis

The changes in the surface structure of the irradiated PVC films were examined using an optical microscope at 400× magnification [49,50]. When the films were exposed to UV light for 300 hours, they displayed dark spots, a change in color, and increased surface roughness, especially the blank film (Figure 18). The changes observed are a result of the photodegradation process, during which small fragments and HCl molecules are removed from the surface of the PVC films under UV light. The PVC films containing ZnO NPs showed less damage compared to the blank ones. The film containing 0.05 ZnO NPs exhibited the least surface damage.

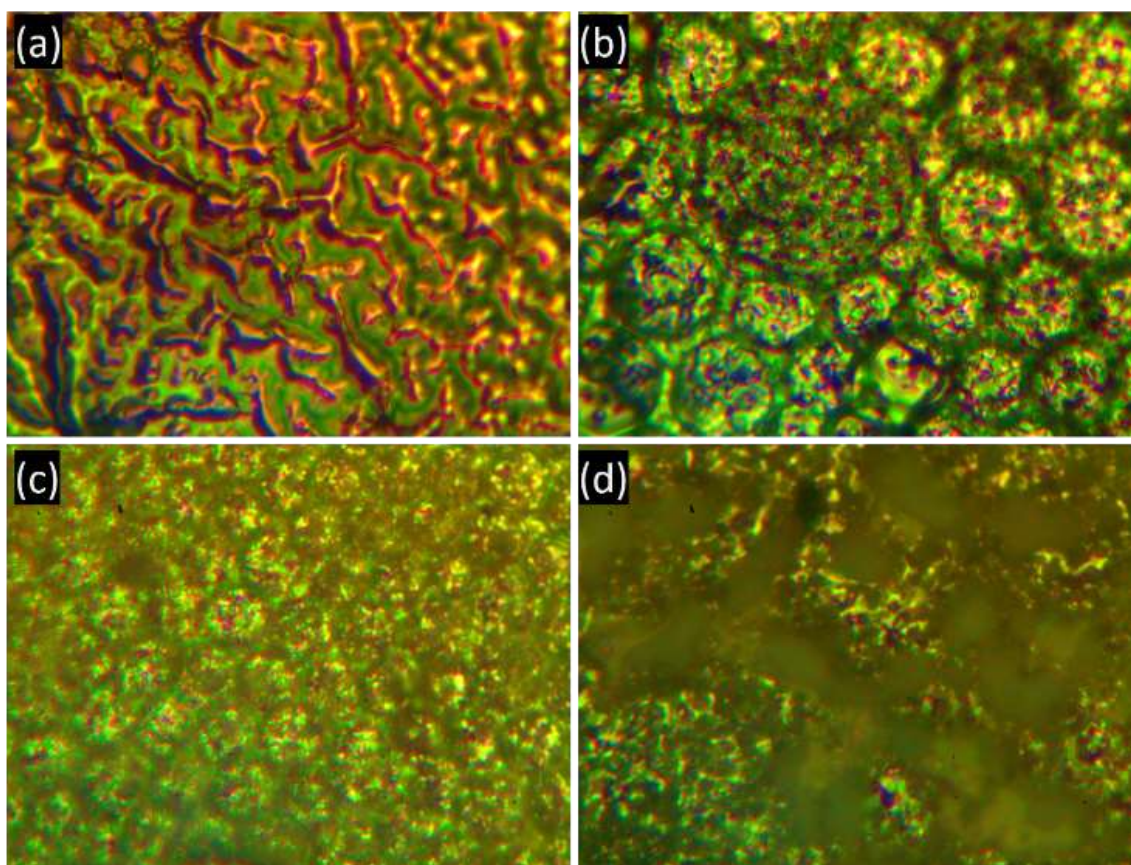


Figure 18. Microscope images (400× magnification) of PVC films after 300 hours of UV exposure (a) blank, (b) PVC/0.01 ZnO NPs, (c) PVC/0.03 ZnO NPs, and (d) PVC/0.05 ZnO NPs.

The surface roughness was analyzed using AFM [51]. The AFM images of the surface of polymeric films before and after irradiating for 300 h are presented in Figure 19. Surface roughness and bond breakage occur due to prolonged radiation exposure. While the blank PVC film suffered severe damage, the surface of the polymers doped with ZnO NPs showed less damaged surface after exposure to UV light. As shown in Table 1, the R_q (nm) of PVC films indicated that the PVC/0.05 ZnO NPs film has less

roughness on its surface compared to other samples. The spherical morphology likely enhances UV absorption and scattering due to isotropic light interaction while also promoting uniform dispersion in the PVC matrix [52]. The measured roughness may contribute to increased surface area and interfacial interactions with the PVC chains, potentially improving photostabilization efficiency [53].

