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Green synthesis of zinc oxide nanoparticles via Zingiber officinale/PEG biopolymer blend matrix: Optimization, physicochemical characterization, antioxidant and photocatalytic activity

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ABSTRACT

There is increasing interest in research on natural antioxidant structures that can be synthesized from plants and scavenge free radicals. This study aimed to successfully synthesize ZnO NPs with *Zingiber officinale* (ZO) extract using ultrasound-assisted plant-mediated synthesis known as the eco-friendly synthesis method. ZnO NPs were synthesized in the plant extract (ZO) and biopolymeric (polyethylene glycol, PEG) blend matrix by optimizing the parameters of volumetric ratio, PEG amount, sonication process amplitude, and process time. The final solutions were characterized by UV–Vis for optimization. The ZnO NPs were characterized by methods such as TEM, XRD, FTIR, and SEM, and additionally, their antioxidant properties were investigated using butylhydroxytoluene and ascorbic acid as standard solutions, and their photocatalytic activities against MB and RhB dyes were investigated. Most of the nano-sized particles exhibit a spherical morphology, the average size of the ZnO NPs is 22.17 nm and has a hexagonal wurtzite crystal structure. The antioxidant activity of ZnO NPs was evaluated as 72 % and increased with increasing concentration. ZnO NPs have acceptable antioxidant activity. It was found that NPs exhibited more active degradation against MB, and the degradation increased with increasing time. These results indicate that the ultrasound-assisted plant-mediated synthesized ZnO NPs exhibit high antioxidant activity, as demonstrated by an IC50 value of 0.0423 M, positioning them as viable candidates for biomedical and pharmaceutical applications.

1. Introduction

The rapid advancement of nanotechnology in recent years has sparked significant interest in the exploration of nanomaterials for various applications [1]. Among these, zinc oxide (ZnO) nanoparticles (NPs) have attracted significant attention because of their unique chemical, optical, and electronic properties [2]. ZnO NPs are an inorganic nanocrystalline metal oxide that contain high surface areas, and are appropriate for functional applications. ZnO NPs find extensive use in photocatalysis [3], biosensors [4], solar cells [5], and medical applications [6]. However, conventional synthesis methods such as chemical and physical routes for these NPs often pose environmental and economic sustainability challenges [7,8]. In this context, the development of eco-friendly and sustainable synthesis methods is of paramount importance. Green synthesis approaches using plant extracts offer notable advantages by minimizing the use of toxic chemicals and reducing energy consumption [9,10]. Based on scientific studies previously conducted in the literature, ZnO NPs were bio-synthesized from plant extracts with different properties. Some examples of these plants *Cassia auriculata, Hibiscus subdariffa, Aloe vera, Duranta erecta, Pongamia pinnata, Cinnamomum verum, Trifolium pretense, Bauhinia tomentosa, Vitex trifolia, Moringa oleifera, Ficus benghalensis, Azadirachta indica, Punica granatum, and Artocarpus gomezianus* [11–15]. The use of plant-based green synthesis method to obtain NPs is safer and more environmentally friendly due to its potential to reduce and stabilize possible damage to the environment. For this purpose, ultrasound-assisted plant-mediated synthesis technique was used in the present study. Ultrasound-assisted technique also known as sonication. This technique also known as sonication, nano-formations are realized by using ultrasonic sound waves and creating high pressure and temperature on the material with cavitation effect [16–18]. It can be preferred as an aid to increase efficiency in various synthesis methods [19]. Plant-mediated synthesis was preferred as the main method. Plant-mediated synthesis stands out as a stabilizing and reducing agent in the

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production of nanomaterials using plant's root, stem, leaf, or fruit parts [1,20,21]. *Zingiber officinale* (ZO), commonly known as ginger, is a plant widely recognized for its medicinal and culinary uses [22,23]. Ginger powder is derived from the dried and ground root of the plant and is rich in biologically active compounds. It contains phenolic compounds such as gingerols, shogaols, zingerone, and paradols, which are known for their strong antioxidant, antimicrobial, anti-inflammatory, and anti-tumor characteristics [24,25]. Additionally, ginger powder is rich in vitamins (especially vitamin C and vitamin B6), minerals (such as manganese and magnesium), and essential oils [26]. These components contribute to ginger powder's versatility as a natural product with numerous health benefits, making it valuable in both traditional medicine and modern scientific research. ZO is a plant renowned for its high antioxidant content and biologically active compounds, making it a promising candidate for the green synthesis of ZnO NPs. PEG is a biocompatible, eco-friendly, and affordable synthetic polymer known for its non-toxic nature and uniform chain structure. It is suitable for various applications such as softening, thickening, and dissolving [19,27,28]. Taha et al., [29] were synthesized ZnO nanostructures using Hibiscus extract. Ragavendran et al. [30], plant extract based synthesis of ZnO NPs using by *Solanum surattense* leaf extract. Al-Radadi et al. [31], were studied on ZO driven bioproduction of ZnO NPs. Numerous studies in the literature have investigated this topic, highlighting the crucial role of plant-derived metabolites in enhancing biological and catalytic activity. These compounds contribute to the stabilization of metal NPs while modifying their surface properties, thereby improving their reactivity and biocompatibility. Additionally, polymer-based additives prevent NPs aggregation, preserving the surface area and facilitating more efficient utilization of active sites. Furthermore, these additives can enhance targeted biological interactions and catalytic processes. In this study, ZnO NPs were synthesized using ZO and PEG to leverage these beneficial effects.

In normal metabolism, the levels of free radicals, and thus antioxidants have become balanced. However, excessive production of free radicals leads to oxidative damage, causing a number of various chronic diseases such as cardiovascular diseases, diabetes, cancer, and inflammation. Antioxidant intake protects against the damage resulting from the presence of free radicals. Therefore, antioxidants can be recommended as an important defense mechanism to reduce the risk of oxidant-related diseases and to ensure a better quality and longer life. However, there are limitations to the use of synthetic antioxidants due to their toxicity. Therefore, research has now turned to naturally derived antioxidants. ZnO NPs are one of the most promising inorganic oxides that have attracted the attention of many academicians in recent years due to their superior properties and their use in many application areas such as personal care products. In biological systems, excessive production of highly reactive radical species (HRRS) is one of the main causes of oxidative stress observed in many diseases with different characteristics such as thyroid, cancer, allergies, cardiovascular diseases, arthritis and diabetes. All biosystems largely depend on antioxidants to function properly. Consequently, there is an urgent need to research and produce innovative and safe antioxidants that have greater efficacy, are less toxic, and are produced from plant-based natural sources. However, further research is required due to the mechanisms of NPs and the lack of standardization. More studies are required for the widespread use of ZnO NPs as antioxidant agents in the future [32–34].

