RASĀYAN *J. Chem.*
Vol. 19 | No. 3 | 1268-1274 | July-September | 2026
ISSN: 0974-1496 | e-ISSN: 0976-0083 | CODEN: RJCABP
http://www.rasayanjournal.com
http://www.rasayanjournal.co.in

DEVELOPMENT OF COST-EFFECTIVE BIODEGRADABLE BIOFILM REINFORCED WITH *Cinnamomum verum*-DERIVED ZNO NANOPARTICLES FOR FUNCTIONAL FOOD PACKAGING APPLICATIONS

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ABSTRACT

Packaging is a vital procedure to prevent damage and contamination to our food, medications, clothing, and other possessions. Conventional packaging materials are developed from non-renewable resources and take a long time to degrade. The present study makes a substantial contribution to the growing field of sustainable food packaging by creating a biodegradable and environmentally friendly biofilm from renewable agricultural waste, polyvinyl alcohol (PVA), and green-synthesised ZnO nanoparticles obtained from *Cinnamomum verum* (cinnamon). In line with that, Innovative materials have been developed in response to the increased need for environmentally friendly food packaging. The Zinc-doped nanoparticles (ZnO NPs) developed from *Cinnamomum verum* extract are infused into polyvinyl alcohol to develop multifunctional films for active food packaging. The integration of ZnO NPs enhanced the mechanistic characteristics of the film, including tensile strength (7.97 MPa) and durability (64.01 %). The nanoparticles exhibited strong antimicrobial activity, with a diameter of the clearing zones measuring 25 mm against *E. coli*, and 15 mm against *Candida utilis* at a 100 µg/ml concentration. Characterization studies were carried out for the prepared film, such as SEM, XRD, and UV-Vis spectroscopy, to provide insights into its structure, morphology, crystallinity, and optical parameters. Biodegradability tests confirmed that the film decomposes naturally within 30 days. Overall, the ZnO NP-reinforced biodegradable film presents a sustainable alternative to synthetic plastic packaging.

Keywords: Sustainable Film, Functional Food Packaging, Film Fabrication, *Cinnamomum verum,* ZnO NPs, Polyvinyl Alcohol (PVA)

RASĀYAN *J. Chem.*, Vol. 19, No.3, 2026

INTRODUCTION

High-performance, environmentally friendly packaging materials are becoming more and more necessary as the emphasis on sustainable food systems and minimizing environmental impact grows. Despite being widely utilized, traditional petroleum-based plastics present serious environmental problems because they are not biodegradable and are not very recyclable.[1] Additionally, they are not actively protected against microbial infection, which compromises public health, shelf life, and food safety. Hence, there is a solid need for innovative biodegradable wrapping solutions that not only reduce pollution but also dynamically combat spoilage and harmful microbes by interacting with food and its surroundings. Nanotechnology presents promising ways to get beyond packaging restrictions by incorporating metal oxide nanoparticles into biopolymer matrices.[2] Zinc oxide nanoparticles, in particular, are becoming more well-known due to their potent antibacterial properties, biocompatibility, and FDA approval for use in food applications.[3] It has multiple bactericidal effects, such as the production of oxygen radicals, cytolysis, and zinc ion release, which contribute to their efficacy.[4] These qualities make ZnO nanoparticles suitable for use in functional edible enclosures designed to enhance food safety and durability. Phyto-synthesis of ZnO nanoparticles using *Cinnamomum verum* offers an eco-friendly alternative to conventional methods. These nanoparticles, when added to biopolymer films such as agar, enhance strength, moisture resistance, and antimicrobial activity. This approach supports sustainable packaging by eliminating toxic reagents and improving the functional properties of biodegradable materials.[5] The primary goal of the study is to create

a sustainable, high-performing biodegradable film for food packaging applications using corn cob waste, polyvinyl alcohol (PVA), and ZnO nanoparticles generated from *C. verum*. Using plant-derived and agro-waste-based reducers, the research aims to develop sustainable solutions by assessing structural, mechanical, and antibacterial properties, leading to the development of green packaging materials that combine agro-waste recycling with enhanced functional properties, thereby advancing a circular economy. The present research work aligns with the United Nations Sustainable Development Goal 12: Responsible Consumption and Production, emphasising the development of eco-friendly materials, waste reduction, and sustainable resource use. Despite numerous biodegradable films being documented, few studies have examined the combined use of low-cost lignocellulosic waste materials with plant-mediated metal oxide nanoparticles for enhanced food packaging applications. Thus, the goal of this research is to offer a novel and green substitute for traditional plastic packaging materials.

