

CENTRAL ASIAN JOURNAL OF THEORETICAL AND APPLIED SCIENCE

https://cajotas.casjournal.org/index.php/cajotas

Volume: 07 Issue: 04 | October 2026 ISSN: 2660-5317

Article

Structural Features of ZnO/CMC Nanoparticle-Embedded Polymer Films for Biomedical Applications

Samara A. Madhloom[1]

1. Department of Science, College of Basic Education, Mustansiriyah University, Baghdad, Iraq

* Correspondence: samaraabbasmadhloom@uomustansiriyah.edu.iq

Abstract: The synthesis of bio-based polymer nanocomposites with adjustable structural, morphological, and optical properties has attracted significant interest for high-end technological and biological applications. The present study is designed to assess the impact of incorporating ZnO NPs into a CMC matrix. A series of (CMC/ZnO) nanocomposite films with different (ZnO) contents (0.002 to 0.008 g) were effectively created using a straightforward solution casting method. UV-visible, FE-SEM, and X-ray diffraction (XRD). The structural, morphological, and optical properties of the synthesized films were systematically investigated. The XRD patterns showed the successful incorporation of hexagonal wurtzite ZnO in the semi-crystalline CMC matrix, which showed a gradual decrease in the polymer crystallinity due to the coordination interactions between the COO- groups and Zn+2 ions. The FE-SEM micrographs showed a uniform dispersion of nanoparticles at lower concentrations, while aggregation tendency was observed at higher loadings. Pure CMC's indirect optical band gap lowered from 5.1 eV to 4.9 eV for the highest ZnO concentration owing to defect-induced localized states and structural amorphization as observed from optical study using the Tauc relation. The systematic control of the optical band gap and structural alteration by ZnO loading shows that CMC/ZnO nanocomposite films are promising green materials for advanced optoelectronic, UV shielding, and biomedical applications.

Keywords: carboxymethyl cellulose (CMC) polymer, Nanocomposite, Nanoparticles, Optical properties, CMC/ZnO Nanoparticles

Citation: Madhloom, S. A. Structural Features of ZnO/CMC Nanoparticle-Embedded Polymer Films for Biomedical Applications. Central Asian Journal of Theoretical and Applied Science 2026, 7(4), 209-218

Received: 13th Jun 2026
Revised: 28th Jul 2026
Accepted: 15th Aug 2026
Published: 26th Sep 2026

Copyright: © 2026 by the authors. Submitted for open access publication under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/)

1. Introduction

Recently, the design of polymer-based nanocomposite substances with adjustable structural, morphological, and optical properties for sophisticated technological applications has received much interest. The insertion of inorganic nanoparticles into polymer matrices is an efficient strategy to change the physicochemical characteristics of polymers, while keeping their inherent benefits such as flexibility, low density, simplicity of processing, and low cost. Cellulose derivatives are the most studied among the several polymeric materials for this purpose because of their renewable nature, biocompatibility, biodegradability, and ability to make flexible and transparent films[1, 2].

Recent research, in particular, has shown the promise of CMC-based nanocomposites with metal-oxide nanoparticles to improve optical, UV-shielding, mechanical, and barrier characteristics [3, 4].

CMC is a water-soluble hydrophobic polymer with a hydrophilic carboxyl group. Because CMC is an inexpensive, biodegradable, semi-crystalline, and environmentally benign polymer, it also possesses good film-forming qualities [5]. Much research has been conducted on carboxymethyl cellulose (CMC) to expand its use in electrolyte systems. Furthermore, CMC's performance in electrochemical devices is limited by its low stability and miscibility [6]

ZnO NPs are commonly employed as an antibacterial substance in industries such as medicine, pharmacology, and wound treatment. [7, 8].ZnO NPs have excellent antibacterial and nontoxic properties, making them ideal for incorporating into cellulose-based materials to develop antimicrobial compounds for applications involving food packaging. [9]. Incorporating ZnO NPs in carbon-based substances generates active regions that filter UV light, creatingit an effective antibacterial packaging material [10]