Photocatalytic activity refers to the ability of a material to absorb light, generate electron-hole pairs, and catalyze chemical reactions under light irradiation [35]. This property is crucial in applications like environmental remediation, energy conversion, and self-cleaning surfaces. NPs play a vital role in enhancing photocatalytic activity due to their high surface area-to-volume ratio, unique electronic properties, and tunable bandgap [36]. They provide active sites for reactions and improve light absorption and charge separation efficiency. Among various types of NPs, ZnO NPs are widely used for photocatalytic applications [37,38]. ZnO NPs exhibit excellent UV light absorption, high electron mobility, and remarkable oxidative power [39]. Their versatility and cost-effectiveness make them a popular choice for degrading organic pollutants and converting solar energy. Recently, plant-based NPs have gained attention as an eco-friendly alternative in photocatalytic applications. These NPs are synthesized using plant extracts that act as reducing and capping agents, avoiding the need for hazardous chemicals. Such green synthesis methods not only reduce environmental impact but also impart additional functionality to the NPs due to the presence of bioactive compounds from the plant extracts [40]. Plant-based ZnO NPs, for example, demonstrate comparable or even enhanced photocatalytic activity due to improved crystallinity and stability conferred by the natural capping agents [41]. In the ZnO NPs synthesis studies carried out with plant extracts, it was observed that the properties of the plant were also transferred to the synthesized NPs. For this reason, studies on the antioxidant activity of ZnO NPs produced by green synthesis methods are increasing day by day.

ZnO NPs offer a wide range of applications and can be produced in a safer way for the environment and human health by green synthesis methods. All biosystems largely require antioxidants to function properly. However, due to the mechanisms of NPs and the lack of standardization, further research is required. As a result, there is an urgent need to investigate innovative and safe antioxidants produced from natural sources that are more effective and less toxic. In this study, a novel ultrasound-assisted plant-mediated synthesis method for ZnO NPs using ZO powder and PEG biopolymer blend matrix. The objective of this study is to develop an environmentally friendly synthesis method for ZnO NPs using ZO/PEG blend matrix and to evaluate the antioxidant properties of these NPs. In addition, the prepared NPs were characterized by various methods to highlight the advantages and potential applications of this new method for ZnO NPs compared to conventional synthesis techniques. This study provides a new insight into antioxidant properties of ZnO NPs synthesize utilizing the ZO plant extract.

2. Materials and methods

2.1. Materials

Zingiber officinale (ZO) powders were obtained from Naturdan Company (Izmir, Turkiye). Zn.$(CH_3COO)_2{\cdot}2H_2O$ were purchased from Sigma-Aldrich (Germany). PEG400 (mW: 400 kDa) were purchased from Fluka Company (Switzerland). DPPH (2,2-diphenyl-1-picrylhydrazyl, $C_{18}H_{12}N_5O_6$, $\geq$90 %), NaOH (molecular weight: 40.00 g/mol), Methylene blue (MB), Rhodamine B (RhB), and Butylhydroxytoluene (BHT) were purchased from Merck Company (Germany).

2.2. Preparation of extract

In the present study, ZO extract was used as a reducing agent. After the ZO powders were washed twice with distilled water to remove dust and impurities, powders were dried in an oven at 100 °C for 8 h. Then, 5 g of dried ZO powder was added to 100 mL of distilled water and kept in a fixed position in a dark environment for 3 days in a sterile container. Then, the extracts were obtained after decantation.

2.3. Optimization of ultrasound-assisted plant-mediated synthesis of ZO/PEG-ZnO NPs

0.447 g Zn.$(CH_3COO)_2{\cdot}2H_2O$ was added to 150 mL of distilled water and stirred for 10 min on a magnetic stirrer. A 0.01 M Zn salt solution was prepared. After, 0.4 g NaOH was added to 150 mL of distilled water and stirred for 10 min on a magnetic stirrer. In the next step, the prepared salt solutions were added dropwise into the ZO extract. Then, PEG was added. The preparation of NPs was carried out by ultrasonic sound wave assisted biological synthesis method.

In the experiments, the total volume for ZO extract and Zn.$(CH_3COO)_2{\cdot}2H_2O$ solution was kept constant as 45 mL. Depending on

Table 1
Examined parameters in optimization of ZO/PEG-ZnO NPs by ultrasound-assisted plant-mediated synthesis.

Sample Number	Volumetric ratios (v/v)	PEG	%Amplitude	Time (sec)
1	2:1	0.2 g	15	5
2	1:1	0.2 g	15	5
3	1:2	0.2 g	15	5
4	1:1	0.1 g	15	5
5	1:1	0.3 g	15	5
6	1:1	0.2 g	10	5
7	1:1	0.2 g	20	5
8	1:1	0.2 g	15	2.5
9	1:1	0.2 g	15	10

this total volume, mixtures were formed at 1:1, 1:2, and 2:1 vol ratios (v/v). For example, a mixture was created by taking 22.5 mL of ZO extract and 22.5 mL of Zn salt solution in a 1:1 ratio and then proceeding to the other steps. Then, the effects of other parameters were examined. A total of 9 aqueous samples were prepared with various parameters given in Table 1. In the study, volumetric ratio, amount of PEG, sonication process amplitude, and process time were examined as parameters. In the study, volumetric ratio, amount of PEG, sonication process amplitude, and process time were examined as parameters. After the prepared solutions were characterized by UV–visible spectroscopy analysis, optimum parameters were determined and other analyses were performed. Fig. 1 shown schematical experimental design of the ultrasound-assisted plant-mediated synthesis of ZO/PEG-ZnO NPs.

2.4. Characterization of synthesized ZO/PEG-ZnO NPs

The ZnO NPs synthesized via ultrasound-assisted plant-mediated method were characterized to evaluate their physical and chemical properties. Characterization of the synthesized NPs was conducted using UV–Vis spectroscopy, X-ray diffraction (XRD), scanning electron microscopy (SEM), transmission electron microscopy (TEM), and Fourier transform infrared spectroscopy (FTIR). UV–Vis analysis was performed to measure absorbance values using a PG Instruments T80 + dual-beam UV–Vis spectrophotometer, assisted by UVWin 5 software. The surface morphology and topographical features of pure ZO and ultrasound-assisted, plant-mediated synthesized ZO/PEG-ZnO NPs were examined using SEM/EDS on a Zeiss-Sigma 300 instrument. TEM analysis was carried out using a Hitachi High Tech HT7700, operating in high vacuum mode at 100 kV, to enable high-resolution imaging of the NPs at the nanoscale level. The functional groups of ZO/PEG-ZnO NPs were identified using the Perkin Elmer Spectrum Two model, operating within the 4000–400 cm^{-1} frequency range with a resolution of 4 cm^{-1} and 8 scans. XRD analysis was conducted using a PANalytical Empyrean XRD instrument, operating at 40 kV and 15 mA with a Cu-Kα beam. The measurements were recorded within the 10° to 90° range to analyze the crystal structures of the sample. The crystallite sizes of the plant-mediated ultrasound-assisted synthesized ZnO NPs were estimated using the Debye-Scherrer equation, as presented in Eq. (2.1).

$$D_p = \frac{0.94.\lambda}{\beta.\cos\theta} \tag{2.1}$$

This method takes into account the X-ray wavelength (λ) of 0.15406 nm, the full width at half maximum (FWHM) of the diffraction peaks (β), and the Bragg's diffraction angle (θ) derived from 2Theta (θ).

