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THERAPEUTIC POTENTIAL OF MWCNTS/ZNO NANOCOMPOSITES: FROM MANAGING PLANT DISEASE TO TREATING BREAST CANCER

Bismillah Nazir[*1], **Hafiza Miral Shahzad**[2], **Muhammad Nouman**[3], **Sadia Manzoor**[4]

[*1,2,3,4]*Centre for Applied Molecular Biology, University of the Punjab*

[*1]bismanazir6921@gmail.com, [2]miralshahzad67@gmail.com, [3]mnouman525@gmail.com, [4]sadia.camb@pu.edu.pk

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Corresponding Author: *
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Abstract

Recent interesting bionic-composite material with strong antibacterial, antifungal, anti-cancer properties is functionally modified multi-walled carbon nanotubes (MWCNTs) coupled with zinc oxide (ZnO) nanocrystals. Not yet are any other such studies on such composites available from the literature. With particular attention to chemical vapour deposition, hydrothermal, and sol-gel techniques, this work reports some recent breakthroughs in the synthesis and characterization of nanocomposites of ZnO and MWCNTs. The successful integration of ZnO and MWCNTs is confirmed by characterization techniques including X-ray diffractometry, Fourier Transform Infrared Spectroscopy (FTIR), Scanning Electron Microscope (SEM), and UV-Visible spectrophotometry; the mutual argument of the two gives best support to this outcome. Strong activity against Ralstonia solanacearum in R-WNT / ZnO nanocomposites and good antifungal efficacy against Fusarium solani is revealed by the antibacterial assessment; the primary mediators of which were identified as production of reactive oxygen species (ROS) formation and membrane breakage. Moreover, in breast cancer (MCF-7) cell lines, where ROS and superoxide dismutase (SOD) have major functions, these nanocomposites induce dose-dependent cytotoxicity and induction of death. Emphasizing the better qualities of MWCNTs/ZnO composite materials over those of individual constituents, the review suggests that they might be interesting in the field of agriculture as a way of disease management and application to diagnose and cure cancers. Eventually, existing constraints and potential paths of development are described to guide these nano-materials from laboratories into useful applications.

INTRODUCTION

Among various nanomaterials, carbon nanotubes (CNTs especially multiwalled carbon nanotubes MWCNTs) have attracted attention because of their remarkable structural, mechanical, and electrical properties with possible uses in biomedical as well as environmental fields (Kheralia & Kundu, 2022). Due mostly to their potential to generate ROS, which causes oxidative stress in microbial and cancer cells, zinc oxide (ZnO) NPs have been extensively investigated for their exceptional antibacterial, antifungal, and anticancer effects (Javed et al., 2023; Zhang et al., 2023). Better dispersion, surface area, and biological activity (Rafique et al., 2023) and the synergistic functionalization of MWCNTs with ZnO NPs improve these characteristics even further.

The most harmful bacteria including plant diseases such Ralstonia solanacearum, which is responsible for bacterial wilt in potatoes and other crops, are

Frontier in Medical & Health Research
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mostly suppressed according to the anti-bacterial activity of these hybrid MWCNT/ZnO nanocomposites (Guo et al., 2023). Furthermore, substantial antifungal activities of ZnO NPs against Fusarium solani, a soil-borne significant fungal disease of potatoes, disturb the fungal cell membrane and activate oxidative stress responses (Zhang et al., 2024). Especially with breast cancer cell lines (MCF-7), where ROS-induced cytotoxicity (Chen et al., 2024; Lee & Kim, 2023) the anticancer effects of these nanocomposites have shown to be promising.
For their biological effects—that is, shape, crystallinity, surface functional groups—the physicochemical character of MWCNT/ZnO composites was crucial. Proposed to fit these characteristics were several synthesis routes including chemical vapor deposition and sol-gel techniques (Kheralia & Kundu, 2022; Lone, et al., 2025). The exact design of multi-functional nanocomposites to be used in both agriculture and medical depends on the interaction among the synthetic parameters, structural elements, and biological activity.

