Journal Homepage: -www.journalijar.com

INTERNATIONAL JOURNAL OF ADVANCED RESEARCH (IJAR)

ISSN (O): 2320-5407
ISSN (P): 3107-4928

Article DOI: 10.21474/IJAR01/23562
DOI URL: http://dx.doi.org/10.21474/IJAR01/23562

RESEARCH ARTICLE

ECO-FRIENDLY SYNTHESIS OF ZINC OXIDE NANOPARTICLES USING *CURCUMA CAESIA* TUBER EXTRACT AND THEIR ANTIOXIDANT AND ANTICANCER ACTIVITIES

Priyanka Shah[1], Hiralal Sonawane[1], Nishi Dixit[1], Deepak Shelke[2] and Kamlakar More[3]

1. PG Research Centre in Botany, PDEA's Prof.Ramkrishnna More, ACS College, Akurdi, Pune, MS, India: Affiliated to Savitribai Phule Pune University.
2. Department of Botany, Amruteshwar Arts, Commerce and Science College, Vinzar, Velhe, Pune, MS, India.
3. Department of Botany, Sant Gadge Baba Amravati University, Amravati, (MS) India.

Manuscript Info

Manuscript History
Received: 16 March 2026
Final Accepted: 18 April 2026
Published: May 2026

Key words:-
Zinc-oxide nanoparticles (ZnO NPs), *Curcuma caesia*, Antioxidant activity, Anticancer activity, Breast cancer-MCF-7 cells.

Abstract

The use of environmentally friendly nanomaterials for biomedical applications has received extensive attention due to their high biocompatibility and therapeutic potential. In the present study, zinc oxide nanoparticles (ZnO NPs) were synthesized by the green synthesis approach using *Curcuma caesia*Roxb. tuber extract. The synthesized nanoparticles were characterized by UV–Visible spectroscopy, Fourier Transform Infrared (FT-IR) spectroscopy, and Energy Dispersive X-ray (EDX) analysis. Formation of nanoparticles was confirmed by UV-Visible spectroscopy from the characteristic absorption peak of ZnO NPs. FT-IR analysis indicated the involvement of different functional groups in the synthesis and stabilization of nanoparticles. The FESEM analysis confirmed the particle average size 29.25nm.The elemental composition and purity of the synthesized nanoparticles were confirme d by EDX analysis.The antioxidant potential of the biosynthesized ZnO nanoparticles was evaluated using free radical scavenging assays, showing concentration-dependent antioxidant activity. Furthermore, the anticancer activity of the ZnO nanoparticles was studied against human breast adenocarcinoma (MCF-7) cells by MTT assay. The ZnO NPs exhibited good cytotoxic activity (IC_{50} 104 µg/mL) and significantly reduced cell viability in a dose-dependent manner. The observed anticancer effect might be due to the increased generation of reactive oxygen species, leading to oxidative stress and subsequent induction of apoptotic pathways in the cancer cells. The results of this study showed that *Curcuma caesia* mediated ZnO nanoparticles exhibit significant antioxidant and anticancer activities and can be used as a potential candidate for future therapeutic applications based on nanomedicine.

Corresponding Author:- Hiralal Sonawane
Address:-PG Research Centre in Botany, PDEA's Prof.Ramkrishnna More, ACS College, Akurdi, Pune, MS, India: Affiliated to Savitribai Phule Pune University.

Introduction:-

Cancer remains one of the top causes of death worldwide, and breast cancer is the most common cancer diagnosed in women. Despite great advances in diagnosis and treatment, conventional therapeutic strategies such as chemotherapy, radiotherapy, and surgery are often associated with adverse side effects, multidrug resistance, and damage to healthy tissues(Sung et al., 2021). Therefore, the development of new therapeutic agents that are effective, biocompatible, and environmentally sustainable is gaining increasing interest. Nanotechnology is a promising interdisciplinary area with broad applications in medicine, particularly in cancer diagnosis and therapy(Hassan et al., 2022). Among different metal and metal oxide nanoparticles, zinc oxide nanoparticles (ZnO NPs) have received significant attention due to their unique physicochemical properties, such as high surface-to-volume ratio, biocompatibility, semiconducting behavior, and selective toxicity to cancer cells(Anjum et al., 2021). ZnO NPs have shown various biological activities such as antimicrobial, antioxidant, anti-inflammatory, and anticancer activities. The anticancer potential of these compounds is mainly due to the generation of reactive oxygen species (ROS), induction of oxidative stress, mitochondrial dysfunction, DNA damage, and activation of apoptosis pathways in malignant cells(Ruddaraju et al., 2019). Green synthesis of nanoparticles using plant extracts has drawn much attention in recent years as an environmentally benign alternative to the traditional chemical and physical methods(Labaran et al., 2024).The plant-mediated synthesis does not require any toxic reducing and stabilizing agents, and thus it is cost-effective, sustainable, and applicable for biomedical applications. The plant extract has phytochemicals like phenolics, flavonoids, terpenoids, alkaloids, and proteins, which act as natural reducing and capping agents during the nanoparticle formation(Ojoet al., 2021).

*Curcuma caesia*Roxb., is a medicinal plant of the family Zingiberaceae and is popularly known for its therapeutic properties. *C. caesia* rhizomes are rich in diverse bioactive compounds, including curcuminoids, flavonoids, essential oils, and phenolic constituents with antioxidant, antimicrobial, anti-inflammatory, and anticancer activities(Gangal et al., 2025). These phytochemicals may be useful in the synthesis of stable nanoparticles and may improve their biological efficiency. Oxidative stress is a major factor in the initiation and progression of many diseases, including cancer(Jayaprakasha, Rao and Sakariah, 2002). Hence, antioxidant agents that are able to scavenge free radicals are of great therapeutic interest. The plant-mediated ZnO NPs showed excellent antioxidant activity because of the synergistic effect of zinc oxide and the phytochemical residues adsorbed on the surface of the nanoparticles(Yılmaz et al., 2023). Further, a number of studies have demonstrated the selective inhibition of breast cancer cell proliferation by ZnO NPs through ROS-induced apoptosis and cell cycle arrest. The human breast adenocarcinoma cell line, MCF-7, is commonly used as an in vitro model to investigate the anticancer potential of novel therapeutic agents(Harbeck et al., 2019). The cytotoxic and apoptotic effects of biosynthesized ZnO NPs on MCF-7 cells were evaluated to understand their potential as anticancer nanotherapeutics(Miri et al., 2019). The physiological behavior of ZnO nanoparticles is significantly influenced by their size, shape, surface charge, and production process. Nanoparticles synthesized by eco-friendly methods frequently exhibit enhanced biological capabilities due to the presence of phytochemical residues on their surfaces. These bioactive compounds function as natural capping agents to enhance the stability of nanoparticles and facilitate interaction with biological systems(Fais et al., 2024). Furthermore, green-synthesized ZnO nanoparticles are normally considered safer for biomedical applications due to the lack of toxic chemicals commonly used in traditional synthesis processes. The antioxidant efficacy of plant-mediated ZnO nanoparticles is typically attributed to the synergistic interaction between zinc oxide and phytochemicals adsorbed on the nanoparticle surface(Rajeshkumar et al., 2018). This synergistic interaction may augment free radical scavenging ability and result in improved biological efficacy.

Breast cancer remains a relevant issue for global health, representing a large proportion of cancer-related morbidity and mortality among women. The emergence of resistance against conventional chemotherapeutic agents and the development of severe adverse effects indicate the urgent need for exploration of alternative treatment modalities(GLOBOCAN, 2020). The innovative approaches based on the use of nanotechnology have appeared as an efficient solution for cancer treatment owing to their ability to selectively target tumor cells and to minimize damage to healthy tissues. In this context, ZnO nanoparticles have shown great promise as anti-cancer agents, due to their ability to preferentially accumulate in cancer cells and induce programmed cell death(Li et al., 2020). Several mechanisms have been proposed to explain the anticancer properties of ZnO nanoparticles. One of the most accepted mechanisms is the production of intracellular reactive oxygen species, leading to oxidative stress, disruption of the mitochondrial membrane, DNA fragmentation, and activation of apoptotic signaling pathways(Zhang et al., 2015).Recent advances in green nanotechnology have highlighted the significance of combining medicinal plants and nanoparticle synthesis to create multifunctional nanomaterials(Jain et al., 2021). The plant-derived nanoparticles show better stability and may also possess the therapeutic property of phytochemicals involved in their synthesis. The use of Curcuma caesia-mediated ZnO nanoparticles is an innovative way to couple the medicinal value of black turmeric and the unique physicochemical properties of zinc oxide nanoparticles and is expected to result in improved antioxidant and anticancer efficacy. Nanotechnology is a developing interdisciplinary field that is applied to medicine for the better diagnosis, prevention, and treatment of disease. The application of nanoscale materials, typically 1-100 nm in size, has transformed biomedical research, resulting in the creation of advanced therapeutic and diagnostic systems(Shrestha et al., 2024).One of the most studied applications for cancer therapy has been nanomedicine. Conventional anticancer treatments are usually characterized by non-specific distribution, systemic toxicity, poor therapeutic efficacy and the development of drug resistance(Acharya et al., 2024). Therapeutic approaches based on nanotechnology have important advantages in the selective accumulation of therapeutic agents at the tumor sites, thus improving the efficacy of treatment and reducing damage to healthy tissues.

Methodology:-

Plant material:-

Rhizomes of *Curcuma caesia* are native to Nagaland; they were collected from a farmer in West Imphal and cultivated in Sangli, Maharashtra, and authenticated by BSI.