Antimicrobial effectiveness in food packaging regulates the development of bacteria responsible for food-borne diseases. Food packaging using bare plastic sheets does not prevent the growth of bacteria. ZnO and CuO NPs are much sought after in food packaging [11] These packaging materials provide advantages over conventional materials, such as increased surface area and the capacity to produce ROS, which can harm bacterial membranes and impede metabolic activity.[12]

The coupling of CMC with ZnO nanoparticles offers an intriguing path for producing polymer/inorganic hybrid materials with enhanced and controllable characteristics. Functional groups of CMC and the surface of ZnO NPs may affect the organization of polymer chains, crystallinity, dispersion of particles, and generation of localized electronic states inside the composite. Therefore, the adjustment of the ZnO content can lead to dramatic changes in the absorption behavior and optical band gap of CMC/ZnO films. Such alterations are of interest especially for applications such as UV shielding, optical materials, sensors, and optoelectronics devices[13, 14]

Absorbance is the ratio of the light strength absorbed (I_A) to the incoming light strength (Io) [13]:

$$A = \frac{I_A}{I_0} \qquad (1)$$

Absorption coefficient (α) refers to a piece's capacity to absorb light at a specific wavelength. [13]:

$$\alpha = 2.303\ \frac{A}{t} \qquad (2)$$

Where

A: is the absorbance and (t) is the thickness of the film.

The following equation may be used to compute the energy band gap:

$$(\boldsymbol{\alpha h\upsilon}) = \boldsymbol{B}\ (h\upsilon - E_g)^r \qquad (3)$$

Where E_g: is the optical energy band gap, hυ: is the photon energy,

B: is a constant, while r: is constant, with values of (1/2, 3/2) for authorized and forbidden direct transitions, and (2, 3) for allowed and forbidden indirect transitions.

To study the structural, morphological and optical characteristics of CMC/ZnO nanocomposite films with varying concentrations of ZnO and to evaluate their potential for optical and UV-shielding applications**.**

2. Materials and Methods

The CMC/ZnO nano-composite films were prepared by a solution casting procedure in which 0.5 g of carboxymethyl cellulose (CMC) was dissolved in 25 ml of distilled water. The mixture was continuously stirred with a magnetic stirrer throughout 24 hours to maintain consistent viscosity of the polymer. After this, ZnO nanoparticles were added to the solution at a weight % of 0.002,0.004, 0.006, and 0.008 grams, along with 5 ml of distilled water. The solution was magnetically agitated throughout 1 hour and then sonicated throughout 1 hour to achieve a uniform dispersion of nanoparticles in the polymer matrix and to avoid clumping. After obtaining a uniform mixture, it was poured into glass Petri dishes (5 cm diameter) and maintained at a regulated room temperature (23–28 °C) for nine days[15].

The transmittance and absorbance spectra of all items were determined through a T70/T80 series UV-visible spectrophotometer. FE-SEM type (FEI COMPANY) produced in Holland. X-ray diffraction patterns study the structural intersystem of crystalline behavior of films under certain conditions. MALVERN PANALYTICAL Holland. They are manufactured with the following specifications: The target is CuKα1 with a wavelength of 1.5406Å, current of 40mA, and voltage of 40KV. The incident and reflected angles are scanned with a 2θ approach.

3. Results

3.1 Structural Characterization by X-ray Diffraction

The XRD pattern of Pure CMC demonstrates a broad peak around 2θ ≈ 20°, which is characteristic of semi-crystalline materials and is associated with the partial ordering of interwoven polymer chains within the largely amorphous region. This finding is consistent with earlier research on CMC films, characteristic halo peak of the polymer was reported at similar 2θ positions, confirming its semi-crystalline nature [16]. Conversely, the XRD pattern of pure ZnO displayed sharp, well-defined peaks at 2θ ≈ 31.5°, 33.9°, 35.8°, 47.4°, 56.5°, 62.7°, and 68.0°, corresponding to the (100), (002), (101), (102), (110), (103), and (112) Planes of crystallography, respectively, the hexagonal wurtzite's characteristic structure of zinc oxide.