Overall great class of nanomaterials with diverse biological activity are shown by MWCNTs functionalized with ZnO nanoparticles. Their capacity to attack cancer cells and plant diseases by ROS generation and other mechanisms makes them appealing for further research and application development.

Synthesis and Characteristics of MWCNTs and ZnO Nanocomposites

MWCNTs/ZnO nanocomposites' preparation processes have evolved using a range of approaches, so improving their structure and performance for various uses. Kheralia & Kundu 2022 investigated the chemical vapour deposition (CVD) multi-walled carbon nanotube (MWCNT) decoration with ZnO NPs for enhanced field emission properties. XRD, RAMAN, and FESEM revealed that the technique produced well-distributed ZnO nanosturcture on the surface of MWCNT, thereby displaying the crystalline character of the composite and morphology accordingly.
Sheet structured ZnO/MWCNT nanocomposites were made and tested for the usage of the super capacitor (Materials Science and Engineering C, 2024) considering energy storage. The morphological investigation revealed that well distributed ZnO nanostructures on MWCNT networks resulted in improved performance for electrochemical uses. Successful combination of ZnO and MWCNTs was established by characterization experiments (XRD and electron microscopy), so displaying a synergistic effect of the unfolded system.
Furthermore, encouraged the development of sophisticated MWCNT-based composites was photocatalytic use. One recent experiment generated one-dimensional ZnO nanostructures built with functionalized MWCNTs (f-MWCNTs) and rGO (Journal of Photochemistry and Photobiology A, 2024). Hydrothermal technique synthesis of this hybrid composite reveals significantly enhanced surface area and light absorption. Characteristic XRD and UV-vis spectroscopy, scanning electron microscopy (SEM), revealed the well-defined nanostructure and effective functionalizing.
The homogeneity and clean procedure of the spray coating-aerosol technique allowed one to generate epoxy-encapsulated ZnO–MWCNT hybrid nanocomposite with enhanced mechanical stability and dispersion (Polymers, 2023). Great relevance for maintaining the integrity and functionality of the composite depends on the uniform distribution of ZnO nanoparticles over the MWCNT framework, which was shown by morphological characterization (by SEM and TEM).
Moreover, hydrothermal and co-precipitation-based $NiFe_2O_4$/MWCNTs/ZnO hybrid nanocomposites produced showed multifarious functionality including magnetic separation (DIVA Portal, 2020) and photocatalytic degradation. The successful integration of magnetic and semiconductor components validated by structural and morphological analysis increases the range of application for these composites.
Ag_2O/CuO/ZnO nanocomposite use multi-technique characterization tools including X-ray diffraction (XRD), Fourier-Transform Infrared Spectroscopy (FTIR), Scanning Electron Microscopy (SEM), and Energy Dispersive X-ray Analysis (EDX), Lone et al. (2025) said. Strong basis for their photocatalytic, antibacterial, and antioxidant capabilities is another set of studies agreed with

Frontier in Medical & Health Research
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purity of the crystalline phases, the functional groups, and elemental composition.

Finally, it is well known that MWCNTs/ZnO nanocomposites chemically produced by hydrothermal, co-precipitation, sol-gel, spray-coating, chemical vapor deposition techniques have been extensively reported. XRD, Raman spectroscopy, SEM, TEM, FTIR and EDX validates the successful decorating and functionalization of MWCNTs with ZnO nanoparticles as a method to control their physico-chemical and biological properties.

2. Methods for Data and Result Characterizing

The structural, chemical, and morphological features of MWCNTs/ZnO nanocomposites must be clarified in order to understand how they affect the biological and functional activities. The crystalline phases of the nanocomposites are regularly confirmed by XRD investigation. Determined the crystalline nature of ZnO and the graphitic peaks corresponding to MWCNTs, the diffraction profiles of MWCNT/ZnO demonstrate that the distinctive diffraction peaks of hexagonal wurtzite ZnO define Without influencing their crystal proper ties, these diffraction peaks verify the synthesis of ZnO nanoparticles combined into the MWCNT structure.