2.5. Antioxidant assay of ZO/PEG-ZnO NPs

The antioxidant measurement of the solution prepared with optimum parameters was carried out by DPPH (2,2-diphenyl-1-picrylhydrazyl) method. DPPH is a chemical compound widely used in the measurement of free radicals. This compound is a purple colored and stable free radical. DPPH is widely used to test antioxidant activities because antioxidants reduce the DPPH radical and change its color. In order to compare whether the antioxidant properties of the prepared NPs are due to the essence or the synthesized NP, antioxidant measurements were carried out in solutions with essence and different ZnO

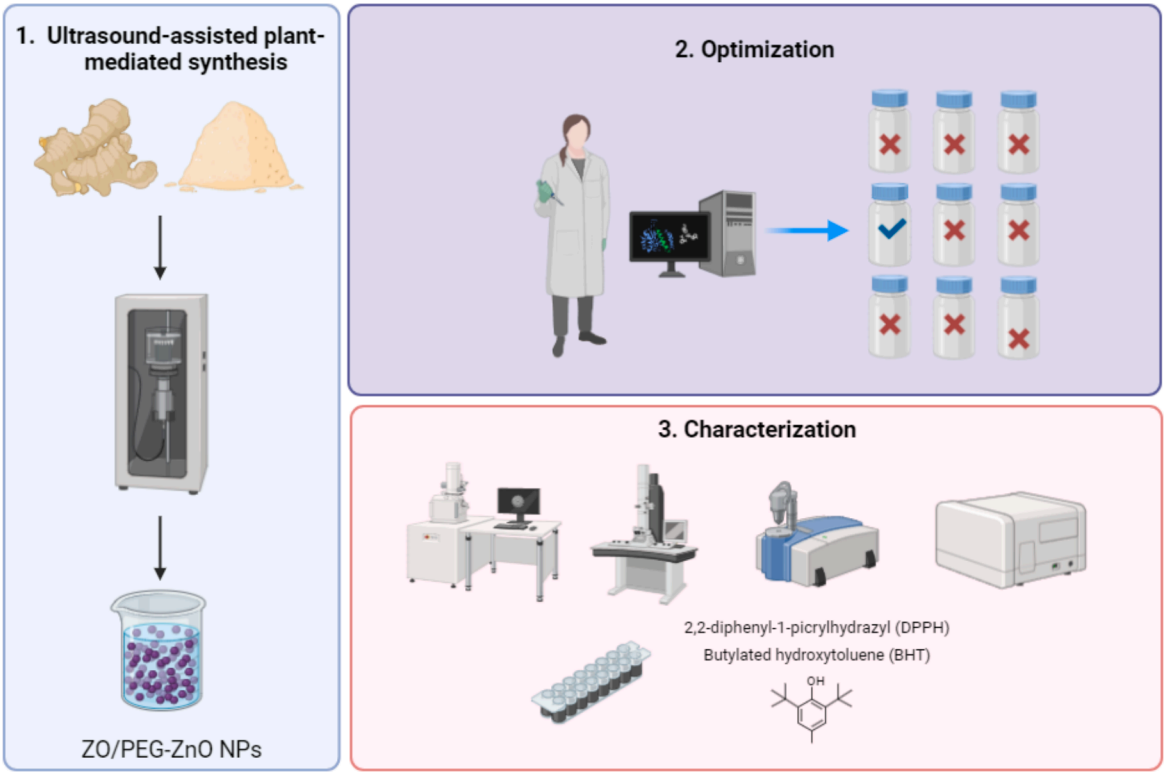

Fig. 1. Experimental steps of the ultrasound-assisted plant-mediated synthesis of ZO/PEG-ZnO NPs.