As the ZnO concentration grew, the intensity of the polymer halo peak diminished progressively., and the ZnO peak characteristics were gradually detected upon the integration of ZnO into the CMC framework (Figure 3, A–D). This behavior reflects a competition between the two phases for crystallization, which may be attributed to the interference of ZnO particles with the chain-reorganization process of CMC during drying, along with the establishment of coordination bonds among the carboxylate groups ($–COO^-$) of CMC and Zn^{2+} ions upon the outside of the nanoparticles — a mechanism documented in similar CMC/ZnO systems, where structural analyses confirmed the formation of ZnO and interaction between zinc ions and the carboxylate moieties within the CMC matrix [17]Similar investigations on CMC composites with other metal oxides (such CuO) have also seen a gradual decline in the intensity of the distinctive peak of pure polymer with increasing dopant content [3], which is similar with the pattern shown by the present samples.

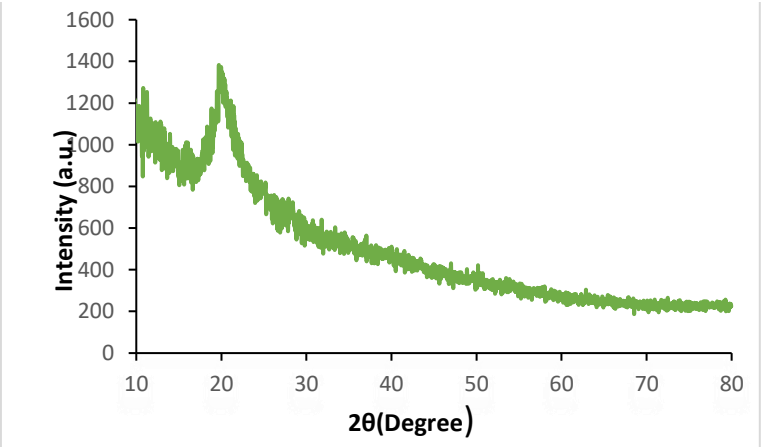


Figure 1. XRD diffraction for pure carboxymethyl cellulose polymer.

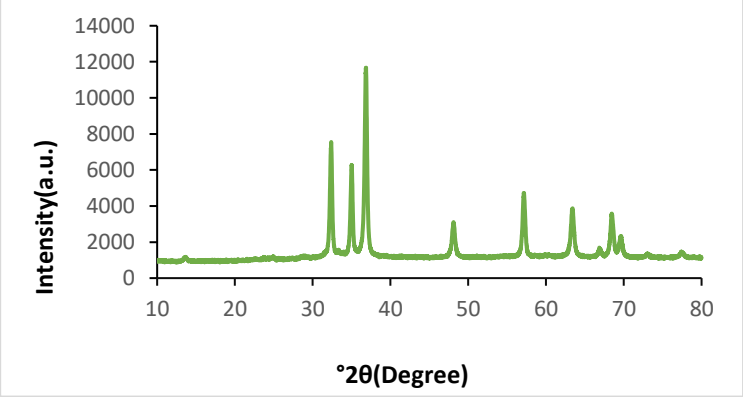


Figure 2. XRD diffraction for Pure ZnO Nanoparticles Powder.