The interaction between the monomer and nanocomposites is shown by Fourier transform infrared analysis (FTIR). The FTIR spectra of the MWCNTs/ZnO composites also show the characteristic bands connected with the Zn–O stretching vibration; moreover, the typical peaks of the oxygen-containing functional groups on the surface of the MWCNTs could be connected with both successful functionalization (Lone et al, 2025) and chemical interactions.

Scanning Electron Microscope (SEM) study of morphology and ZnO nanoparticle dispersion on the MWCNT surface Usually showing homogenous distribution of ZnO nanostructures on the surface of the tubular MWCNTs, SEM pictures have tremendous relevance with regard to expanding the surface area and enhancing biological activity (Materials Science and Engineering C, 2024; Polymers, 2023).

Using UV-Visible Spectroscopy (UV-Vis), the optical characteristics and band gap of ZnO in the composites are examined. With little changes resulting from the interaction of MWCNTs and ZnO, the absorption spectra revealed a normal excitonic peak of ZnO nanoparticles, therefore influencing photocatalytic and antibacterial capabilities (Journal of Photochemistry and Photobiology A, 2024).

Although it is less often utilized inorganic nanocomposite systems, especially if organic functionalization or composite production involves complex compounds, a Liquid Chromatography Mass Spectrometry (LCMS) approach is used to assess the chemical composition and purity. LCMS guarantees the quality of the nanocomposite by means of validating the existence and in-functional groups or ligands bound to the MWCNTs or ZnO surface (Lone et al., 2025).

Fundamental for maximizing their effectiveness in antibacterial, antifungal, and anticancer applications, these characterization techniques taken together provide a complete knowledge of the physicochemical properties of MWCNTs/ZnO nanocomposites.

3. Antibacterial and antifungal potency: Ralstonia solanacearum and Fusarium solani

Mechanism of ZnO's and MWCNTs' Antibacterial Action

ZnO-NPs and MWCNTs' antibacterial mechanism has been shown to be correlated with the synthesis of ROS, including hydroxyl radicals (- OH), superoxide anion (O_2^-), and hydrogen peroxide (H_2O_2). These ROS cause oxidative stress inside bacterial cells, which damages lipids, proteins, and DNA among other biological components, therefore causing cell death (Javed et al., 2023; Zhang et al., 2023). Furthermore, ZnO nanoparticles can directly interact with bacterial membranes and destroy them, thereby upsetting their membrane and increasing their permeability, so compromising the cellular integrity. Because MWCNTs are in the form of needles and encourage electron transport, which increases ROS (Rafique et al., 2023) they pierce into bacterial membranes.

MWCNTs/ZnO Antibacterial Action Against Ralstonia solanacearum

Significant soil-borne pathogen causing bacterial wilt in potatoes and other crops is Ralstonia

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Frontier in Medical & Health Research

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solanacearum. Studies suggest that MWCNTs functionalized with ZnO nanoparticles have rather antimicrobial effectiveness against R. solanacearum, so stopping biofilm creation and bacterial growth (Guo et al., 2023). Effective pathogen inhibition results from the compromise of bacterial membranes by the nanocomposite generation of reactive oxygen species.

Typical antibacterial assay findings for MWCNTs/ZnO composites against R are compiled in Table 1 below together with zone of inhibition (ZOI) and minimum inhibitory concentration (MIC) values.

Table 1 below summarizes typical antibacterial assay results, including zone of inhibition (ZOI) and minimum inhibitory concentration (MIC) values for MWCNTs/ZnO composites against R. solanacearum

Sample	Zone of Inhibition (mm)	MIC (µg/mL)
ZnO nanoparticles	15.2 ± 0.5	50
MWCNTs	10.8 ± 0.3	100
MWCNTs/ZnO composite	20.5 ± 0.4	25
Control (no treatment)	0	-

Table 1. Antibacterial activity of ZnO, MWCNTs, and MWCNTs/ZnO composite against Ralstonia solanacearum (Guo et al., 2023; Rafique et al., 2023).