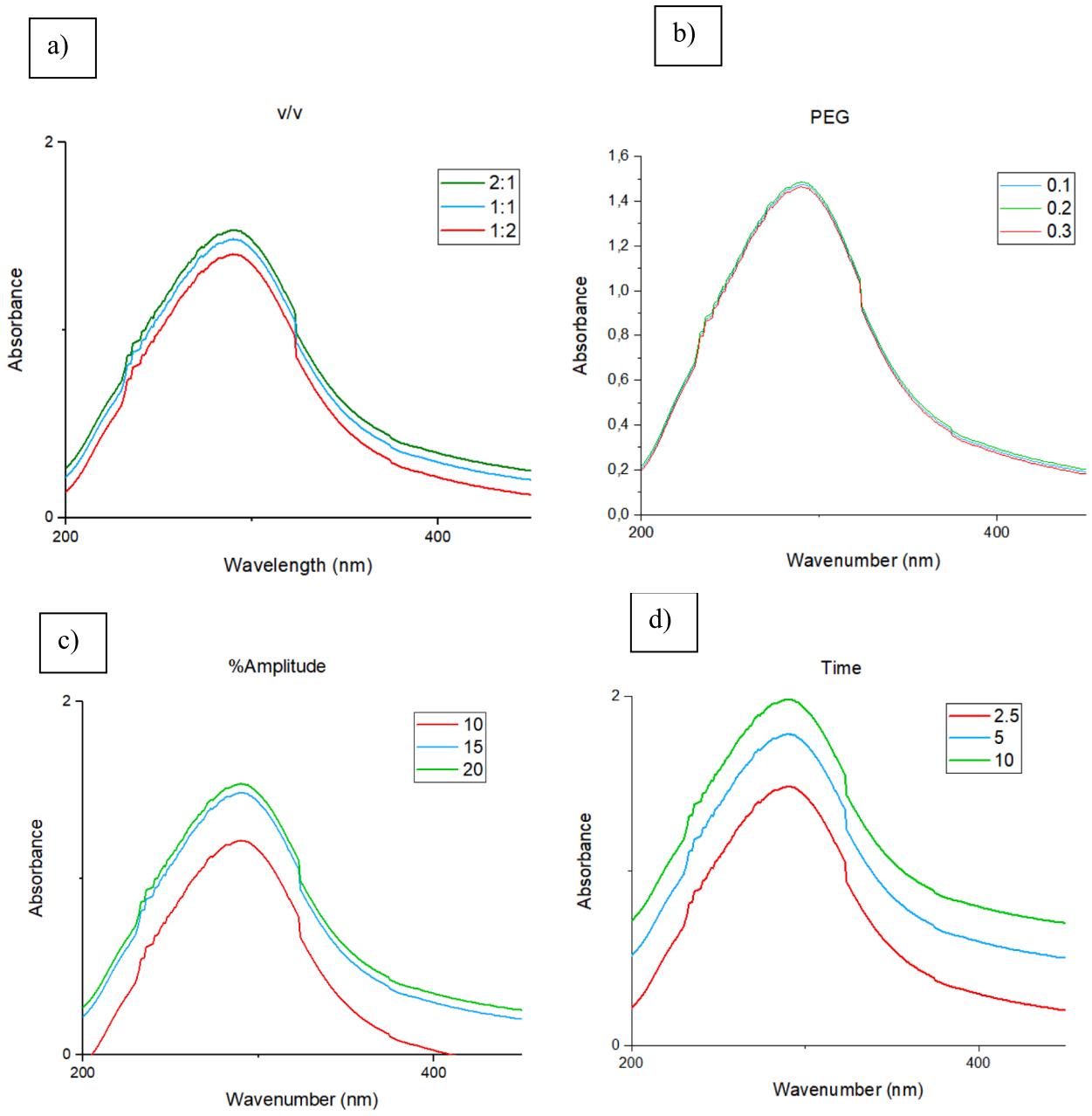

Fig. 2. UV–Vis spectral analysis results of ZO/PEG-ZnO NPs solutions synthesized under different conditions a) volumetric ratio, b) amount of PEG, c) amplitude, and d) sonication time.

NPs concentrations. Butylhydroxytoluene (BHT) and ascorbic acid (Vitamin C) were used as positive controls in the experiments. 3 different concentrations were studied in the experiment. The optimum solution prepared has a concentration of 0.01 M. Antioxidant measurements were also carried out for 0.005 M and 0.0025 M concentrations. All measurements were repeated three times. 2 mL of the samples were taken and added to the test tube. Then, 2 mL of DPPH solution was added to them and mixed. After waiting for 30 mins in the dark, absorbance measurements were performed at 517 nm. DPPH radical scavenging activity (RSA) was expressed as percentage of inhibition using the Eq. (2.2).

$$\%RSA = \frac{AbsorbanceControl - AbsorbanceSample}{AbsorbanceControl} \times 100 \quad (2.2)$$

2.6. Photocatalytic activity measurement

The photocatalytic activity of ultrasound-assisted plant-mediated synthesized ZnO NPs using ZO extract was investigated for the degradation of MB and RhB dyes under sunlight at room temperature. First, 0.01 g of ZnO NPs was dispersed in 100 mL of 10 ppm aqueous dye solution, and the mixture was magnetically shaken in the dark for 30 min., and the mixture was magnetically shaken in the dark for 30 min. The suspension was then exposed to sunlight for various times (0 min, 30 min, 60 min, 90 min, 120 min, 150 min and 180 min), after which the absorbance values at 663 nm and 564 nm for MB and RhB, respectively, were measured with a UV–Vis spectrophotometer. The calculation of degradation efficiency was conducted for both dye with ZnO NPs, as outlined in Eq. 2.3 [42].

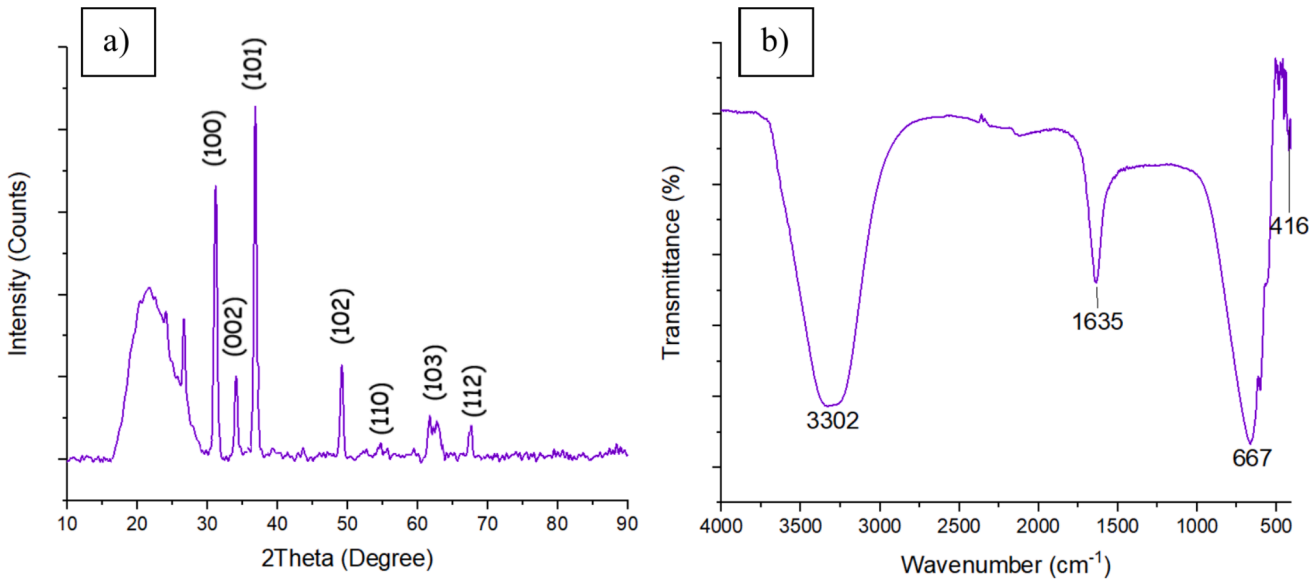

Fig. 3. Analysis results of a) XRD and b) FTIR.

$$\%\,\text{Degradation} = \frac{C_0 - C_t}{C_0} \times 100 \quad (2.3)$$

Whereas, C_0 represent the initial absorbance (at time 0) and and C_t present the absorbance at time t.

3. Results and discussions

3.1. Optimization results of ZO/PEG-ZnO NPs

UV–Vis spectroscopy is a method used to observe the presence of metal-based NPs and to examine the relevant surface plasmon resonance (SPR) band and get ideas about shape, size and distribution [43]. The SPR mechanism plays an important role in the UV–Vis analysis of metal-based NPs. In UV–Vis analysis, the light coming from the light source interacts with the free electrons of the metal, causing them to oscillate collectively. As a result of the light resonating at a certain frequency, surface plasmons are excited on the metal. At this resonance point, the light is absorbed or reflected at a certain angle, which creates a sharp SPR peak in the UV–Vis spectrum. Peaks occur in a certain range for each metal [44]. Fig. 2 (a-d) shows graphs used for optimization of different parameters. In all graphs, ZnO NPs prepared with ZO extract appearance of an SPR peak at 301 nm. In the literature, ZnO NPs synthesized through plant extracts are stated to form a peak between 300–380 nm [45,46]. Plant extracts usually contain organic molecules containing flavonoids, phenolic compounds, and other conjugated systems. These compounds can create characteristic peaks in the UV–Vis spectrum. Since plant extracts can contain many different compounds, each of these compounds absorbs with small energy differences. Pure ZnO NPs usually exhibit absorption of around 370 nm. However, particle size, surface modifications, and environmental factors may affect the position and shape of this absorption. The interaction of ZnO NPs with plant extracts can change the absorption properties of compounds. In particular, organic molecules in plant essence can form a complex with ZnO NPs or connect to the surface, which can lead to changes in spectral properties. Ravendran et al. [47], reported that the synthesized ZnO NPs by using *Costus pictus* D. leaf extract was shown a broad peak at 301 nm. Fig. 2**a** shows the volumetric ratio results of the extract and Zn salt solution. A singular peak was observed in all obtained spectra indicating the presence of ZnO NPS in the produced materials. As seen in the graphs below, 2: 1 (v/v), 0.2 g PEG, 20 Hz, and 10 min duration of sonication are optimum conditions. In detail, it is seen that the PEG contribution does not make a significant change and the degree of amplitude and sonication time has a significant effect.