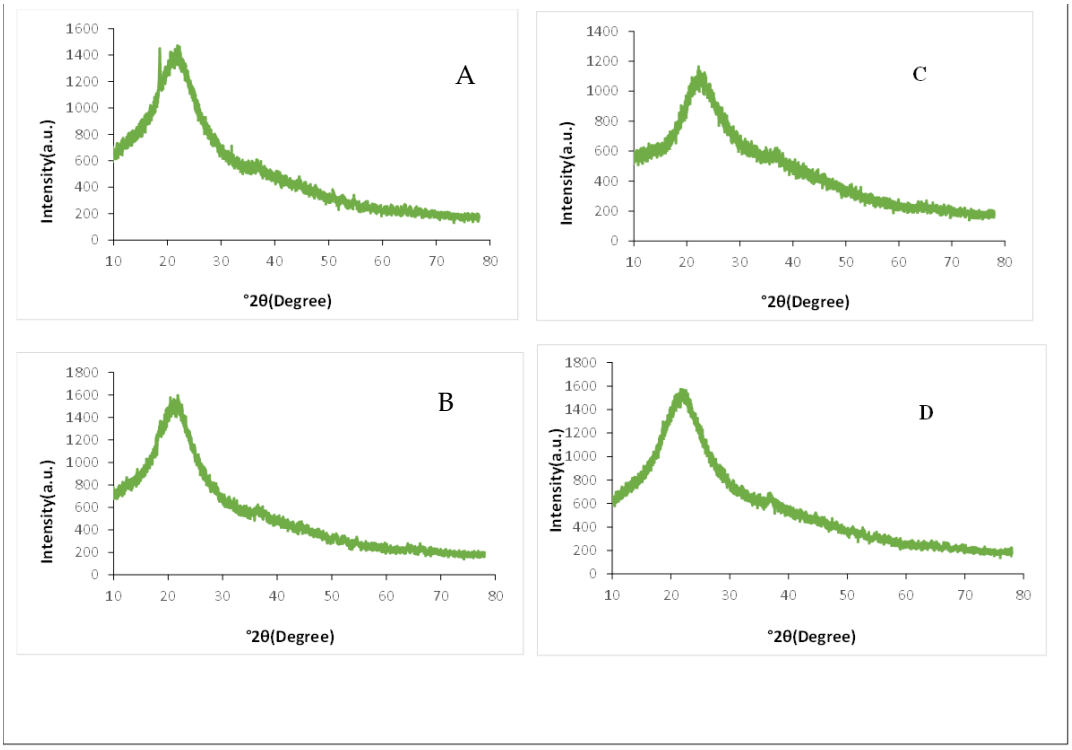


Figure 3. XRD diffraction for CMC/ZnO Nanocomposites films A) 0.002 g B) 0.004 g C)0.006 g and D)0.008 g.

3.2 Morphological Characterization (FE-SEM)

The FE-SEM images (Figure 4) show a significant alteration in surface morphology, from the somewhat fibrous surface of pure CMC (a), to the irregular granular aggregates of pure ZnO (b), and then to the composite films (c–f), where a progressive distribution of ZnO particles in the polymer matrix is noted, with a notable increase in the density and size of granular aggregates at high concentrations (e, f). This shows that the nanoparticles were well dispersed at low concentrations, while at higher concentrations agglomeration tendencies were seen, which is a common behaviour in polymer/zinc oxide nanocomposites and is generally attributed to the higher surface energy of nanoparticles at higher loadings.