Preparation of plant extract:

To obtain a uniform range of *Curcuma caesia* rhizome powder, the rhizomes were broken up and ground into a powder in a mixer before being sieved. A 200 mL flask was filled with 5 grams of powdered plant extract, followed by 100 mL of methanol. The mixture was shaken thoroughly and then left for 24 hours(Klein et al., 2023). Figure 1 depicts the entire sample extraction procedure.

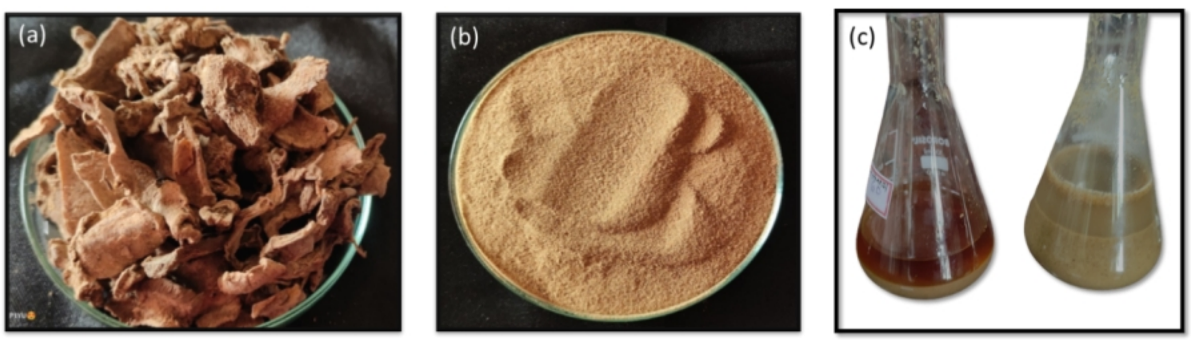


Figure 1. Sample extraction process: (a) Dried Curcuma caesia Rhizome, (b) fine powdered dried Curcuma caesia, and (c) methanol extract of Curcuma caesia.

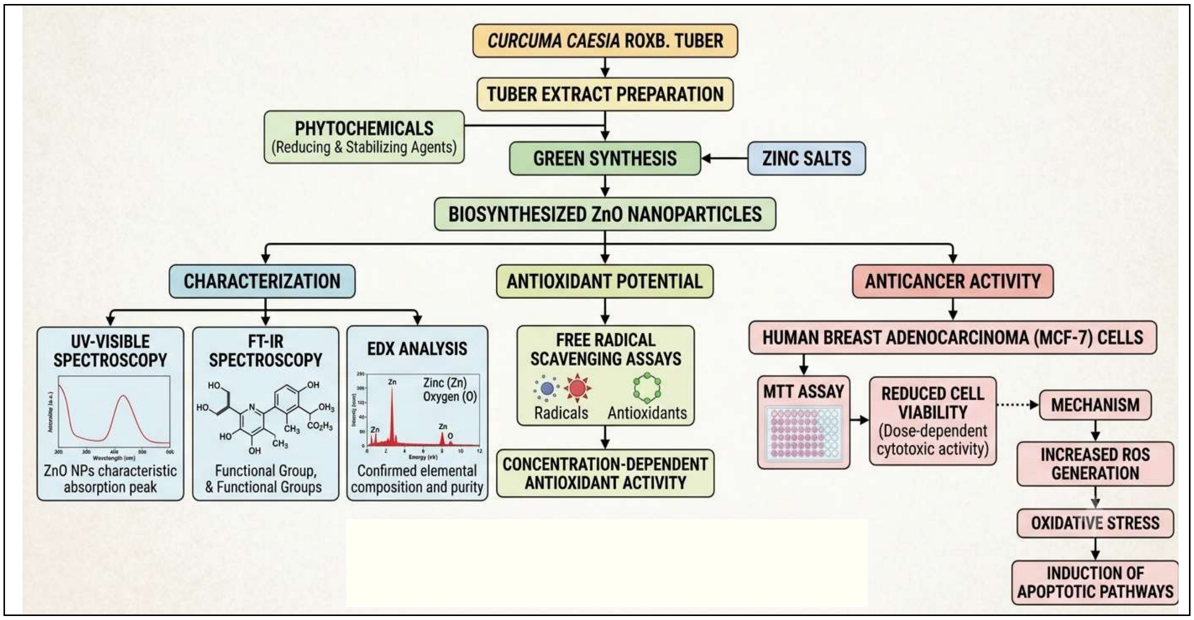


Figure 2: Schematic representation of the biosynthesis of zinc oxide (ZnO) nanoparticles using *Curcuma caesia* tuber extract, followed by spectroscopic characterization (UV–Vis, FT-IR, EDX), evaluation of antioxidant potential via free radical scavenging assays, and assessment of anticancer activity against MCF-7 breast cancer cells through MTT assay, highlighting ROS generation and apoptosis induction.

Green Synthesis of Zinc Oxide Nanoparticles:-

The extract of *Curcuma caesia* tuber was used as a reducing and stabilizing agent for the synthesis of zinc oxide nanoparticles (ZnO NPs). A 0.5 M solution of zinc acetate dihydrate was prepared by dissolving the appropriate amount of zinc nitrate in 100mL of distilled water under continuous magnetic stirring. The extract was added subsequently to the zinc acetate dihydrate solution with continuous stirring. Synthesis of ZnO nanoparticles. The reaction mixturewas magnetically stirred for 2 h at 70 °C. At the end of the reaction, a pale white precipitate was produced and was collected by centrifugation. The resulting precipitate was washed several times with distilled water. The product was purified and dried to obtain ZnO nanoparticles in the form of pale-yellow powder. The dried powder was annealed in a muffle furnace at 400 °C for 2 hr to improve its crystallinity and phase purity (Fig. 2) (Reddy et al., 2016).

Analytical characterization:-

The formation of zinc oxide nanoparticles (ZnO NP) was confirmed preliminarily using UV–Visible spectrophotometry in the wavelength range of 200-800 nm. Energy Dispersive X-ray (EDX) spectroscopy was used for elemental analysis of the synthesized nanoparticles and samples were mounted on a copper grid for analysis. The functional groups responsible for the synthesis and stabilization of the nanoparticles were confirmed by recording the Fourier Transform Infrared (FT-IR) spectra. Spectra were recorded from 4000 to 400 cm^{-1} with 128 scans per sample. The results obtained by these characterization techniques provided useful information on the optical properties, elemental composition, and surface chemistry of the synthesized nanoparticles, thus giving a complete understanding of their physicochemical characteristics(Dey et al., 2024).

Anti-Oxidant Activity:-

The antioxidant activity was assessed by using a previous method reported by Puri, Patil, and Sonawane (Sonawane et al., 2021; Puri and Patil, 2022). 5 µL of each test stock solution was placed in 0.1 mL of 0.1 mM DPPH solution inside a 96-well plate. The assignment was completed alongside blanks and samples with various concentrations of the 0.2 mL methanol sample. The treated wells were for control, but blanks were in the untreated wells. Following incubation in the dark for 30 minutes, the decolorization was measured at 517 nm with an iMarkBioRad microplate reader. Scavenging activity was represented as % inhibition over the control, and IC50 was determined from GraphPad Prism 6 by plotting sample concentration on the X-axis and % inhibition on the Y-axis.

$$\%\ Inhibition = \frac{Absorbance\ of\ control - Absobance\ of\ Sample}{Absorbance\ of\ control} \times 100$$

Cytotoxic Activity:-
The toxic impact of ZnO NPs against the MCF-7 breast carcinoma cell line, derived from NCCS Pune, was assessed using the MTT assay. In DMEM media enriched with a 10% fetal bovine serum or 1% antibiotic liquid at 37°C with 5% CO_2, the cells (10000 cells/well) were grown using 96-well plates for 24 hrs. The cells were then exposed to different formulation quantities at a later incubation. MTT solution (5 mg/mL) was added to the cultures and were incubated for adhering, to another 24 hours. The cell layer matrix in 100 µl of dimethyl sulfoxide (DMSO) was eliminated once the experiment was over. The resulting optical density at a wavelength of 540 nm was estimated with an ELISA plate reader (iMark, Bio-Rad, USA). GraphPad Prism 6 enabled the precise calculation of the IC_{50} value. An inverted microscope (Olympus EK2) and an AmScope digital camera (10MP Aptina CMOS) served to record images of excellent quality(Khorrami et al., 2018).

Apoptosis Activity:-
At their IC_{50} concentrations, Zinc nanoparticles were added to cells. We washed the treated and untreated control cells once more with cell staining buffer before putting the cells back in Annexin V binding buffer at a concentration of 0.25-1.0 × 10^7 cells/ml. We transferred 100 µL of cell suspension to a tube, then added 5 µL of FITC Annexin V and 10 µL of Propidium Iodide Solution. The cells were gently mixed and incubated in the dark at room temperature (25ºC) for 15 minutes. Finally, 400 µL of Annexin V Binding Buffer was added to each tube, and they were analyzed with flow cytometry (Ullah et al., 2020).

Statistical analysis:-
The cytotoxic activity of plant extract and ZnO NPs were performed in triplicate. The data were subjected to one way analysis of variance by statistical package SPSS 16.0. The means were compared by DMRT test at the significance level 0.05.

Results:-

Characterization:-

UV -Visible spectroscopy:-
The first sign of a successful synthesis of ZnO NPs was the formation of a yellow precipitate after the addition of the plant extract to the zinc acetate dihydrate (Figure 3). UV-visible spectrophotometric measurement after 2 h of incubation showed the absorption peaks of extract-to-zinc acetate at 379.6 nm, which confirmed the presence of ZnO NPs.