Table 2
XRD patterns were obtained for the phyto/sonosynthesized ZnO NPs.

Miller indices	(100)	(002)	(101)	(102)	(110)	(103)	(112)
2θ value	31.52°	34.47°	37.59°	48.84°	55.25°	63.21°	68.12°

3.2. Characterization results of ZO/PEG-ZnO NPs

Various characterization studies were carried out on ZnO NPs prepared under optimum conditions and their properties were defined. XRD analysis was performed on ZnO NPs to determine their crystalline structure and phases. FTIR spectroscopy is used to identify functional groups and confirm the chemical bonding in ZnO, especially in cases involving green synthesis. In Fig. 3**(a) and 3(b),** XRD and FTIR spectra were give, respectively. Table 2 shows the peaks of the ZnO NPs as a result of the XRD analysis. The XRD pattern reveals that the peaks are significantly broader, suggesting that the synthesized particles have dimensions at the nanoscale. As a result of XRD analysis, peaks corresponding to (100), (002), (101), (102), (110), (103), and (112) planes were detected. In this case, it was observed that the phyto/sono synthesized ZnO NPs had a hexagonal wurtzite crystal structure. The main objective of this study is to produce multifunctional ZnO NPs using ZO plant powders. The detected peaks reveal a clear crystallinity and have been accurately referenced against the JCPDS data file No. 36-1451 [48]. The crystal size was calculated according to the Debye-Scherrer formula expressed in **Eq. (2.1)**. The crystallite average size of the ZO/PEG-ZnO NPs is 22.17 nm. The peaks occurring at 22.57° and 26.54° originate from the organic structures in the ZO/PEG matrix [19,49]. The presence of the ZnO NPs peak confirmed the purity of the synthesized NPs, indicating no contamination. As a result of FTIR analysis, 3302 nm^{-1} vibration is hydroxyl group (O–H) stretching vibrations, indicating the presence of water or phenolic compounds originating from ZO/PEG blend matrix, 1635 nm^{-1}C=O stretching vibrations indicate carbonyl groups of flavonoids in ZO extracts. The peak at 667 nm^{-1}corresponds to Zn ions-carboxylic group and another peak at the 416 nm^{-1} peaks indicating the presence of Zn–O bonds, confirming the formation of ZnO NPs [31,50,51]. According to the FTIR analysis results, the amine group also shows that proteins bind more easily to metal

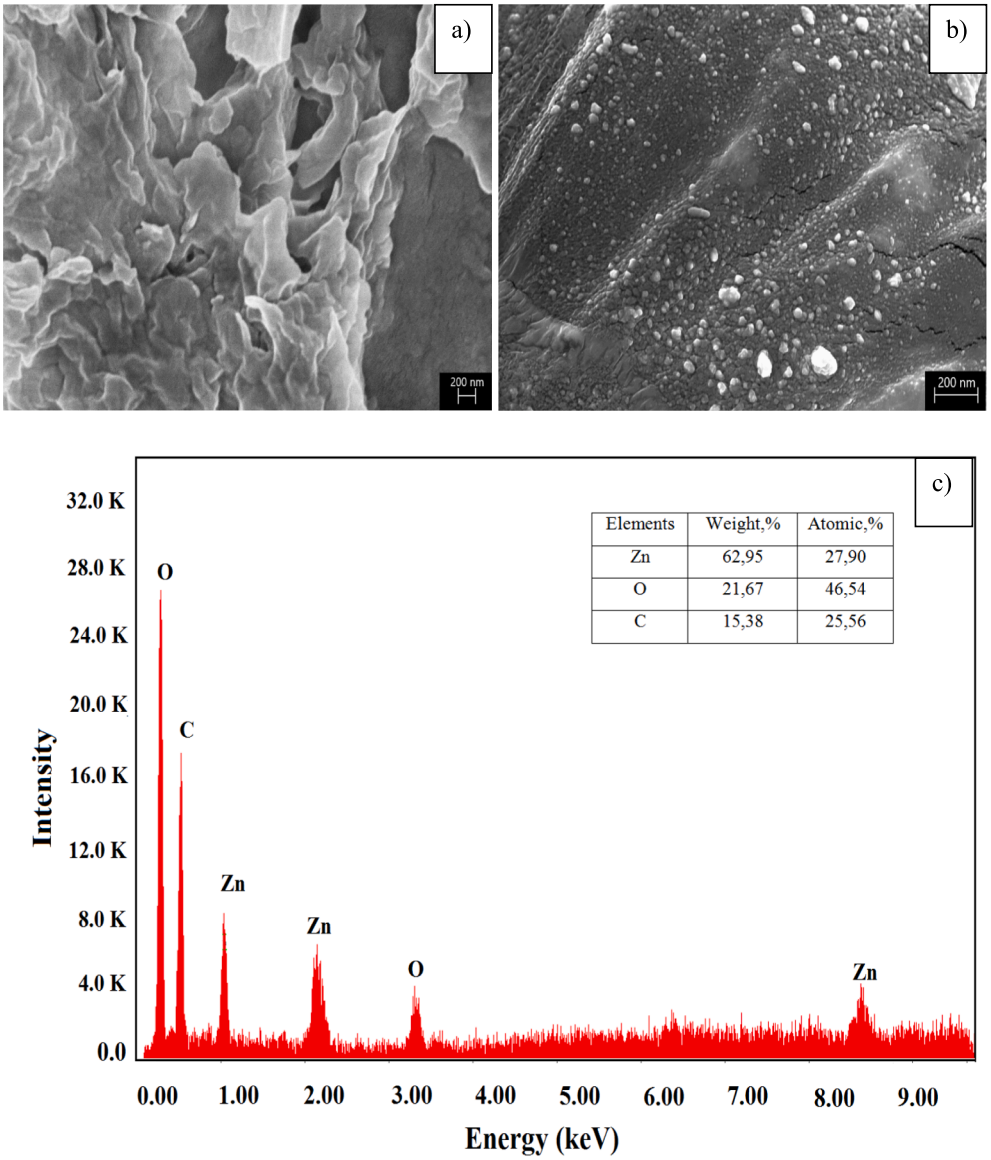

Fig. 4. SEM images of a) ZO powders, b) ZO/PEG-ZnO NPs and c) EDX results of ZO/PEG-ZnO NPs.

based NPs. The presence of functional groups originating from the plant extract we used indicates that it has a dual function as both a coating and a reducing agent.