EXPERIMENTAL

Material and Methods

Green Synthesis of *Cinnamomum verum* bark extract using Zinc Oxide Nanoparticles (ZnO NPs). The thermal-assisted extraction method was adopted to extract the bark powder of *Cinnamomum verum* using distilled water (1:10 w/v). The filtrate was then collected and kept at 4°C. ZnO nanoparticles were synthesised via a green method using cinnamon bark extract as both reducing and stabilizing agent. 0.4 g of zinc oxide was combined with 45 mL of demineralised water, with subsequent addition of 10 mL of cinnamon extract. The blend was stirred in a rotary shaker for 20 min. and kept at room temperature for 48 hours for nanoparticle formation. The appearance of white precipitates confirmed successful synthesis. These were strained, treated with demineralised water, and dehydrated at 50°C for six hours to obtain the final ZnO nanoparticles.[6]

Fabrication of Biodegradable Film

Biodegradable films were formulated using polyvinyl alcohol (PVA) blended with corn cob powder and ZnO nanoparticles. 20 g of PVA were solubilized in deionised water under constant agitation at a high temperature for three hours. Finely ground corn cob powder was then added at varying concentrations, along with ZnO nanoparticles. The uniform mixture was transferred into Petri dishes and desiccated at room temperature for 24 hours in a desiccator to form films. Once dried, the films were carefully removed and stored under controlled conditions for further study.[7]

Evaluation of Anti-infective Activity

The prepared ZnO NPs were tested for their antibacterial and antifungal properties using the agar well diffusion method against *Staphylococcus aureus*, *Bacillus subtilis*, *Escherichia coli*, and *Pseudomonas aeruginosa* using Muller-Hinton Agar (MHA) and *Candida albicans* and *Aspergillus niger* using Potato Dextrose Agar (PDA). The plates were smeared using the corresponding microbial strain. After complete drying, a 6 mm well was created, and varying concentrations of ZnO NPs were added to each well. The zones of inhibition were evaluated after the plates were incubated for 24 hours at 37°C. Gentamycin and fluconazole were used as positive controls for antibacterial and antifungal activity, respectively.[8]

Characterization Studies

UV-Visible Spectrophotometry

A known concentration of ZnO NPs dispersed in distilled water was scanned over the 200–800 nm range using a double-beam UV-Vis spectrophotometer (Shimadzu, UV-1900i Plus). The absorption maxima were recorded to evaluate particle formation and assess band gap energy.

X-Ray Crystallography (XRD) Analysis

Crystallographic analysis of the ZnO NPs was performed by means of XRD. The diffraction outlines were recorded in the 2θ range using Cu Kα radiation (λ = 1.5406 Å). The resulting peaks were analysed to fix the crystal lattice, phase purity, and average crystallite size using the Debye–Scherrer equation. The presence of sharp, well-defined peaks confirmed high crystallinity and a hexagonal wurtzite phase.

Scanning Electron Microscopic Analysis (SEM)

The surface morphology of the generated film was measured using the FEI Quanta FEG 200 Scanning Ele ctron Microscope (SEM). It had an acceleration voltage of 10 kV, a working distance of 7.5–8.5 mm, an acquisition time of 40 s, and a beam current of 18 pA. Image analyses were obtained at 1000X, 500X, and 200X magnifications.[9]

Tensile Strength (TS) and Elongation at Break (EAB) of Film

Tensile strength (TS) was assessed using a 50 Hz 3-phase Twin Screw Digital Tensile Tester (PACORR UTM, India) in compliance with ASTM D882-02 standards. The prepared films were cut into 165 mm × 13 mm with a 50 mm gauge length and mounted on the tester. Testing was performed at 5 mm/min for TS and 1 mm/min for modulus. Elongation at break (EAB) was calculated by comparing the original and final lengths after the film broke under applied stress.[10]

Bio-degradability Test of Film

The soil burial test method was used to assess the biodegradation of the produced bioplastic sheets. After recording the specimen's initial weight, the samples were buried for 15 and 30 days. The weight of the sample after decomposition was recorded, and then the degradation percentage was calculated using the equation below.[11,12]

$$\text{Percentage biodegradation} = \frac{W0 - W}{W0} \times 100$$

Where, W0 = weight before being buried in the soil; W = weight after being taken out of the soil.