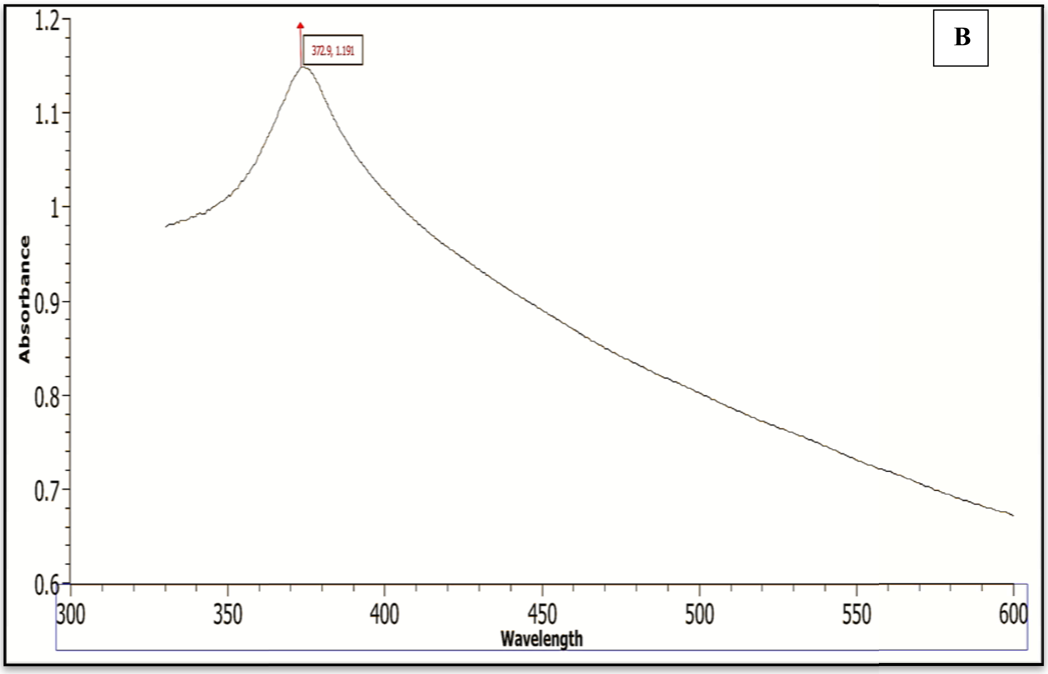


Figure 3: The green synthesis of (A) ZnO NPs (B)The UV- spectra graph of ZnO NPs.

FESEM-EDS Analysis:

The phytochemical-mediated biosynthesized ZnO nanoparticles are spherical shape with average size was 29.25nm (Figure 4A). Although significant aggregation was seen, most likely as a result of the particle surfaces not being fully stabilized. Furthermore, the existence of nanorod-like structures raises the possibility that anisotropic development, which synthesized heterogeneous particle morphologies, was influenced by an excess of capping agents in the reaction media. The high purity of ZnO nanoparticles with Zn and O content of 92.54% was confirmed by SEM-EDS analysis and was further stabilized with phytochemical residues of the Curcuma caesia extract (Figure 4B). The complementary XRD analysis confirmed the crystalline nature of the nanoparticles with strong diffraction peaks consistent with the hexagonal wurtzite structure of ZnO. The combined results show that the green synthesis method produces crystalline ZnO nanoparticles with different morphologies, which are governed by the interplay of reaction conditions and phytochemical capping agents with high purity.

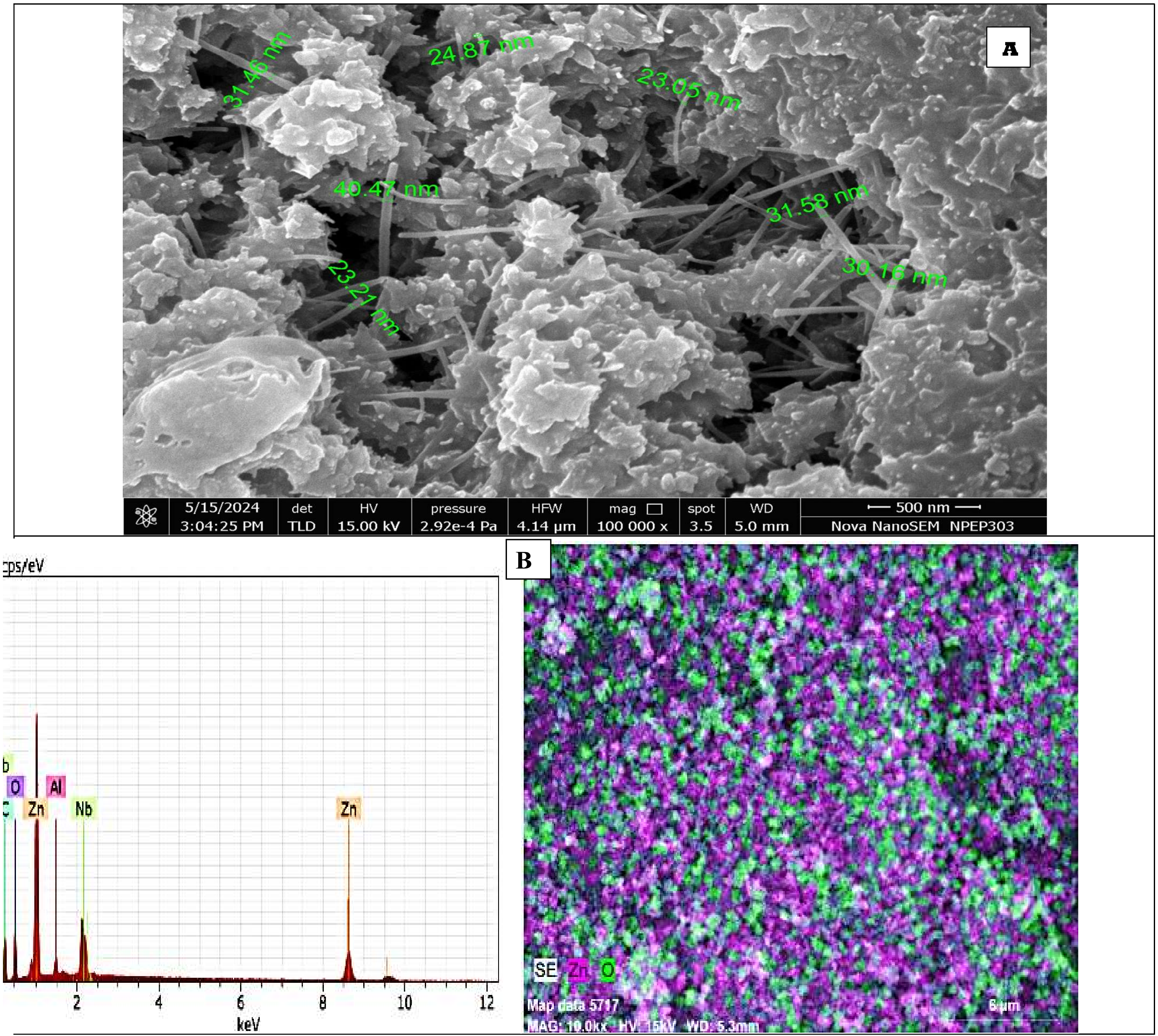


Figure 4:(A) The FESEM analysis of ZnO NPs (B) EDS analysis of ZnO NPs.

XRD Analysis: -

XRD analysis of ZnO nanoparticles synthesized using zinc acetate and Curcuma caesia extract revealed a prominent peak at 36.2° (101 plane), accompanied by minor shifts at 36.240°, 36.200°, and 36.140°. These observations indicate potential variations in crystallite size or internal strain. The observed pattern matched the JCPDS card number 0361451 (Bala et al., 2015), thereby confirming the synthesis of pure ZnO nanoparticles with a rod-like structure (Figure 5).