SEM-EDX analyses were conducted to characterize the morphology and elemental composition of NPs and plant powders. These techniques help confirm the successful synthesis and surface interaction of NPs with plant-based materials. In this study, a green ZO/PEG blend matrix was utilized for stabilizing ZnO NPs. The SEM image and EDX analysis results of the ZO plant powders and the synthesized ZnO NPs are given in Fig. 4 **(a-c)**, respectively. As seen in the SEM image, the raw ZO powders are in the form of rather irregularly shaped particles before the process. It is in a rough and layered form due to the reflection of natural biological structures. The image of ZnO NPs stabilized with the ZO/PEG biopolymer matrix after phyto/sonosynthesis clearly shows nano-sized particles, predominantly spherical in shape, with some exhibiting irregular forms. Similar observations have been reported for green-synthesized ZnO NPs from various other plant [13]. The elemental composition of the synthesized ZO/PEG-ZnO NPs was further examined using the EDX spectrum confirmed that the elementary composition of the particles consisted largely of Zn and O elements. In particular, the elemental composition of Zn and O was 62.95 % and 21.67 %, respectively **(**Fig. 4**.c).** At the same time, the EDX spectrum of ZnO NPs shows peak of C elements. These minimal elements were probably caused by residues of *Zingiber officinale* or PEG. The absence of characteristic contamination peaks further confirmed the purity of the phyto/sono-synthesized NPs. These results are further supported by previously documented literature for the production of ZnO NPs [52,53].

TEM analysis was performed on NPs to provide high-resolution imaging, enabling precise characterization of NPs morphology. Fig. 5 shows the TEM image of the phyto/sonosynthesized ZnO NPs. The presence of ZnO NPs is noted as the dark colored spots. As shown in the figure, the ZO/PEG-ZnO NPs exhibited a spherical shape, with particle sizes smaller than 30 nm. It was also observed that the ZnO NPs were uniformly distributed and well-dispersed within the ZO/PEG biopolymer blend matrix. Histogram of ZO/PEG-ZnO NPs size distribution was established as displayed in Fig. 5**(b)**. The average particle size of ZnO NPs was determined from the distribution histogram to be 20 $\pm$ 1.3 nm. This result is consistent with the SEM results of ZO/PEG-ZnO NPS and previous studies examining the plant-mediated synthesis of ZnO NPs [54].

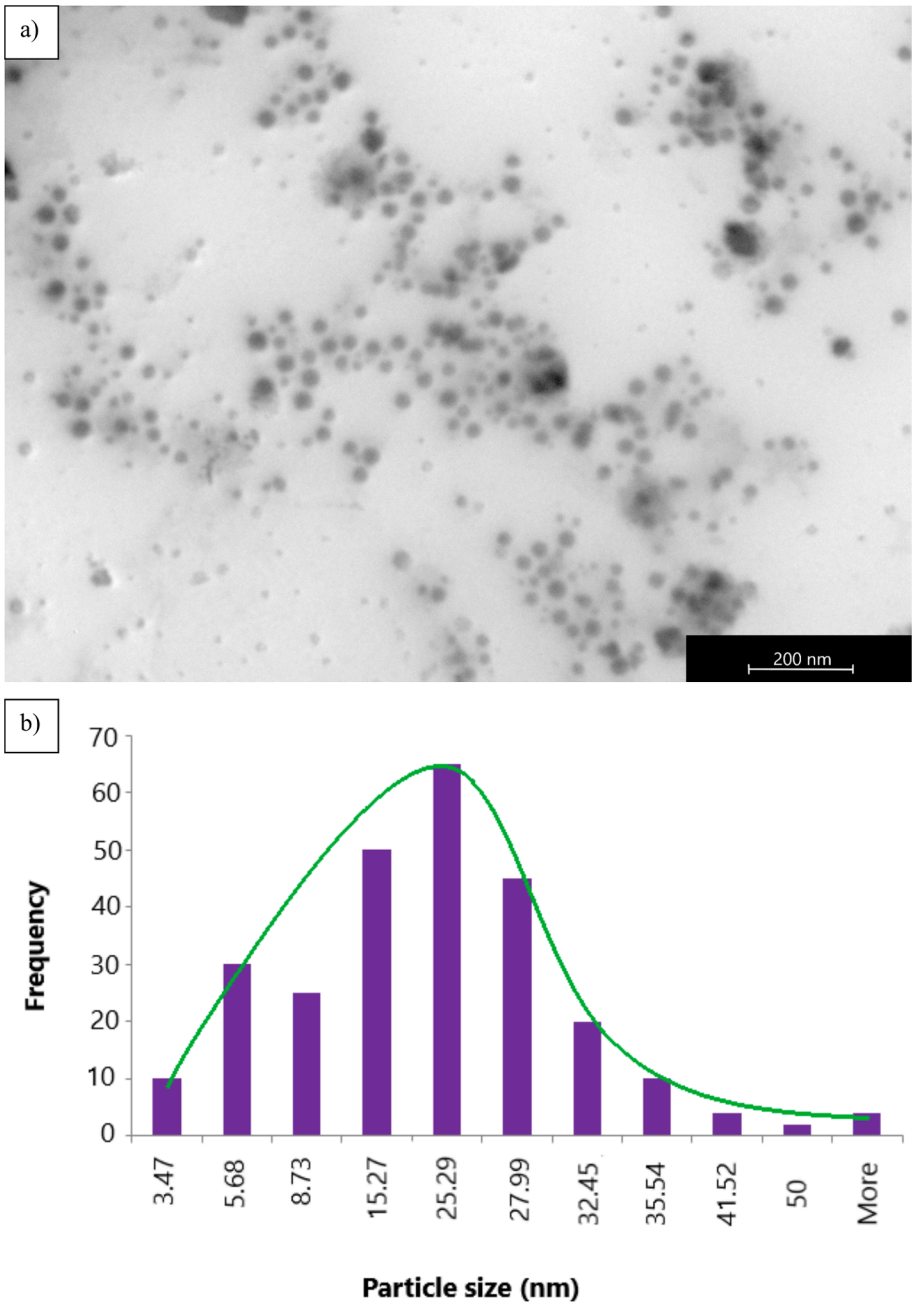

Fig. 5. a)TEM images and b) particle size histogram of ZO/PEG-ZnO NPs.