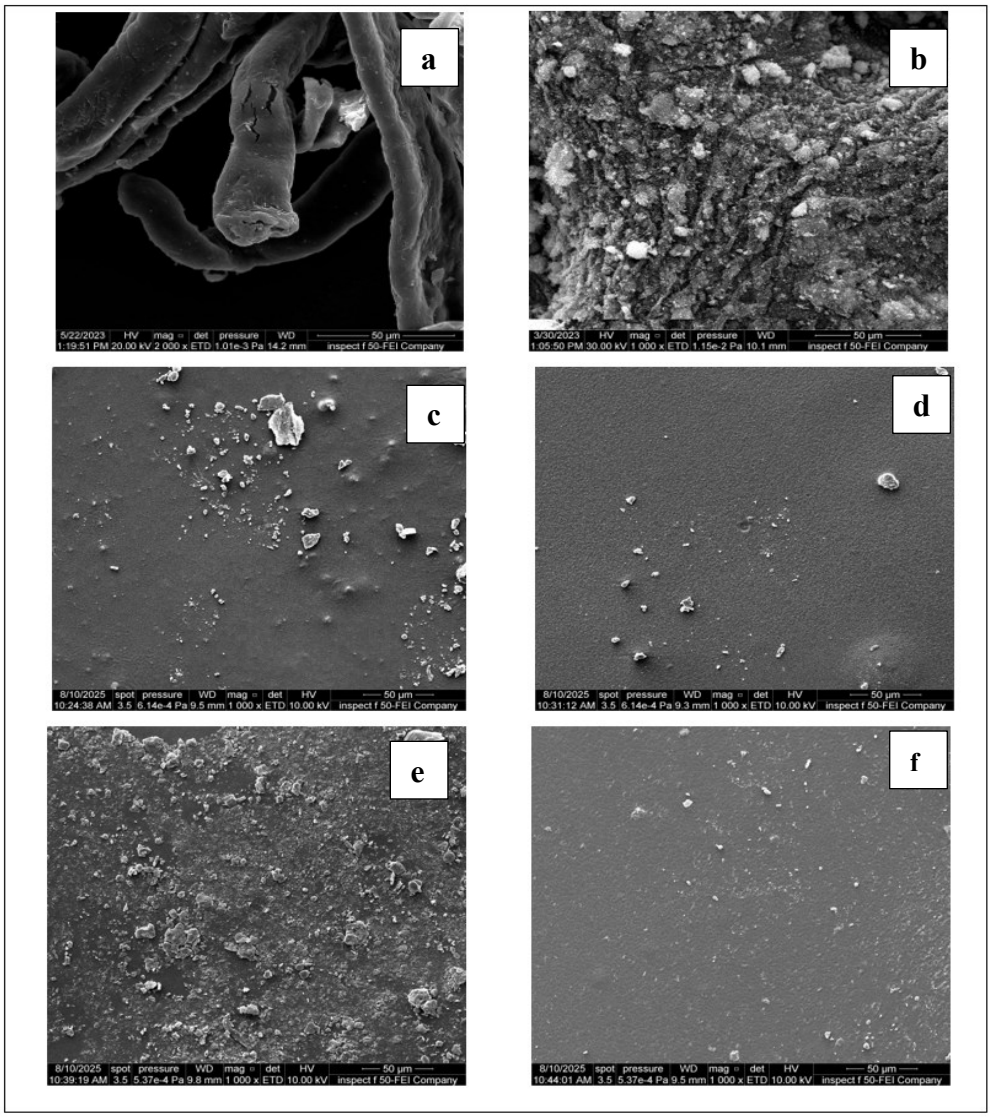


Figure 4. FE-SEM Images of (a) pure CMC polymer, (b) pure ZnO NPs, and CMC/ ZnO nano-composites for (c) 0.002 g ZnO NPs, (d) 0.004 g ZnO NPs, (e) 0.006 g ZnO NPs and (f) 0.008 g ZnO NPs.

4. Discussion

4.1 Optical Properties and Energy Gap

The absorption and transmittance spectra (Figures 5 and 6) revealed a regular variation relative to the rising ZnO concentration, which was directly mirrored by the indirect optical band gap values obtained from the Tauc relation and shown in Table 1. With increasing concentration of ZnO, a gradual and steady drop of the energy gap from 5.1 eV in pure CMC to 4.9 eV in the maximum concentration examined (0.008 g ZnO) was found, which corresponds to an overall reduction of 0.2 eV.

This tendency is in agreement with the literature for CMC systems doped with metal-oxide nanofillers. It has been shown that the optical band gap of CMC lowers rapidly significantly increasing CuO concertation in CMC/CuO composites[18]. The band gap of CMC composites containing ZnO/GO was lowered from 5.53 to 3.43 eV combined with a UV-shielding characteristics enhancement [4]. More recently, the inclusion of 0.15 wt% of the nanoparticles reduced the band gap from 4.60 to 3.52 eV in a work on PVA/CMC/ZnO-Au [19]

It can be seen that the magnitude of the decrease in the present study (0.2 eV) is relatively smaller than those reported in the above studies. This can be reasonably adequately by the fact that the concentrations used here (0.002–0.008 g) are considerably

lower than the weight percentages (wt%) used in those studies, resulting in a more moderate effect on the electronic structure of the matrix.

Physical mechanisms of the band-gap narrowing and biomedical implications The reduction in optical band gap of the CMC/ZnO nano-composite has a significant role in influencing the optoelectronic characteristics, providing a direct correlation between the physical structure of the material and the tailored functional performance of the material in biomedical applications.