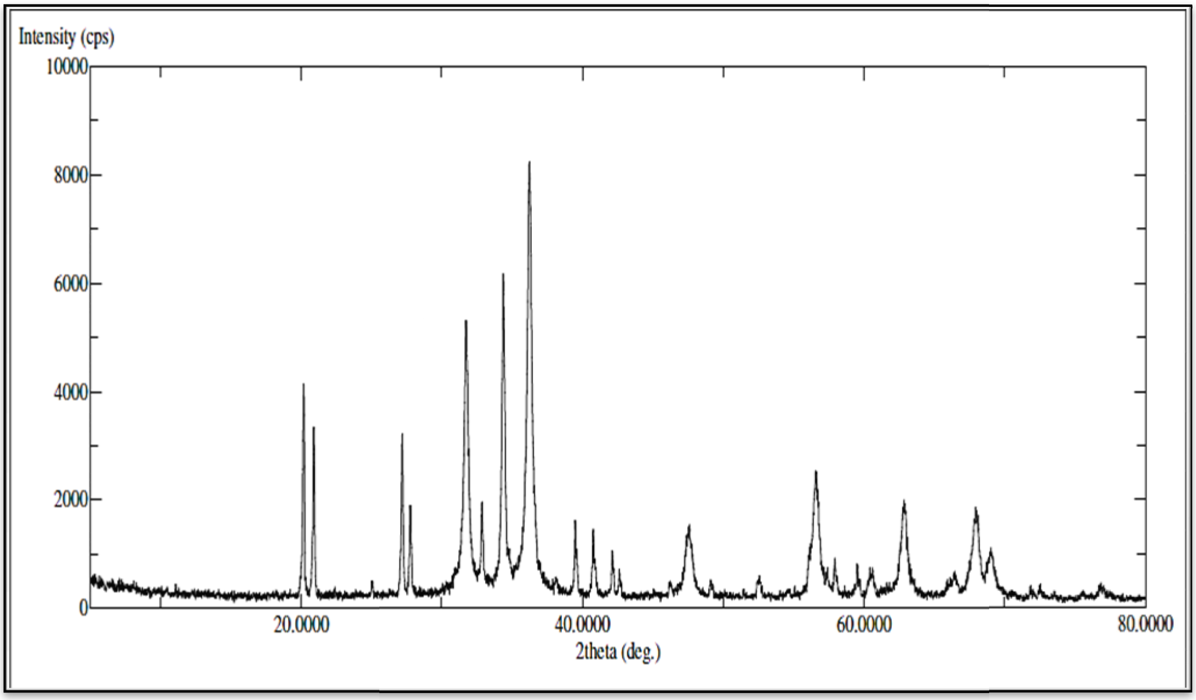


Figure 5: The XRD photograph of Zinc NP

FTIR Analysis:
The FTIR analysis of the plant extract revealed distinct absorption bands at 3290, 2929, 2835, 1646, 1450, 1246, and 1109 cm^{-1}, which are associated with hydroxyl, aliphatic C–H, aromatic C=C, and C–O functional groups (Figure 6). These findings reveal the presence of phenolic compounds, flavonoids, terpenoids, and polysaccharides, which could serve as reducing and capping agents during nanoparticle biosynthesis. FTIR analysis of ZnO nanoparticles capped with phytochemicals from Curcuma caesia demonstrated the presence of various functional groups derived from the plant extract, highlighting their significant role in the reduction and stabilization of the nanoparticles. The findings offer a solid foundation for comprehending the role of compounds derived from plants.

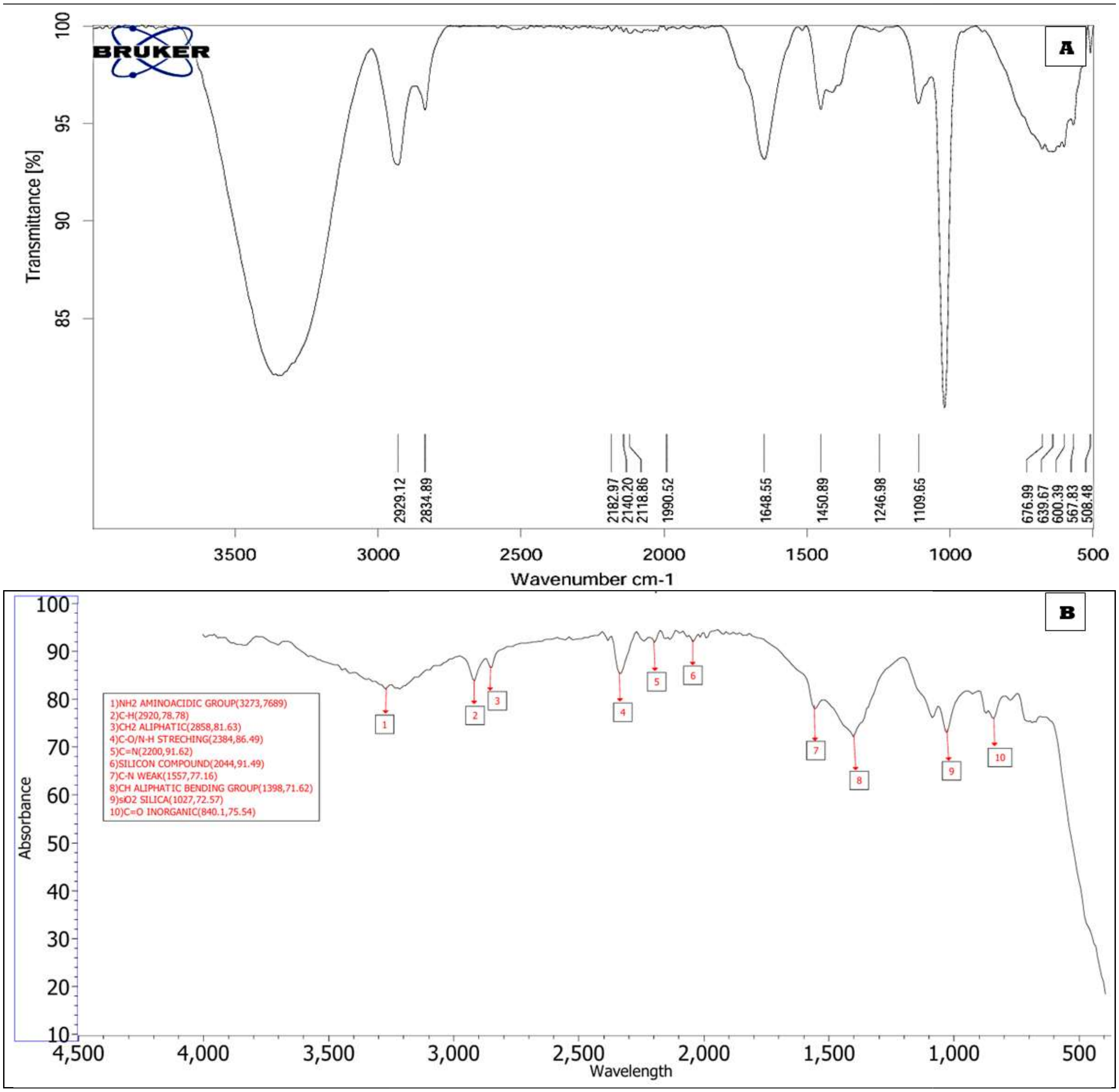


Figure 6: The graph of FTIR analysis of (A)Plant Extract and (B) zinc NPs

Antioxidant Activity:

The antioxidant efficacy of the Curcuma caesia tuber extract and the green-synthesized ZnO nanoparticles (ZnO NPs) was assessed and contrasted with a standard antioxidant across a concentration of 100–500 µg/mL. The figure 7 shows that the standard exhibited the greatest free radical scavenging activity, with a percentage inhibition ranging from approximately 67.5% to 68.2%. The plant extract exhibited continuously elevated antioxidant capacity, with inhibitory values of approximately 64.8–65.0% at lower concentrations (100–300 µg/mL), followed by a minor reduction to 64.1% and 63.4% at 400 and 500 µg/mL, respectively. The ZnO nanoparticles demonstrated modest antioxidant activity, with inhibition values between 60.6% and 63.5%. The peak activity of ZnO nanoparticles occurred at 100 µg/mL (≈63.5%), followed by a slow decline, resulting in around 60.7–60.9% at elevated concentrations. The stronger antioxidant activity of the plant extract is due to the high concentration of bioactive phytochemicals, including phenolics, flavonoids, terpenoids, and other reducing compounds found in C. caesia, recognized for their capacity to donate electrons or hydrogen atoms and neutralize free radicals.The observed results indicate that the biosynthesized ZnO nanoparticles exhibit the antioxidant effects conferred by plant metabolites while also developing distinct physicochemical characteristics linked to their nanoscale shape. The results demonstrate that both the plant extract and green-synthesized ZnO nanoparticles exhibit considerable antioxidant activity, with the plant extract displaying slightly greater efficacy, underscoring the potential of *C. caesia*-mediated ZnO nanoparticles as a viable natural antioxidant and candidate for nanomedicine in biomedical applications.

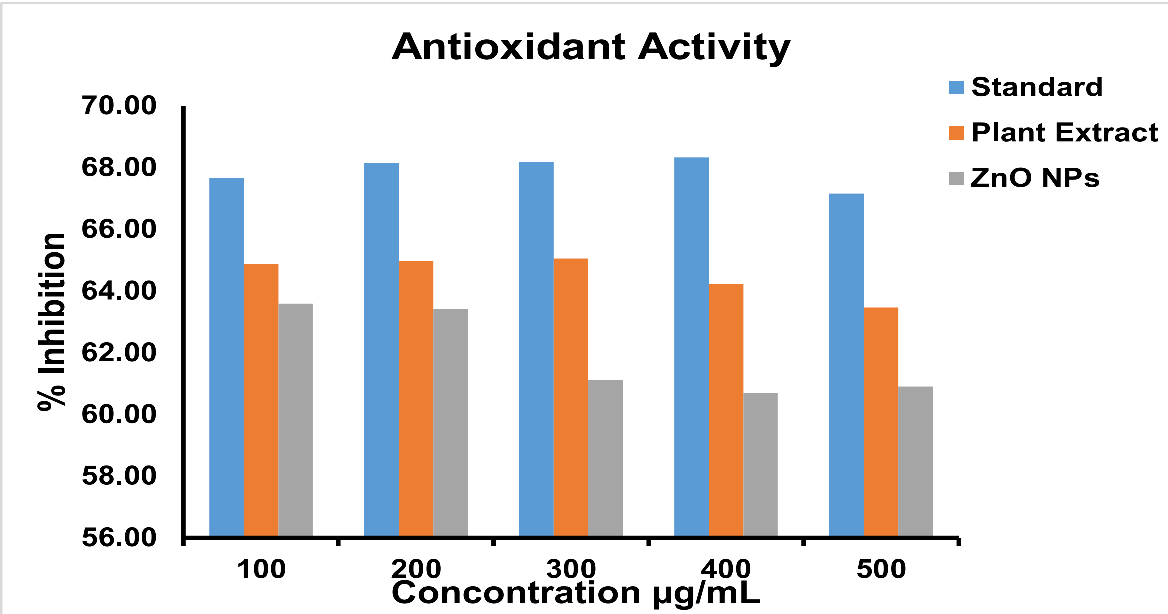


Figure 7.Antioxidant activity of standard, plant Extract and ZnONPs.