RESULTS AND DISCUSSION

The present study demonstrated an effective approach that combines agricultural waste, synthetic polymer support, and green-synthesized nanoparticles to produce biodegradable, functional food packaging materials. The study contributes significantly to the expanding field of sustainable biopolymer nanocomposites by using maize cob as an inexpensive, renewable resource and ZnO nanoparticles generated from *C. verum* as a natural reinforcing agent. Further, it demonstrates how waste-derived materials can be converted into high-value packaging films with enhanced mechanical, barrier, and possibly antibacterial properties. The findings of the study, which show how corn cob agricultural waste can be successfully transformed into a biodegradable packaging material with added value, amply support UN Sustainable Development Goal 12: Responsible Consumption and Production.

Extraction and Fabrication of Biodegradable Film

Aqueous extract of *Cinnamomum verum* bark was prepared using distilled water in the ratio of 1:10. The phytonutrients present in the extract, including polyphenols, flavonoids, and cinnamaldehyde, served as an effective reducing and capping agent in the Phyto-synthesis of zinc oxide nanoparticles (ZnO NPs).[13] Biodegradable films were developed using polyvinyl alcohol (PVA) as a matrix, corn cob powder as a natural filler, and ZnO NPs as functional antimicrobial agents. Films incorporated with ZnO NPs exhibited superior mechanical strength and flexibility compared to control films. Visual inspection and structural integrity assessments demonstrated that PVA-corn cob-ZnO films showed higher durability and potential barrier properties, making them appropriate for use in food packaging (Fig.-1).

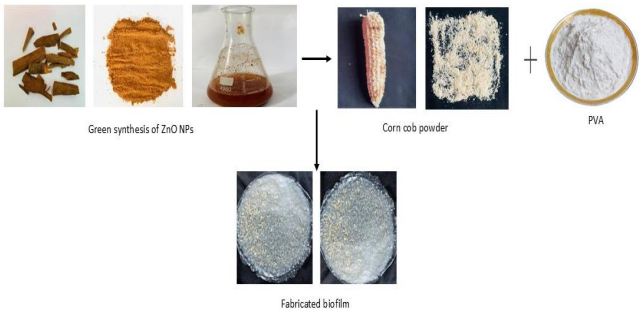


Fig.-1: Green Synthesis of ZnO NPs and Fabrication of Biofilm

Antimicrobial Activity

The antimicrobial susceptibility test (well diffusion method) was used to assess the antimicrobial and antifungal efficacy of ZnO NPs on two fungal strains, *Candida utilis* and *Aspergillus niger*, and four pathogenic bacterial strains, *Pseudomonas aeruginosa*, *Bacillus subtilis*, *Staphylococcus aureus*, and *Escherichia coli*. Maximum inhibition (25 mm) was recorded for *E. coli* at 100 µg/ml, comparable to the standard Ciprofloxacin used (Fig.-2). The maximum antifungal activity was noticed for *Candida utilis* (15 mm) at 100 µg (Fig.-2). Although the antifungal effect was relatively moderate compared to antibacterial results, it validates the bio-functional potential of ZnO NPs in combating fungal pathogens. [14]

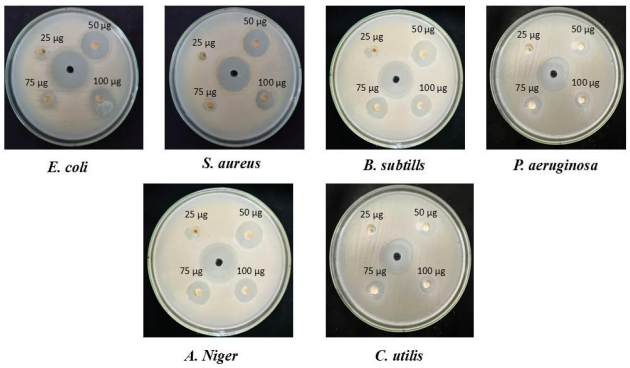


Fig.-2: Antimicrobial Activity of Zno Nps. Positive Control Used: Antibacterial - Cip 5µg; Antifungal - Fluconazole