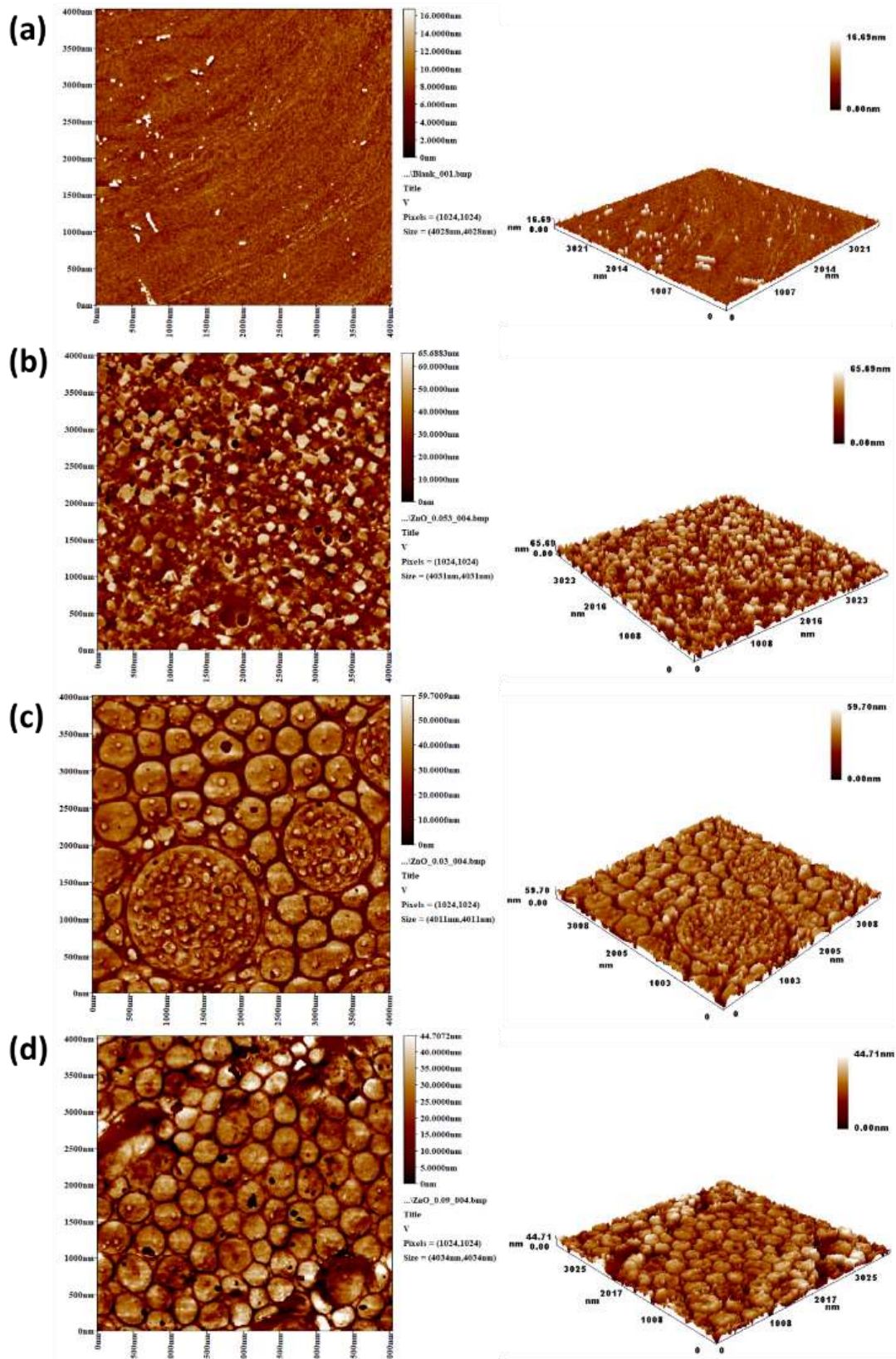


Figure 19. AFM images of PVC films (a) blank, (b) PVC/0.01 ZnO NPs, (c) PVC/0.03 ZnO NPs, and (d) PVC/0.05 ZnO NPs.

Table 1. The average roughness of the irradiated PVC sheets.