Cytotoxic activity:

The cytotoxic efficacy of the plant extract and biosynthesized zinc nanoparticles (ZnONPs) against MCF-7 breast cancer cells was assessed via the MTT test at doses between 12.5 and 200 µg/mL. Both treatments demonstrated a concentration-dependent decrease in cell viability; however, ZnONPs showed significantly stronger cytotoxic effects than the crude plant extract (Figure 8 and 9). At the maximum evaluated concentration (200 µg/mL), the plant extract inhibited cell viability to 46.24%, whereas ZnNPs significantly lowered viability to 25.93%. At a concentration of 150 µg/mL, cell viability was 58.78% for the plant extract and 42.45% for ZnONPs. The increased cytotoxicity of ZnONPs was apparent at all concentrations beyond 25 µg/mL, demonstrating that nanoparticle manufacturing significantly augmented the anticancer efficacy of the bioactive phytochemicals. The superior effectiveness of ZnONPs can be ascribed to their nanoscale dimensions, augmented surface area, improved cellular absorption, and capacity to produce reactive oxygen species (ROS), resulting in oxidative stress, mitochondrial impairment, and death in cancer cells. The findings indicate that green-synthesized ZnONPs have enhanced antiproliferative activity against MCF-7 cells relative to the associated plant extract, underscoring their potential as viable nanomedicine candidates for breast cancer treatment.The determined IC_{50} value for the plant extract was roughly 182 µg/mL, whereas the ZnONPs demonstrated a lower IC_{50} value of about 104 µg/mL, thereby substantiating the superior cytotoxic efficacy of the biosynthesized zinc nanoparticles against MCF-7 cells. The reduced IC_{50} value signifies that a lesser concentration of ZnONPs was necessary to impede 50% of cell proliferation, illustrating their superior therapeutic efficacy compared to the crude extract.

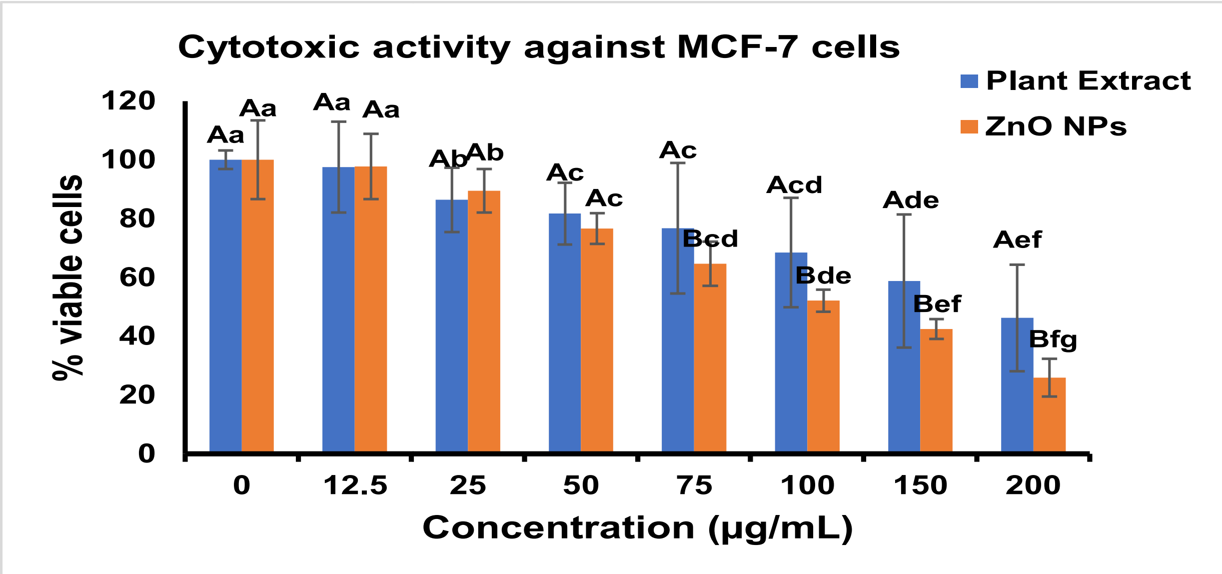
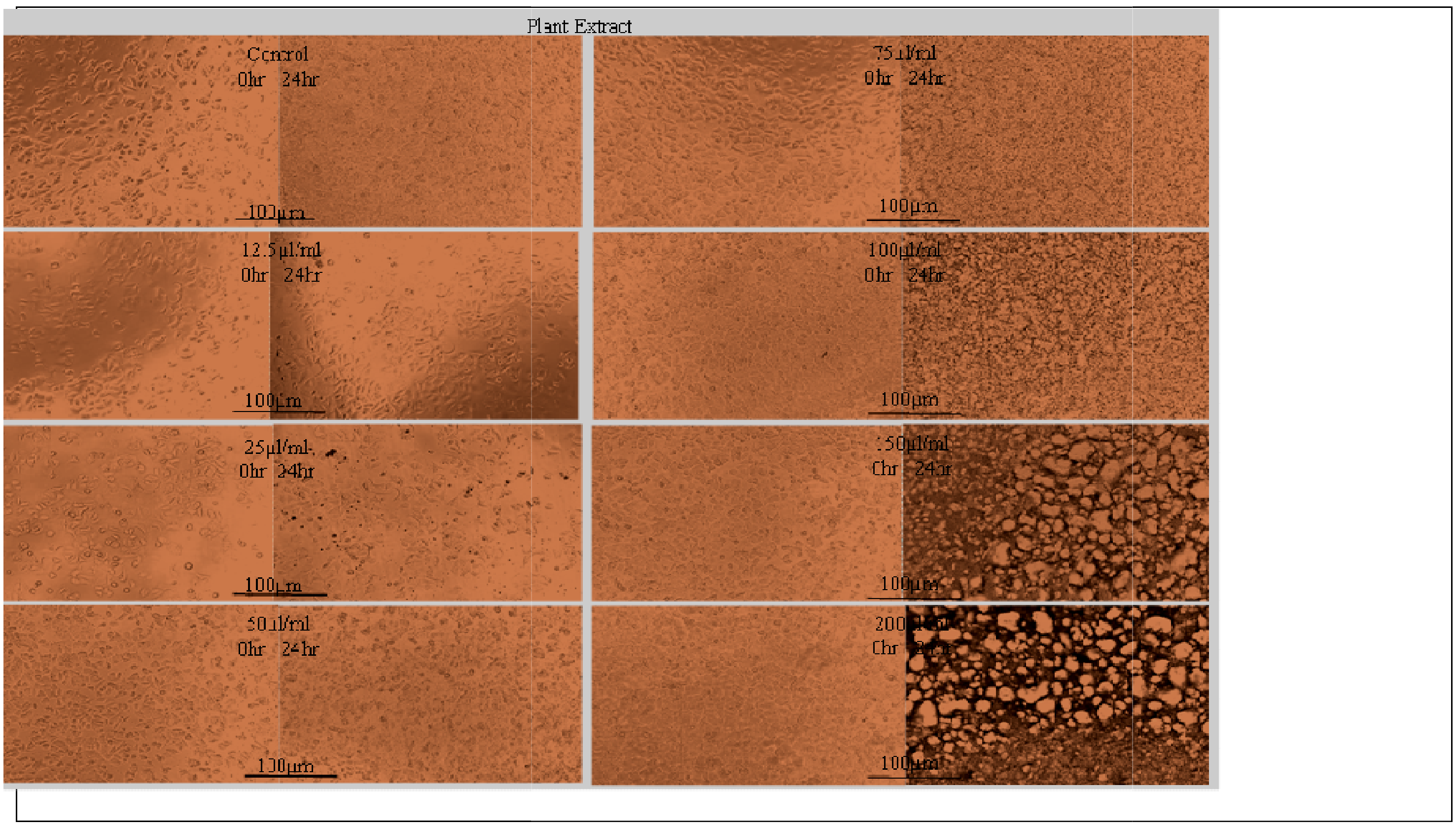


Figure 8. Cytotoxic activity of Plant Extract and ZnONPs.