3.3. Antioxidant assay results of ZO/PEG-ZnO NPs

The scavenging activity of ZnO NPs was measured using UV–Vis by changing the color of DPPH from purple to yellow. The percentage of inhibition of DPPH radical scavenging activity is presented in Fig. 6. Antioxidant activity of ZO extract and prepared 0.0025 M, 0.005 M and 0,01 M ZnO NPs at different concentrations were showed inhibition at 32 % ±1.58, 40 % ±0.8, 59 % ±1.18 and 72 % ±1.44, respectively. ZnO NPs have acceptable antioxidant activity. The standard solutions showed 97 % inhibition. These results show that the antioxidant property changes depending on the dose and the antioxidant property increases with increasing concentration. The fact that ZnO NPs solutions show significantly more antioxidant property than the extract may be due to the surface properties of the ZnO NPs. As a result of, the IC50 value of ZO/PEG-ZnO NPs was determined as 0.0042 M. Al-Radadi et al. [31], were studied about the antioxidant activity of ZO driven biosynthesized of ZnO NPs. In the study, it was observed that antioxidant properties increased with increasing concentration. However, the amount of scavenging (%) remained around 40 %. Dianati et al. [55] reported that curcumin-mediated ZnO NPs exhibited an antioxidant activity of 18.06 % at a concentration of 500 µg/mL, as measured by the DPPH assay. Ihsan et al. [56] reported antioxidant activity with DPPH at 1000 µg/mL concentration of using *Curcuma zedoaria* and *Momordica charantia* plant-mediated synthesized were 58.16 % and 55.76 %, respectively. In another study, Ratney and David [57] were studied about antioxidant activity of ZnO NPs synthesis by chemical and green method. At the end of the study, it was stated that ZnO NPs synthesized biologically using *Zingiber Zerumbet* showed better antioxidant properties (~56 %) and a concentration-dependent increase was observed. The common point of these studies in the literature is that the differences in antioxidant activity of ZnO NPs prepared from various plant extracts may be attributed to their varying sizes and specific surface areas, which

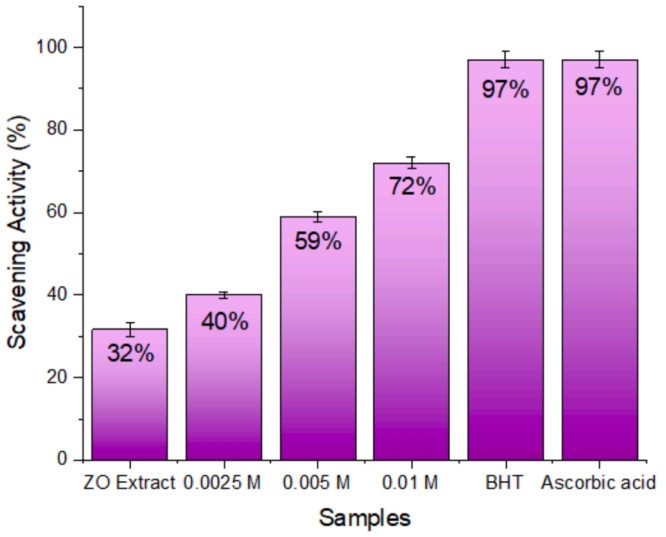

Fig. 6. Antioxidant potential of extract and prepared ZnO-NPs at different concentrations.

are influenced by the type of plant extract used. These variations in size and surface characteristics can impact the reactivity and interaction of the NPs with reactive oxygen species, thus affecting their antioxidant activity. Plant extracts have antioxidant capacity due to the metabolic compounds they contain. Especially in the case of NPs, a large surface area can help create a more stable and well-distributed structure, thus increasing reactivity and interaction surface. Antioxidant activity is usually associated with reactive functional groups or electron transfer mechanisms on the surface. NPs or biological systems with a larger surface area can capture or neutralize free radicals more effectively. Nanomaterials or biopolymer-coated structures with a larger surface area can increase antioxidant activity, increase free radical scavenging capacity and provide more effective protection in biological systems. When the studies in the literature are evaluated, the results suggest that the high content of phenolic compounds in plant extracts contributes to their strong antioxidant activity, making them effective in preventing oxidative stress. These results suggest that ZO stabilized ZnO NPs were in good harmony in terms of antioxidant activity. The obtained IC50 value of 0.0423 M indicates a high antioxidant activity compared to this range, indicating that ZnO NPs prepared with ginger extract effectively suppressed free radicals. All tested compounds exhibited low radical scavenging activity compared to ascorbic acid and BHT. There are studies correlating the redox potential and the number of hydroxyl groups of compounds with antioxidant activity. In addition, it is thought that steric hindrance limiting the reaction of compounds with DPPH radical may be related to low antioxidant activity [58].

Antioxidant activity is known to improve our overall health by neutralizing free radicals in our systems. Studies have shown that NPs have antioxidative properties. Compared to traditional antioxidants, plant-based synthesized metal/metal oxide based NPs have been reported to have many advantages. The use of an encapsulated delivery system enhances antioxidant protection, bioavailability, precise targeting, and controlled release. Previous studies have demonstrated that NPs synthesized with plant extracts are effective free radical scavengers, improving their ability to neutralize oxidative stress and offer enhanced therapeutic benefits. Green synthesized ZnO NPs exhibit high antioxidant efficacy, making them suitable for a variety of industrial applications, including health and hygiene products, pharmaceuticals, and antibacterial products [52,59,60]. In this respect, the study is important for the widespread use of Zn NPs as antioxidant agents in the future.

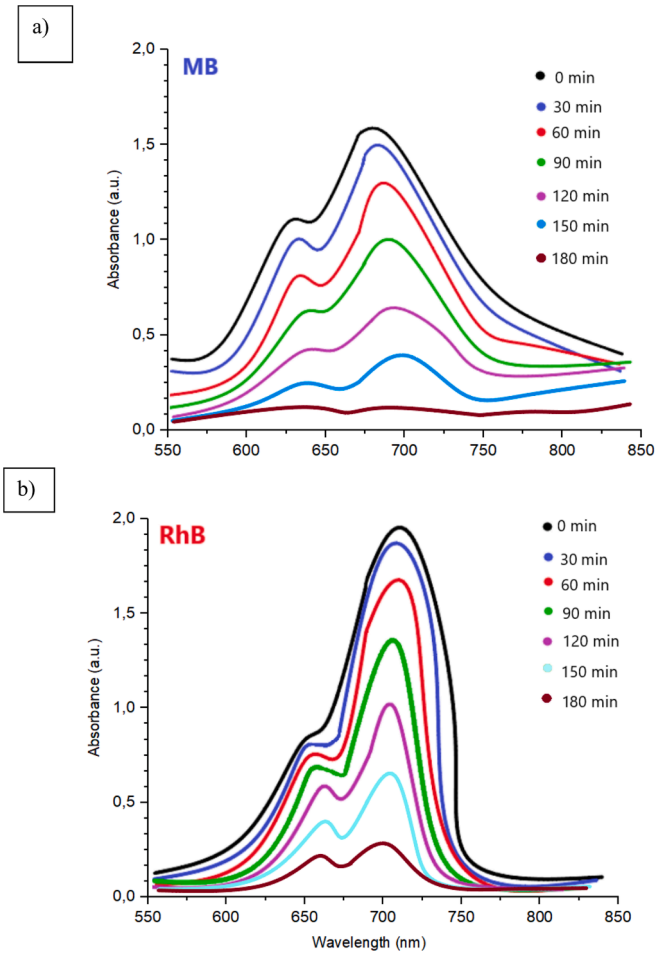

Fig. 7. Photocatalytic activity measurements results a) MB and b) RhB.