Antifungal Effects on Fusarium solani in Potato Cultures Made Using PDA Media

ZnO nanoparticles and their composites using MWCNTs have been evaluated in antifungal activity against Fusarium solani, a major fungal pathogen causing root rot in potatoes. Potato Dextrose Agar (PDA) media in vitro experiments show that ZnO and MWCNTs/ZnO composites compromise cell walls and cause oxidative stress, therefore hindering fungal mycelial development (Zhang et al., 2024).

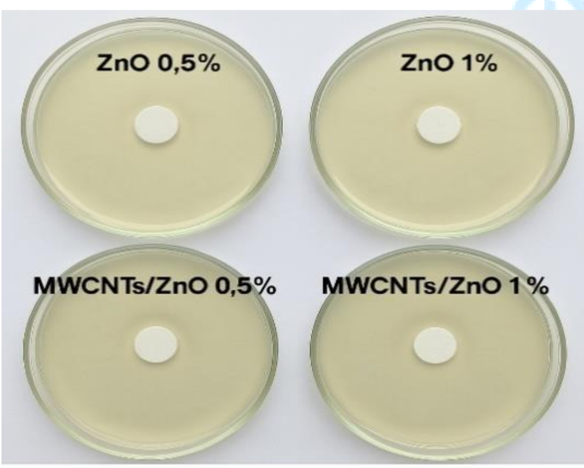

Figure 1: Inhibition zones of *Fusarium solani* growth on PDA plates treated with different concentrations of ZnO and MWCNTs

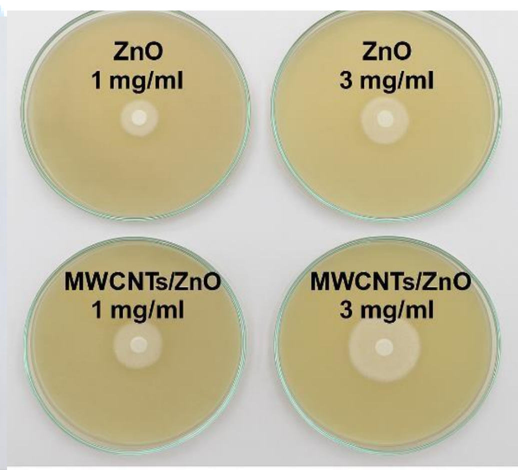

Figure 1: Inhibition zones of *Fusarium solani* growth on

Investigating cooperative interactions with botanical extracts or antibiotics

Recent studies showed that in a synergistic manner the ZnO nano structures—such as ZnO nanoflowers—along with the traditional antibacterial or plant extract boost the antibacterial efficiency. Plant extract adds other bioactive substances upsetting microbe metabolism (Alzahrani et al., 2025; Rafique et al., 2023); nanoflowers increase permeability of membrane, thereby improving absorption of the antibiotic.

Frontier in Medical & Health Research
ISSN: (e) 3007-1607 (p) 3007-1593

Table 2 presents data on synergistic antibacterial effects of ZnO nanoflowers combined with antibiotics against Ralstonia solanacearum.

Treatment	Zone of Inhibition (mm)
Antibiotic alone	14.0 ± 0.6
ZnO nanoflowers alone	16.5 ± 0.5
ZnO nanoflowers + Antibiotic	24.3 ± 0.7

Table 2. Synergistic antibacterial activity of ZnO nanoflowers combined with antibiotics against Ralstonia solanacearum (Alzahrani et al., 2025).