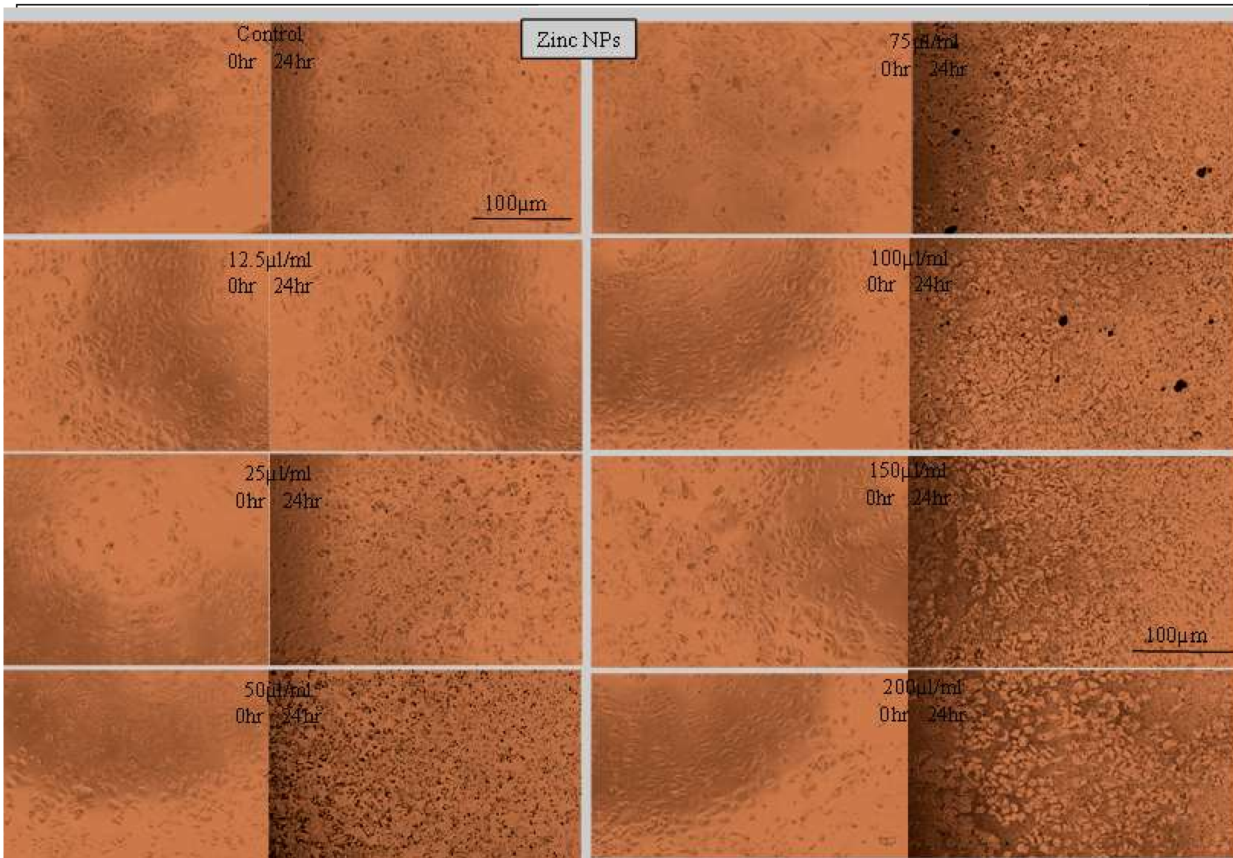


Figure 9.Cytotoxic analysis of (A)Plant Extract and (B) zinc NPs

Apoptosis Activity:

The apoptotic activity of the plant extract and zinc nanoparticles (ZnO NPs) was determined through fluorescence staining and apoptotic population analysis. The untreated control cells exhibited predominantly viable morphology with few apoptotic features, indicating normal cellular integrity. On the other hand, the treatment with plant extract was found to induce concentration-dependent stimulation of apoptosis as revealed by increased chromatin condensation and nuclear fragmentation as characteristic markers of early and late apoptosis, respectively (Figure 10). Fluorescence micrographs revealed a gradual increase in apoptotic cells with increasing concentrations of the extract (5–100 µL/mL), which was further confirmed by a significant shift in cell populations towards the apoptotic quadrants in the scatter plot analysis. Similarly, treated cells with ZnO NPs showed a significant increase in the apoptotic activity as compared to the control group. The apoptotic response increased with the concentration of nanoparticles, showing a higher percentage of cells undergoing early and late stages of apoptosis. Interestingly, the apoptotic effect of ZnO NPs was higher in comparison to the plant extract at the same concentrations, which revealed a more efficient cytotoxic effect. The increased activity is attributed to the role of nanoparticles in causing oxidative stress, impairing mitochondrial function and activating pathways related to apoptosis. The observed enhancement in chromatin condensation, alteration in membrane architecture and nuclear fragmentation strongly suggest that the ZnO NPs successfully induce programmed cell death.Apoptosis was induced by both the plant extract and ZnO NPs in a dose-dependent manner, but the apoptotic potential of ZnO NPs was higher. These results suggest that the formulation of nanoparticles can possibly increase bioactivity of plant-derived components to improve their effectiveness against cancer by inducing programmed cell death.

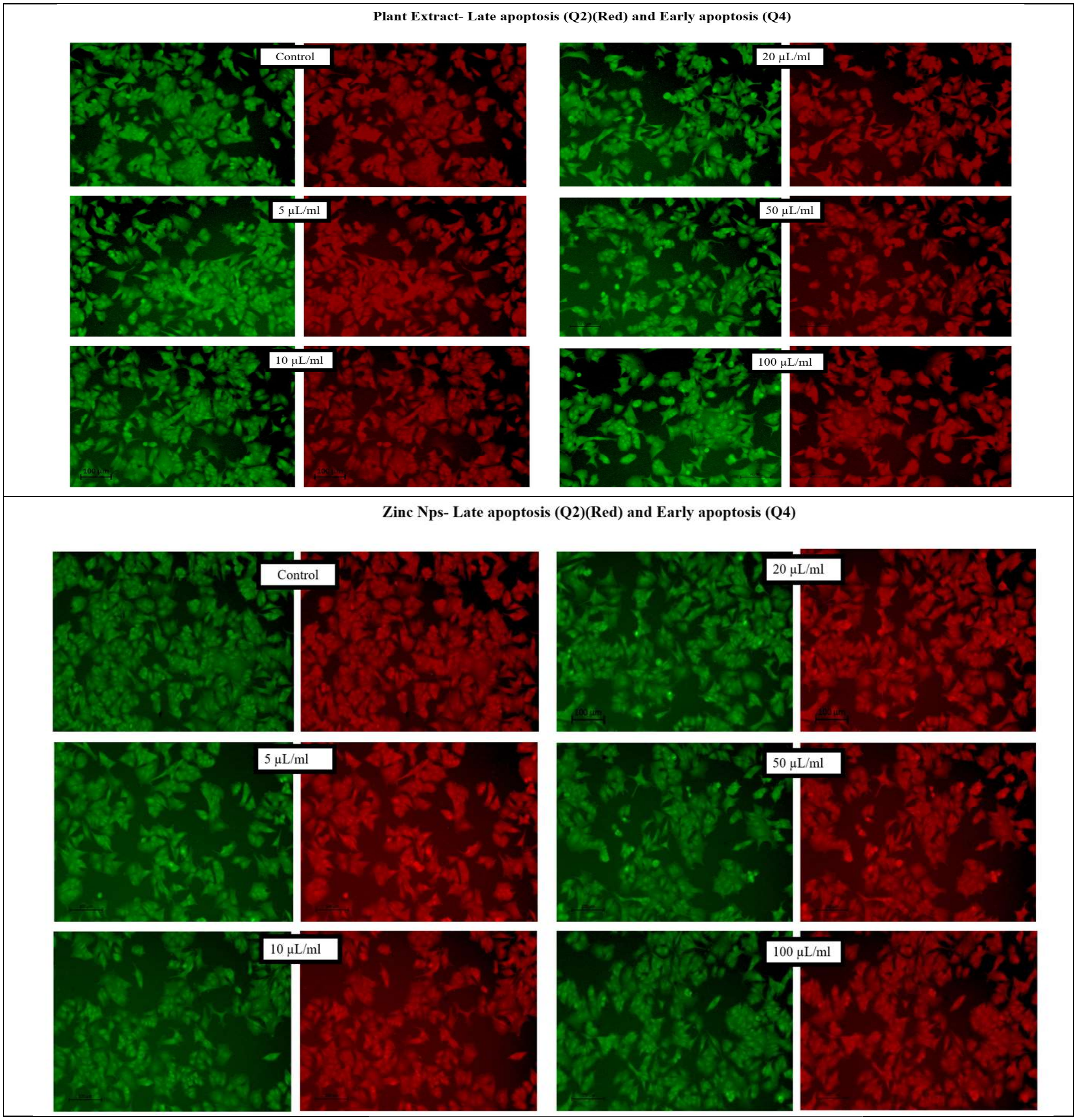


Figure 10. The fluorescence microscopic images of apoptosis analysis of plant extract and ZnO NPs.

Discussion:-

In the current study, zinc oxide nanoparticles (ZnO NPs) were prepared efficiently in an eco-friendly manner by a green method using Curcuma caesia tuber extract. The extracted phytochemicals may be involved in the reduction and stabilization of nanoparticles such as phenolics, flavonoids, terpenoids, and alkaloids. The change of colour during synthesis was indicative of the formation of ZnO nanoparticles, which was later confirmed by physicochemical characterisation. UV–Visible spectroscopy confirmed the production of ZnO nanoparticles by a distinct absorption peak. This study synthesized ZnO nanoparticles using extracts from Acacia catechu, Artemisia vulgaris, and Cynodondactylon. The produced ZnO nanoparticles exhibited an ultraviolet-visible spectrum at 370 nm, as reported(Acharya et al., 2024)

FTIR analysis revealed the presence of hydroxyl, carbonyl, amine, and aromatic functional groups, indicating involvement of plant metabolites in the reduction and stabilization of nanoparticles. The work confirms that ZnO nanoparticles are formed by using Lippiaadoensis extract as a reducing and capping agent(Demissie et al., 2020).The research indicates that green synthesis significantly affects the bioavailability of seed germination and growth characteristics in mung beans. *Curcuma longa* tubers were utilized to produce zinc nanoparticles, which were then analyzed using FT-IR to identify the numerous distinctive functional groups associated with the synthesized nanoparticles(Reddy et al., 2016).

X-ray diffraction study shows the high purity and crystalline nature of the rod-shaped ZnO structure. SEM photos showed a very homogeneous shape with minor agglomeration, while EDX spectra confirmed the predominance of zinc and oxygen as the main constituents.The study highlights the environmentally friendly phytosynthesis of zinc oxide nanoparticles (ZnONPs) utilizing flower extract from *Candelabra cacti*. Using a variety of instruments, the structural and functional characteristics of the produced ZnONPs were investigated. Analysis using transmission electron microscopy showed sphere-shaped ZnONPs with sizes ranging from 10 to 30 nm(Govarthananet al., 2020).