UV-visible Spectrometry and X-Ray Diffraction (XRD)

The absorption spectrum exhibited distinct peaks between 280 nm and 375 nm, which match the typical band gap shift in ZnO. The sharp absorption peak around 360 nm confirms the successful synthesis of ZnO NPs. Stability studies carried out over 10 days revealed consistent peak positions (~285 nm), indicating the structural stability of the nanoparticles post-synthesis (Fig.-3a). XRD investigation showed distinct diffraction peaks that matched ZnO's hexagonal wurtzite structure. Prominent peaks at planes (100), (002), (101), and (102) established that the nanoparticles were crystalline. The Debye-Scherrer equation was used to estimate the average crystallite size, which was found to be between 9.96 and 29.98 nm, indicating the formation of nanoscale particles (Fig.-3b).[15] The purity of the synthesised nanoparticles was validated through the absence of secondary peaks, which demonstrates the effectiveness of the green synthesis route using *C. verum* extract.

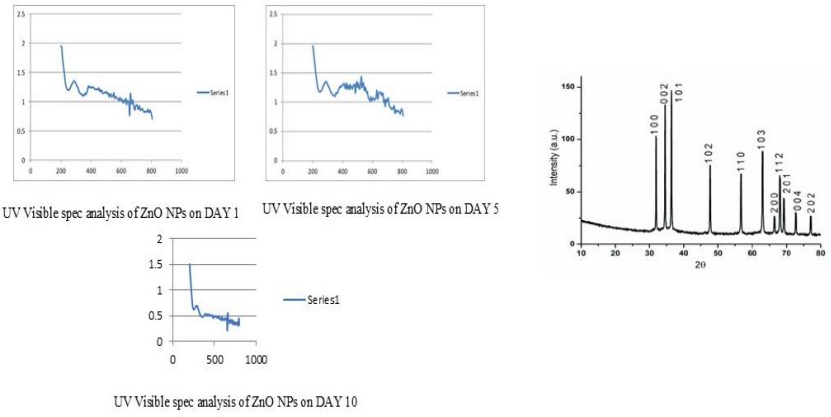


Fig.-3: (a) UV-Vis Spec. Analysis of ZnO NPs; (b) XRD analysis of ZnO NPs

Scanning Electron Microscope Analysis (SEM)

The SEM images of the ZnO NPs confirmed the formation of nanoparticles in their agglomerated form. Numerous studies documented the impact of surface shape and its correlation with ZnO's synergistic action. Most of the particles were in spherical to hexagonal shapes[16] (Fig.-4) and were previously confirmed by XRD analysis (Fig.-3b).

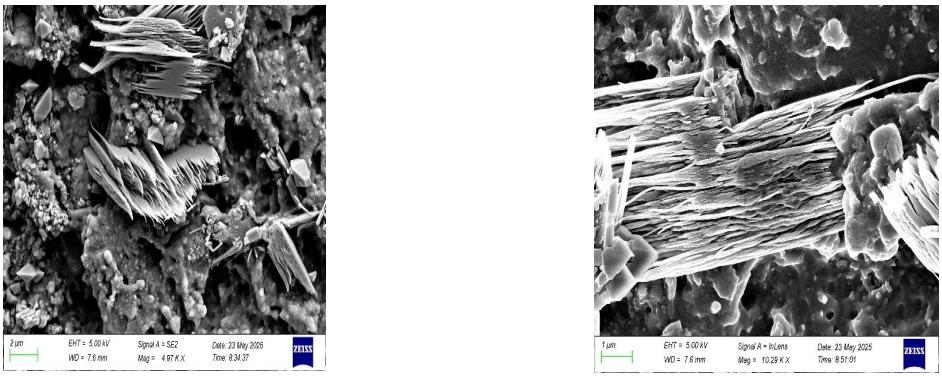


Fig.-4: SEM Analysis of ZnO NPs at Various Magnifications

Tensile Strength (TS) and Elongation at Break (EAB) of Film

The EAB value of the film (PVA with NP) was 63.01%, and its TS value was 7.97 MPa (Fig.-5). The starch present in the powdered corn cob significantly interacted with the PVA in the starch combination, acting as a filler and providing the film with strength and durability, which resulted in the increased TS value.[17]