Table 3
Photocatalytic degradation results.

Time	30 min	60 min	90 min	120 min	150 min	180 min
Dye						
MB	%5.75	%18.6	%37	%56	%75.3	%92.7
RhB	%0.9	%10.14	%27.55	%45.54	%65.8	%85

3.4. Photocatalytic activity assay results

Measuring photocatalytic activity typically involves evaluating the degradation of organic dyes, pollutants, or other target compounds under controlled light exposure [61]. In this study, MB and RhB were used as organic dyes for the measurement of the photocatalytic activity of ZO/PEG-ZnO NPs. In Fig. 7, UV–Vis graph of the test result were given. During the study, the photocatalytic degradation potential of MB and RhB by phytoproduced NPs under sunlight was evaluated at different time intervals. In Table 3, Degradation efficiency of the dyes with ZO/PEG-ZnO NPs were presented. It was observed that the amount of degradation of both dyes increased with increasing time. When examined comparatively, it is seen in Fig. 7 that MB removal is higher. For MB, the band observed at 664 nm indicates that 92.7 % of the dye is degraded at exactly 150 min due to the catalytic efficiency of ZO/PEG-ZnO NPs. On the other hand, for RhB, 85 % of the dye is degraded at 150 min. Metal oxide structures are good photocatalytic agents and are important for environmental protection. It is known that ZnO NPs exhibit photocatalytic behavior and dye removal by a general

Table 4
Comparison of degradation efficiency of ZnO NPs synthesized from different plant extract.

Plant	Size of ZnO NPs (nm)	Dye	Concentration	Degradation efficiency (%)	Time (min)	Reference
Solanum nigrum	22	MB	100 ml of 5 × 10^{-3}M aqueous MB solution and 0.2 g of ZnO NPs	98	50	[41]
Borreria hispida	21.87	MR	10 mg L^{-1} of MR in a flask at 1 gL^{-1}	94.22	40	[64]
Myrica esculenta	31.67	MB	10 mg of ZnO in 100 mL of MB	91	180	[66]
Eriobotrya japonica	13.4	MB	5 mg catalyst and MB dye solution (10 mg/L; 50 mL)	72	160	[70]
Cyanometra ramiflora	13.33	RhB	20 mg of CR–ZnONPs was added to 100 mL of RhB dye solution (10 μM)	98	200	[71]
Alchemilla vulgaris	20	RhB	40 mg of ZnO NPs were dispersed in 80 mL of 10 mg/L RhB	75	120	[72]
Zingiber officinale	22.17	MB RhB	0.01 g of ZnO NPs in 100 mL of 10 ppm aqueous dye solution	92.7 85	150	In this study

mechanism. Photocatalytic activity behavior occurs with the promotion of the redox potential transition between the benefactor and the acceptor through the mechanism known as the electron relay effect [41]. Photocatalytic activity is related to the different amounts of oxygen vacancies. The separation of electron-hole pairs is related to the number of oxygen vacancies present [62,63]. The main factor that has brought plant extract-based NPs to the forefront recently is that their green production processes play an important role, as well as usage areas. The comparison of the results with the literature is presented in Table 4. As shown by the available studies in the literature, plant-based ZnO NPs show good performance in terms of photocatalytic activity [42,64–69]. Muthuvel et al. [41] reported in their study that ZnO NPs produced by plant-based synthesis using *Solanum Nigrum* showed better activity than ZnO NPs synthesized by chemical routes. When the studies are reviewed, it is seen that an acceptable degradation efficiency is achieved at similar concentration values. A comprehensive evaluation should be made by considering the plants used in the studies and factors such as NP sizes together. From this point of view, the ZO/PEG-ZnO NPs prepared in this study gave good results in MB and RhB removal. In conclusion, the choice of NPs, including traditional ZnO NPs and plant-based alternatives, significantly influences photocatalytic activity. As research progresses, integrating sustainable synthesis methods with advanced materials science is expected to yield more efficient and environmentally friendly photocatalysts for diverse applications.

4. Conclusions

This study attempted to develop antioxidant ZnO NPs using *Zingiber officinale* powders using an environmentally friendly green synthesis method. The results can be summarized as follows:

- These results suggest that *Zingiber officinale* extract is an effective reducing agent for the green synthesis of ZnO NPs with significant antioxidant and wound healing potential.
- The ZnO NPs exhibited a distinct absorption peak at 370 nm in the UV–Vis spectrum. XRD analysis revealed a hexagonal wurtzite crystal structure with characteristic sharp peaks, and the crystallite size was determined to be 22.17 nm.
- The FTIR spectrum displayed characteristic peaks of ZnO NPs at 667 cm^{-1} and 416 cm^{-1}. These peaks confirmed the presence of functional groups that may have played a role in the bioreduction and stabilization of Zn ions in the plant-mediated synthesis of ZnO NPs.
- The use of plant extracts for green synthesis provides an environmentally friendly, straightforward, and efficient pathway for the synthesis of NPs. The biological synthesis of ZnO NPs using plant extracts represents a highly effective, rapid, and versatile approach for the production of ZnO NPs.
- ZO/PEG-ZnO NPs exhibit high antioxidant activity, as demonstrated by an IC50 value of 0.0423 M, positioning them as viable candidates for biomedical and pharmaceutical applications. This study provides new insights into developing antioxidant properties. Further investigation is needed on the other properties of the innovative antioxidant nanomaterial and its use in different areas.
- The synthesized ZO/PEG-ZnO NPs exhibited promising activities that can be explored for medical, agricultural and industrial application areas. The findings of this study may open up new avenues for developing antioxidant properties.
- Only the antioxidant activity was assessed *in vitro*, which may not fully represent the potential of green-synthesized NPs to be used in biomedical applications. Future studies to assess the cytotoxic potential of the NPs are needed in order to utilize them to their full potential.

CRediT authorship contribution statement

Gizem KARABULUT ŞEVK: Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Tugce DİLBER:** Writing – original draft, Formal analysis. **Nuray BEKÖZ ÜLLEN:** Writing – original draft, Supervision, Methodology.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: [Nuray BEKOZ ULLEN reports financial support was provided by Istanbul University-Cerrahpasa. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper].

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Data availability

Data will be made available on request.

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