Both Curcuma caesia tuber extract and green-synthesized ZnO nanoparticles have significant free radical scavenging activity, but the plant extract is slightly more effective due to its high phenolic, flavonoid, and other bioactive phytochemical content. ZnO nanoparticles have moderate antioxidant activity due to phytochemical capping agents adsorbed on their surfaces during biosynthesis, which preserve the parent extract's antioxidant properties. ZnO NPs may have lower activity than crude extract because nanoparticle formation partially utilizes these compounds. These findings are consistent with previous reports on plant-mediated ZnO nanoparticles and suggest that *C. caesia*-derivedZnO NPs may be promising biomedical and nanomedicine antioxidants. The study indicated that the observed results suggest that the free radical scavenging activity may be ascribed to the high levels of phenolics and flavonoids with enhanced reducing capacity(Tanvir et al., 2017).This review examines the biomedical applications of metal oxide and ZnO nanomaterials in experimental, preclinical, and clinical stages of development. The benefits, methods, and restrictions related to the use of metal oxide nanoparticles for drug delivery and cancer applications are discussed.

This article focuses on ZnO and other metal oxide nanomaterial systems, their suggested mechanisms of cytotoxic action, and current strategies to enhance their cytotoxicity and targeting against cancer cells(Tayyeb et al., 2024). The antitumor activity of ZnO nanoparticles was examined on MCF-7 breast cancer cells by the MTT test. The nanoparticles demonstrated a significant decrease in cell viability in a dose-dependent manner and were more cytotoxic in comparison to the plant extract alone. The enhanced anticancer effect might be due to higher uptake by cells and interaction with intracellular targets, as well as oxidative stress through ROS generation, causing cellular damage. Annexin V staining was used to confirm the cell death mechanism for apoptosis studies. Treated MCF-7 cells exhibited typical features of apoptosis, such as an increased number of Annexin V-positive cells, cell contraction, and membrane blebbing. The results suggest that apoptosis plays a critical role in the cytotoxicity of ZnO NPs, and the nanoparticle formulation enhances the pro-apoptotic effects of phytochemicals of C. caesia. The results show the possible antioxidant and anticancer activities of the ZnO nanoparticles produced in green. The higher biological activity of crude extract indicates the potential of Curcuma caesia mediated ZnO nanoparticles as a nano therapeutic agent for breast cancer treatment.This is an extensive overview of recent developments about the application of green ZnO nanoparticles as nanocarriers for anticancer drugs. The paper will address the manufacturing methods of ZnO nanoparticles, their characterisation, direct anticancer efficacy, applications in drug delivery, and documented health hazards(Katarzyna Łukowiak, 2026).However, further in vivo assessments and molecular pathways are required for validation of their therapeutic application.

Conclusion:-

The research showed how to synthesize zinc oxide nanoparticles (ZnO NPs) in an environmentally benign manner by employing *Curcuma caesia* tuber extract as a natural stabilizing and reducing agent. The synthesis of pure, crystalline ZnO NPs with desired physicochemical characteristics was confirmed by characterization. In comparison to the pure extract, the nanoparticles demonstrated high, concentration-dependent antioxidant activity and increased cytotoxicity against MCF-7 breast cancer cells. Apoptosis was identified as the main mechanism of cell death by Annexin V staining. These results demonstrate how ZnO and phytochemicals produced from plants work in concert to produce higher biological activity and therapeutic potential. ZnO NPs mediated by *Curcuma caesia* thus show promise for antioxidant and anticancer applications; however, more mechanistic, toxicological, and in vivo research is needed to confirm therapeutic value.

Acknowledgement:-
The authors would like to express their appreciation to the Central Instrument Facility (CIF) at Savitribai Phule Pune University (SPPU) as well as the research centre in botany at Prof. Ramkrishna More College in Akurdi, Pune, for providing the research resources and support. When it comes to the examination of nanoparticles, Pune.

References:-
1. Acharya, R. et al. (2024) 'Bioinspired synthesis and characterization of zinc oxide nanoparticles and assessment of their cytotoxicity and antimicrobial efficacy', Discover Applied Sciences, 6(3). doi:10.1007/s42452-024-05719-2.
2. Anjum, S. et al. (2021) 'ZnO-cancer drugs.pdf'.
3. Demissie, M.G. et al. (2020) 'Synthesis of Zinc Oxide Nanoparticles Using Leaf Extract of Lippia adoensis (Koseret) and Evaluation of Its Antibacterial Activity', Journal of Chemistry, 2020. doi:10.1155/2020/7459042.
4. Dey, S. et al. (2024) 'A critical review on zinc oxide nanoparticles: Synthesis, properties and biomedical applications', Intelligent Pharmacy, 3(1), pp. 53–70. doi:10.1016/j.ipha.2024.08.004.
5. Fais, G. et al. (2024) 'Cytotoxic Effects of ZnO and Ag Nanoparticles Synthesized in Microalgae Extracts on PC12 Cells', Marine Drugs, 22(12). doi:10.3390/md22120549.
6. Gangal, A. et al. (2025) 'Green nanotechnology: nanoparticle synthesis using Curcuma amada, Curcuma caesia, Curcuma longa, and Curcuma zedoaria', Green Chemistry Letters and Reviews, 18(1), pp. 1–18. doi:10.1080/17518253.2024.2449122.
7. GLOBOCAN (2020) 'The Global Cancer Observatory - CANCER FACT SHEETS', International Agency for Research on Cancer - WHO, 419, pp. 199–200. Available at: https://gco.iarc.fr/today/home.
8. Govarthanan, M. et al. (2020) 'Utilization of funnel-shaped ivory flowers of Candelabra cactus for zinc oxide nanoparticles synthesis and their in-vitro anti-cancer and antibacterial activity', Materials Letters, 273, p. 127951. doi:10.1016/j.matlet.2020.127951.
9. Harbeck, N. et al. (2019) Breast cancer, Nature Reviews Disease Primers. doi:10.1038/s41572-019-0111-2.
10. Hassan, T. et al. (2022) 'Nanoparticles in Cancer Treatment: A Narrative Review', Proceedings of the Pakistan Academy of Sciences: Part B, 58(3), pp. 1–18. doi:10.53560/PPASB(58-3)664.
11. Jain, N. et al. (2021) 'Green synthesized plant-based silver nanoparticles: therapeutic prospective for anticancer and antiviral activity', Micro and Nano Systems Letters, 9(1). doi:10.1186/s40486-021-00131-6.
12. Jayaprakasha, G.K., Rao, L.J.M. and Sakariah, K.K. (2002) 'Improved HPLC method for the determination of curcumin, demethoxycurcumin, and bisdemethoxycurcumin', Journal of agricultural and food chemistry, 50(13), pp. 3668–3672. doi:10.1021/JF025506A.
13. Katarzyna Łukowiak, E.U.S. (2026) 'Green Synthesis of Zinc Oxide Nanoparticles and Their Application in Anticancer Drug Delivery – A Review', (January).
14. Khorrami, S. et al. (2018) 'Selective cytotoxicity of green synthesized silver nanoparticles against the MCF-7 tumor cell line and their enhanced antioxidant and antimicrobial properties', International Journal of Nanomedicine, 13, pp. 8013–8024. doi:10.2147/IJN.S189295.
15. Klein, W. et al. (2023) 'Green-Synthesized Silver Nanoparticles: Antifungal and Cytotoxic Potential for Further Dental Applications', Journal of Functional Biomaterials, 14(7). doi:10.3390/jfb14070379.
16. Labaran, A.N. et al. (2024) 'Biosynthesis of copper nanoparticles using Alstonia scholaris leaves and its antimicrobial studies', Scientific Reports, 14(1), pp. 1–10. doi:10.1038/s41598-024-56052-y.
17. Li, Z. et al. (2020) 'Zinc oxide nanoparticles induce human multiple myeloma cell death via reactive oxygen species and Cyt-C/Apaf-1/Caspase-9/Caspase-3 signaling pathway in vitro', Biomedicine and Pharmacotherapy, 122(July 2019), p. 109712. doi:10.1016/j.biopha.2019.109712.
18. Miri, A. et al. (2019) 'Zinc oxide nanoparticles: Biosynthesis, characterization, antifungal and cytotoxic activity', Materials Science and Engineering C, 104(June). doi:10.1016/j.msec.2019.109981.
19. Ojo, O.A. et al. (2021) 'Nanoparticles and their biomedical applications', Biointerface Research in Applied Chemistry, 11(1), pp. 8431–8445. doi:10.33263/BRIAC111.84318445.
20. Puri, A. and Patil, S. (2022) 'Tinospora cordifolia Stem Extract-mediated Green Synthesis of Selenium Nanoparticles and its Biological Applications', Pharmacognosy Research, 14(3), pp. 289–296. doi:10.5530/pres.14.3.42.
21. Rajeshkumar, S. et al. (2018) 'Biosynthesis of zinc oxide nanoparticles usingMangifera indica leaves and evaluation of their antioxidant and cytotoxic properties in lung cancer (A549) cells', Enzyme and Microbial Technology, 117, pp. 91–95. doi:10.1016/j.enzmictec.2018.06.009.
22. Reddy, P.R. et al. (2016) 'Zinc Oxide Nanoparticles Synthesized From Curcuma Longa Extract for Seed Germination', World Scientific Research, 3(1), pp. 70–74. doi:10.20448/journal.510/2016.3.1/510.1.70.74.