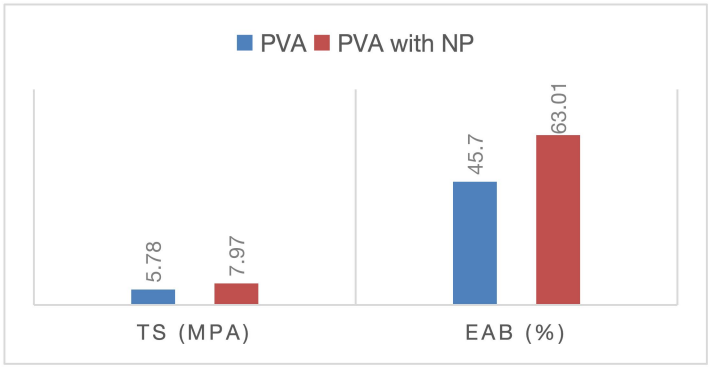
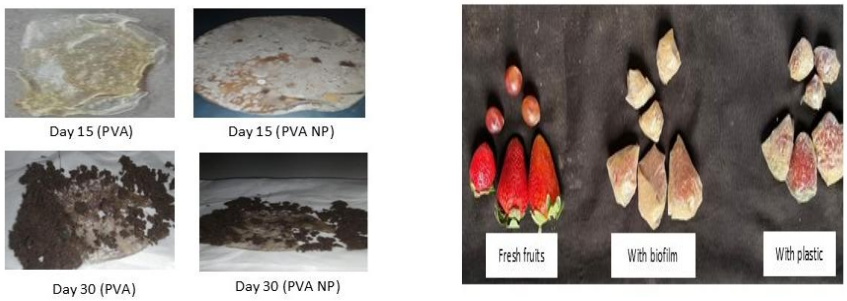


Fig.-5: TS and EAB of the Prepared Film

Biodegradability of Film and Fruit Packaging Evaluation

The soil buried samples of PVA and PVA incorporated with ZnO NPs were taken out at various time intervals. During the 15th day, the colour and size of both the films were changed and started to shrink respectively, started to crumble, combined well with soil, and fungal growth was noticed (Fig.-6a).



(a) (b)

Fig.-6: (a) Biodegradability Study of Prepared Film; (b) Fruit Packaging Evaluation Using Prepared Film

On the 30th day, both films degraded to 90 % with a lesser number of residues left in the soil. Hence, the present study indicates that when compared to synthetic plastics, starch-based bioplastics have the capacity to decompose more rapidly. The PVA-corn cob-ZnO biofilms were tested for real-time applications in fruit packaging. Compared to fruits covered with plastic wrap, the fruits wrapped in ZnO-

incorporated films exhibited delayed microbial spoilage and enhanced shelf-life, validating the biofilm's functionality (Fig.-6b). The antimicrobial nature of ZnO NPs, combined with the biodegradable and moisture-resistant nature of PVA and corn cob, makes these films an eco-friendly alternative to traditional plastic packaging.

CONCLUSION

The present study investigates a modest, cost-effective, and greener process of development of biofilm using *C. verum*-derived ZnO NPs, PVA, and corn cob, which is in line with the UN's SDG – 12: Responsible Consumption and Production. SEM and XRD analysis revealed the presence of the ZnO NPs, their size, and structure. The real-time fruit packaging application of film was tested, and hence it can be used as an alternative to synthetic plastics in food packaging with further evaluations.

CONFLICT OF INTERESTS

The authors declare that there is no conflict of interest.

AUTHOR CONTRIBUTIONS

The present work is related to *SDG-12: Responsible Consumption and Production*. All the authors contributed significantly to this manuscript, participated in reviewing/editing and approved the final draft for publication. The research profile of the authors can be verified from their ORCID ids, given below:

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Cite this article as: B. Gayathri *et al.*, *Rasayan J. Chem.*, 19(3), 1268-1274(2026), https://doi.org/10.31788/RJC.2026.1939717

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