Sample	Average roughness (R_a ; nm)
PVC	11.0
PVC/0.01 ZnO NPs	9.6
PVC/0.03 ZnO NPs	8.5
PVC/0.05 ZnO NPs	0.8

SEM was used to capture high-resolution images of the surfaces of polymeric films [54]. Figure 20 shows that the plain PVC film's surface before irradiation was smooth and uniform compared to irradiated samples. The SEM images of the surface of the

irradiated polymers were consistent with those recorded using AFM. The particles have a honeycomb-like structure. Similar observations have been made previously with irradiated PVC [55].

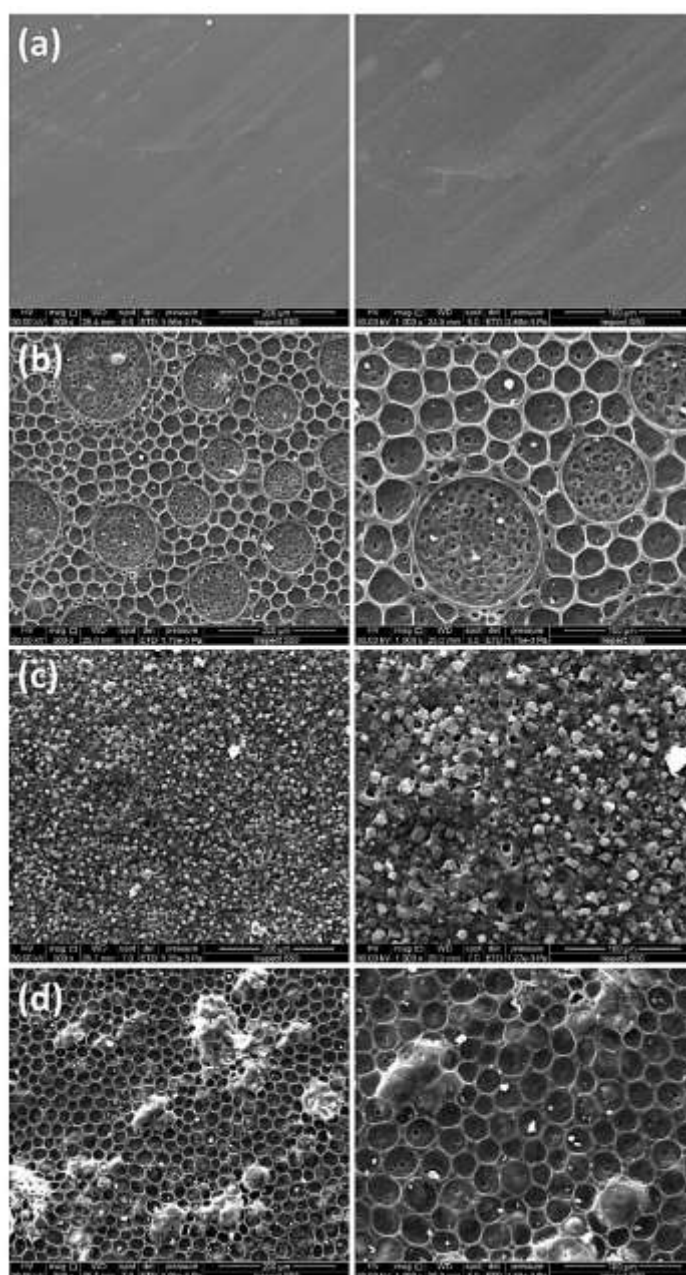


Figure 20. SEM image of PVC film, (a) nonirradiated and irradiated films: (b) PVC/0.01 ZnO NPs, (c) PVC/0.03 ZnO NPs, and (d) PVC/0.05 ZnO NPs.

4. Conclusions

The successful synthesis of high-quality ZnO NPs using a green method involving orange peel extract was demonstrated, while the characterization results confirmed that orange peel extract is an effective and sustainable reducing agent in the synthesis process. The study aimed to develop environmentally friendly photostabilizers to mitigate the photodegradation of PVC. The synthesized ZnO nanoparticles were incorporated into PVC at various concentrations, and their effectiveness as photostabilizers was systematically evaluated. Experimental findings confirmed that ZnO nanoparticles reduced irradiation-induced damage in PVC chains, enhancing material stability. However, while the results suggest promising photostabilization properties, further research is necessary to assess the long-term impact of these additives under real-world conditions. Furthermore, the potential environmental risks and hazards associated with nanoparticle release after PVC degradation must be thoroughly investigated to ensure their safe application in sustainable materials.

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Conflicts of Interest: The authors declare that there is no known conflict.

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