23. Ruddaraju, L.K. et al. (2019) 'Antibiotic potentiation and anti-cancer competence through bio-mediated ZnO nanoparticles', Materials Science and Engineering C, 103, p. 109756. doi:10.1016/j.msec.2019.109756.
24. Shrestha, D.K. et al. (2024) ' Synthesis of Silver and Zinc Oxide Nanoparticles Using Polystichum lentum Extract for the Potential Antibacterial, Antioxidant, and Anticancer Activities ', Journal of Chemistry, 2024(1). doi:10.1155/2024/1876560.
25. Sonawane, H. et al. (2021) 'Rhizoctonia bataticola: From plant pathogen to a potential source of pharmaceutically relevant metabolites', Current Research in Green and Sustainable Chemistry, 4(October), p. 100171. doi:10.1016/j.crgsc.2021.100171.
26. Sung, H. et al. (2021) 'Global Cancer Statistics 2020: GLOBOCAN Estimates of Incidence and Mortality Worldwide for 36 Cancers in 185 Countries', CA: A Cancer Journal for Clinicians, 71(3), pp. 209–249. doi:10.3322/caac.21660.
27. Tanvir, E.M. et al. (2017) 'Antioxidant properties of popular turmeric (Curcuma longa) varieties from Bangladesh', Journal of Food Quality, 2017. doi:10.1155/2017/8471785.
28. Tayyeb, J.Z. et al. (2024) 'Multifunctional curcumin mediated zinc oxide nanoparticle enhancing biofilm inhibition and targeting apoptotic specific pathway in oral squamous carcinoma cells', Molecular biology reports, 51(1). doi:10.1007/S11033-024-09407-7.
29. Ullah, I. et al. (2020) 'Green-Synthesized Silver Nanoparticles Induced Apoptotic Cell Death in MCF-7 Breast Cancer Cells by Generating Reactive Oxygen Species and Activating Caspase 3 and 9 Enzyme Activities', Oxidative Medicine and Cellular Longevity, 2020. doi:10.1155/2020/1215395,.
30. Yılmaz, G.E. et al. (2023) 'Antimicrobial Nanomaterials : A Review', pp. 269–290.
31. Zhang, J.Y. et al. (2015) 'Combinational treatment of curcumin and quercetin against gastric cancer MGC-803 cells in vitro', Molecules, 20(6), pp. 11524–11534. doi:10.3390/molecules200611524.
32. Acharya, R. et al. (2024) 'Bioinspired synthesis and characterization of zinc oxide nanoparticles and assessment of their cytotoxicity and antimicrobial efficacy', Discover Applied Sciences, 6(3). doi:10.1007/s42452-024-05719-2.
33. Anjum, S. et al. (2021) 'ZnO-cancer drugs.pdf'.
34. Demissie, M.G. et al. (2020) 'Synthesis of Zinc Oxide Nanoparticles Using Leaf Extract of Lippia adoensis (Koseret) and Evaluation of Its Antibacterial Activity', Journal of Chemistry, 2020. doi:10.1155/2020/7459042.
35. Dey, S. et al. (2024) 'A critical review on zinc oxide nanoparticles: Synthesis, properties and biomedical applications', Intelligent Pharmacy, 3(1), pp. 53–70. doi:10.1016/j.ipha.2024.08.004.
36. Fais, G. et al. (2024) 'Cytotoxic Effects of ZnO and Ag Nanoparticles Synthesized in Microalgae Extracts on PC12 Cells', Marine Drugs, 22(12). doi:10.3390/md22120549.
37. Gangal, A. et al. (2025) 'Green nanotechnology: nanoparticle synthesis using Curcuma amada, Curcuma caesia, Curcuma longa, and Curcuma zedoaria', Green Chemistry Letters and Reviews, 18(1), pp. 1–18. doi:10.1080/17518253.2024.2449122.
38. GLOBOCAN (2020) 'The Global Cancer Observatory - CANCER FACT SHEETS', International Agency for Research on Cancer - WHO, 419, pp. 199–200. Available at: https://gco.iarc.fr/today/home.
39. Govarthanan, M. et al. (2020) 'Utilization of funnel-shaped ivory flowers of Candelabra cactus for zinc oxide nanoparticles synthesis and their in-vitro anti-cancer and antibacterial activity', Materials Letters, 273, p. 127951. doi:10.1016/j.matlet.2020.127951.
40. Harbeck, N. et al. (2019) Breast cancer, Nature Reviews Disease Primers. doi:10.1038/s41572-019-0111-2.
41. Hassan, T. et al. (2022) 'Nanoparticles in Cancer Treatment: A Narrative Review', Proceedings of the Pakistan Academy of Sciences: Part B, 58(3), pp. 1–18. doi:10.53560/PPASB(58-3)664.
42. Jain, N. et al. (2021) 'Green synthesized plant-based silver nanoparticles: therapeutic prospective for anticancer and antiviral activity', Micro and Nano Systems Letters, 9(1). doi:10.1186/s40486-021-00131-6.
43. Jayaprakasha, G.K., Rao, L.J.M. and Sakariah, K.K. (2002) 'Improved HPLC method for the determination of curcumin, demethoxycurcumin, and bisdemethoxycurcumin', Journal of agricultural and food chemistry, 50(13), pp. 3668–3672. doi:10.1021/JF025506A.
44. Katarzyna Łukowiak, E.U.S. (2026) 'Green Synthesis of Zinc Oxide Nanoparticles and Their Application in Anticancer Drug Delivery – A Review', (January).
45. Khorrami, S. et al. (2018) 'Selective cytotoxicity of green synthesized silver nanoparticles against the MCF-7 tumor cell line and their enhanced antioxidant and antimicrobial properties', International Journal of Nanomedicine, 13, pp. 8013–8024. doi:10.2147/IJN.S189295.
46. Klein, W. et al. (2023) 'Green-Synthesized Silver Nanoparticles: Antifungal and Cytotoxic Potential for Further Dental Applications', Journal of Functional Biomaterials, 14(7). doi:10.3390/jfb14070379.
47. Labaran, A.N. et al. (2024) 'Biosynthesis of copper nanoparticles using Alstonia scholaris leaves and its antimicrobial studies', Scientific Reports, 14(1), pp. 1–10. doi:10.1038/s41598-024-56052-y.

48. Li, Z. et al. (2020) 'Zinc oxide nanoparticles induce human multiple myeloma cell death via reactive oxygen species and Cyt-C/Apaf-1/Caspase-9/Caspase-3 signaling pathway in vitro', Biomedicine and Pharmacotherapy, 122(July 2019), p. 109712. doi:10.1016/j.biopha.2019.109712.
49. Miri, A. et al. (2019) 'Zinc oxide nanoparticles: Biosynthesis, characterization, antifungal and cytotoxic activity', Materials Science and Engineering C, 104(June). doi:10.1016/j.msec.2019.109981.
50. Ojo, O.A. et al. (2021) 'Nanoparticles and their biomedical applications', Biointerface Research in Applied Chemistry, 11(1), pp. 8431–8445. doi:10.33263/BRIAC111.84318445.
51. Puri, A. and Patil, S. (2022) 'Tinospora cordifolia Stem Extract-mediated Green Synthesis of Selenium Nanoparticles and its Biological Applications', Pharmacognosy Research, 14(3), pp. 289–296. doi:10.5530/pres.14.3.42.
52. Rajeshkumar, S. et al. (2018) 'Biosynthesis of zinc oxide nanoparticles usingMangifera indica leaves and evaluation of their antioxidant and cytotoxic properties in lung cancer (A549) cells', Enzyme and Microbial Technology, 117, pp. 91–95. doi:10.1016/j.enzmictec.2018.06.009.
53. Reddy, P.R. et al. (2016) 'Zinc Oxide Nanoparticles Synthesized From Curcuma Longa Extract for Seed Germination', World Scientific Research, 3(1), pp. 70–74. doi:10.20448/journal.510/2016.3.1/510.1.70.74.
54. Ruddaraju, L.K. et al. (2019) 'Antibiotic potentiation and anti-cancer competence through bio-mediated ZnO nanoparticles', Materials Science and Engineering C, 103, p. 109756. doi:10.1016/j.msec.2019.109756.
55. Shrestha, D.K. et al. (2024) ' Synthesis of Silver and Zinc Oxide Nanoparticles Using Polystichum lentum Extract for the Potential Antibacterial, Antioxidant, and Anticancer Activities ', Journal of Chemistry, 2024(1). doi:10.1155/2024/1876560.
56. Sonawane, H. et al. (2021) 'Rhizoctonia bataticola: From plant pathogen to a potential source of pharmaceutically relevant metabolites', Current Research in Green and Sustainable Chemistry, 4(October), p. 100171. doi:10.1016/j.crgsc.2021.100171.
57. Sung, H. et al. (2021) 'Global Cancer Statistics 2020: GLOBOCAN Estimates of Incidence and Mortality Worldwide for 36 Cancers in 185 Countries', CA: A Cancer Journal for Clinicians, 71(3), pp. 209–249. doi:10.3322/caac.21660.
58. Tanvir, E.M. et al. (2017) 'Antioxidant properties of popular turmeric (Curcuma longa) varieties from Bangladesh', Journal of Food Quality, 2017. doi:10.1155/2017/8471785.
59. Tayyeb, J.Z. et al. (2024) 'Multifunctional curcumin mediated zinc oxide nanoparticle enhancing biofilm inhibition and targeting apoptotic specific pathway in oral squamous carcinoma cells', Molecular biology reports, 51(1). doi:10.1007/S11033-024-09407-7.
60. Ullah, I. et al. (2020) 'Green-Synthesized Silver Nanoparticles Induced Apoptotic Cell Death in MCF-7 Breast Cancer Cells by Generating Reactive Oxygen Species and Activating Caspase 3 and 9 Enzyme Activities', Oxidative Medicine and Cellular Longevity, 2020. doi:10.1155/2020/1215395,.
61. Yılmaz, G.E. et al. (2023) 'Antimicrobial Nanomaterials : A Review', pp. 269–290.
62. Zhang, J.Y. et al. (2015) 'Combinational treatment of curcumin and quercetin against gastric cancer MGC-803 cells in vitro', Molecules, 20(6), pp. 11524–11534. doi:10.3390/molecules200611524.