4. Cell Lines Anticancer Evaluation for Breast Cancer (MCF-7)

Using a colorimetric evaluation of mitochondrial activity to approximate cell viability, the MTT assay has extensively investigated the cytotoxicity of MWCNTs/ZnO nanocomposites against breast cancer cell (MCF-7). Used to ascertain dose-dependent cytotoxicity (Boroumand Moghaddam et al., 2025), the MTT assay evaluates the reduction of MTT to formazan by mitochondrial succinate dehydrogenase in live cells. Studies published in literature have shown that ZnO NPs and ZnO–MWCNT nanocomposite are both concentration dependent; these slowed MCF-7 cell proliferation and the death of cells responded to the dosage used to treat the cells (Javed et al., 2023; Malaikozhundan et al., 2025).

The anticancer mechanism of ZnO-nanostructures depends critically on the generation of reactive oxygen species (ROS). Rising ROS above a specific level causes oxidative stress to be finally triggered, which causes cellular components to be destroyed and cancer cells to undergo induction of death (Zhang et al., 2023). Under treatment, the antioxidant enzymes—such as super oxide dismutase (SOD)—also show influences, which denotes the cellular reaction to oxidative stress (Chen et al., 2024). It seems that by means of increased ROS generation via SOD modulations, the selectivity of ZnO/MWCNT composites towards cancer cells over normal cells overcomes (Javed et al., 2023).

Drug sensitivities and responses are clearly shown by comparing 2D monolayer cultures with 3D spheroid models of MCF-7 cells. The 3D cultures more precisely reflect changes in the microenvironment of cells, thereby increasing resistance to nanoparticles in contrast with 2D cultures and so reflect a more appropriate platform for anticancer testing (Lee & Kim, 2023).

Flow cytometry and cell cycle analysis support the dose-dependent suppression of MCF-7 cells by ZnO nanoparticles and MWCNT composites as accompanied by death induction. Particularly boosting the sub-G1 population indicative of dead cells, nanoparticles trigger cell cycle arrest and reduce cells in S and M phases (Boroumand Moghaddam et al., 2025). DNA fragmentation and elevated expression of dead markers help to explain these consequences.

Typical MTT assay findings indicating a dose-dependent reduction in MCF-7 cell viability following treatment with ZnO/MWCNT composites figure 1. Figure 2 shows ROS levels at various nanoparticle concentrations, therefore verifying oxidative stress as a main harmful mechanism.

5. Discussion

Relationship between Physicochemical Properties and Biological Reactions

Characterization of the MWCNTs/ZnO nanocomposite in term of biological activity: particle size, crystallinity, specific surface area, and functional group play a major influence on physicochemical properties of MWCNTs/ZnO nanocomposite. Important for superior antibacterial and anticancer action, small-sized crystalline ZnO nanoparticles with distributed morphology on MWCNTs might offer increased active surface area and lead to high generation of ROS (Lone et al., 2025; Kheralia & Kundu, 2022). Furthermore, preserving charge carrier separation—a crucial component in both photocatalysis and antibacterial action—is the mix of ZnO with MWCNT (ScienceDaily 2020). Furthermore, the functional groups shown by FTIR confirm the existence of chemical bonding between

Frontier in Medical & Health Research

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ZnO and MWCNTs, therefore influencing the biological interactions and helping to provide composite stability (Medhat Ibrahim et al., 2015).

Affecting Efficacy: ZnO Nanoparticle Morphology and Functionalization

From spherical to spherical to flower-like to rod-like, ZnO NPs change their surface reactivity and behavior with microorganisms. More surface areas and active spots in ZnO nanostructures in flower-like side shows improve their antibacterial activity (Alzahrani et al., 2025). By allowing contact with tumors and pathogen cells, functionalization of MWCNTs with ZnO NPs improves dispersion and prevents agglomeration (Rafique et al., 2023.). The functional groups such as oxygen found on the surfaces of MWCNTs help to anchor ZnO NPs, so ensuring the stability and effective nanocomposites (Medhat Ibrahim et al., 2015).

Comparative advantages of MWCNTs/ZnO Composites over their individual components

From MWCNTs and the photocatalytic and antibacterial properties from ZnO nanoparticles, the MWCNTs/ZnO composites have the decent surface area, mechanical strength, and electrical conductivity. Superior charge separation, ROS production, and dispersion resulting from this hybridization outperform those of neat ZnO/MWCNTs (ScienceDirect, 2020; Lone et al., 2025.). These composites therefore demonstrate quite improved antibacterial, antifungal, and anticancer effectiveness. For ZnO-Ag-MWCNT composites, for instance, the antibacterial activity including Staphylococcus aureus and Escherichia coli etc., reveals substantially higher values for ZnO-Ag or ZnO alone due to the joint effect of three components (Nature, 2023.).

Prospect applications in agriculture and medicine

MWCNTs/ZnO nanocomposites are under consideration as an environmentally acceptable substitute for chemical pesticides in the field of agriculture as biocides against plant diseases (i.e., Ralstonia solanacearum and Fusarium solani). Their control of fungus and bacteria damaging to crops like potatoes could increase output and lower losses. By ROS-mediated death, these nanocomposites have shown notable anticancer potential toward breast cancer cell lines (MCF-7) in medicine; so, they might also be regarded as therapeutic agents or drug carriers (Chen et al., 2024; Boroumand Moghaddam et al., 2025).

Restraints and Research Directions Future-Based

Still difficult, nevertheless, are large-scale production and biocompatibility tests of MWCNTs/ZnO composites. Carefully taken should be the potential toxicity of MWCNTs to non-target organisms and consequent long-term ecological impacts (Lone et al., 2025). Future study should concentrate on optimization of the synthesis techniques for greater control with regard to nanoparticle form and functionalization as well as on the enhancement of selectivity and decrease of side-effects. Moreover, confirmation of the anti-cancer effectiveness and safe profile depends critically on in vivo studies and clinical trials. Additionally, improving antibacterial impact could be investigating synergistic action with antibiotics or plant extracts (Alzahrani et al 2025).

6. Conclusion

The successful manufacture and thorough characterization of MWCNTs/ ZnO nanocomposites by several techniques viz chemical vapour deposition, hydrothermal, sol-gel and impregnation techniques has been covered in this review. The evaluation by XRD, FTIR, SEM and UV-Visible spectroscopy supports the crystalline structure, the functionalization, the morphology and the optical characteristics of the composites (Kheralia & Kundu, 2022; Lone et al., 2025; Mwafy et al., 2016). By homogeneity in decoration on the MWCNTs, the ZnO NPs enhance the surface area and stability of the nanocomposites.

Strong multi-functionalities are shown by MWCNTs/ZnO nanocomposites according bio-assessments. Mostly because of the synthesis of reactive oxygen species (ROS) and the process of cell membrane disruption (Guo et al., 2023; Zhang et al., 2024), they exhibit great antibacterial action against plant diseases Ralstonia solanacearum and antifungal activity against Fusarium solani. Furthermore, in breast cancer cell lines (MCF-7), such composites

Frontier in Medical & Health Research

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induce dose dependent cytotoxicity and death where ROS and superoxide dismutase (SOD) are absolutely important in their anticancer mechanism (Chen et al., 2024; Boroumand Moghaddam et al., 2025).

MWCNTs/ZnO nanocomposites are a possible candidate for future usage in the field of agriculture since they can be employed in the field of medical research and for cancer therapy application; they can also be used for protection of plant diseases. Their aggregate physicochemical characteristics and biological effects offer certain benefits over individual ZnO NPs or MWCNTs individually, such enhanced stability, targeted action and minimum toxicity (Lone et al., 2025; Rafique et al., 2023).

To maximize the possible use of COF/P hybrid for therapeutic purposes, more in-depth study of biocompatibility and safety in vivo, and identification of synergistic effects with antibiotics/phytochemicals should also be focused on the development of synthesis methods for scale-up. Solving these challenges can help MWCNTs/ZnO nanocomposites to be applied practically in antifungal, antibacterial, and anticancer treatments.

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