The first one is related to the increase of localized energy states in the forbidden band as a consequence of the interfacial structural imperfections between the CMC polymeric matrix and zinc oxide nanoparticles, which causes the formation of intermediate energy levels at the band edges. This structural manipulation greatly improves the photocatalytic antibacterial efficiency of the composite at lower photon energy from the biomedical aspect. The nanocomposite decreases the threshold of electronic transitions to allow the generation of electron-hole (e-/h+) pairs under irradiation with ambient or visible light. These photogenerated carriers react with adsorbed moisture and oxygen at the surface of the material to form Reactive Oxygen-derived species (ROS), exemplified by hydroxyl radicals (OH) and superoxide anions (O2-). further affects the prokaryotic cell membranes and intracellular elements (e.g. in Staphylococcus aureus with Escherichia coli, resulting in these nanocomposites excellent candidates for self-sterilizing smart wound dressings and antibacterial surgical coverings [20, 21]

Secondly, the introduction of ZnO nanoparticles leads to the loss of semi-crystalline order of the CMC network; hence, the macromolecular dynamics is considerably disturbed. The increased degree of amorphous character is as a result of the malfunction of intra- and intermolecular hydrogen interactions in the CMC matrix. In medical applications, this decrease in crystallinity has a direct impact on the biodegradation kinetics and drug delivery properties of the system. The amorphous polymeric regions have a higher free volume and chain mobility, which promotes the flow of physiological fluids and speeds up the matrix swelling. So, it allows controlled and sustained release of encapsulated therapeutic agents (e.g., anti-inflammatory drugs or growth factors) in targeted drug delivery mechanisms and slow and biocompatible degradation of the matrix without surgical removal. [22–24].

Finally, the effect of the nanoparticle size and the consequent increase in light scattering greatly enhances the optical absorption coefficient (\alpha). The improved absorption properties in the UV and near-UV band make the CMC/ZnO nanocomposite an effective UV-shielding barrier. The material is effective in attenuating high intensity UV radiation (UVA and UVB) and thereby reduces radiation-induced oxidative damage to regenerating tissue as medical films, topical dressings or protective artificial skins. Furthermore, this localised light collecting ability has great promise for photothermal therapeutic applications where absorbed sunlight is released locally as heat to destroy pathogenic biofilms or targeted cells. [25, 26]

The occurrence of defect-induced localized states, polymer amorphization and nanoscale optical scattering in the summaries not only accounts for the energetic band-gap narrowing in CMC/ZnO nanocomposites but also intrinsically governs their multifunctional response in modern clinical and biomedical applications.

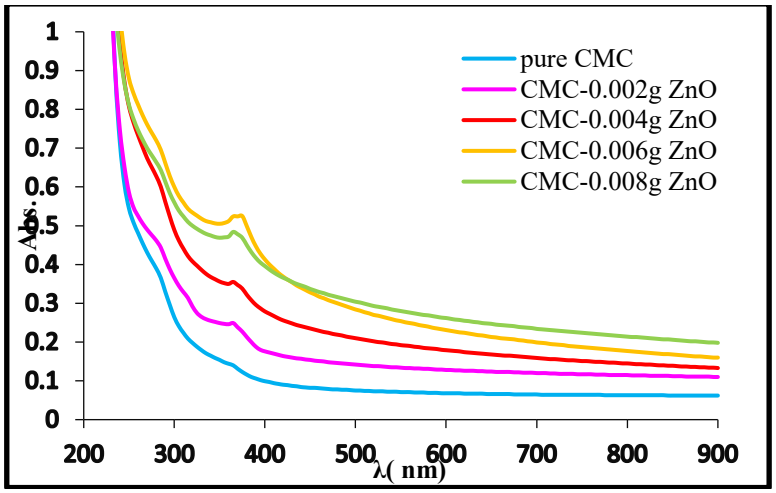


Figure 5. Absorption spectrum of different ratio of CMC/ZnO nano-composite films.

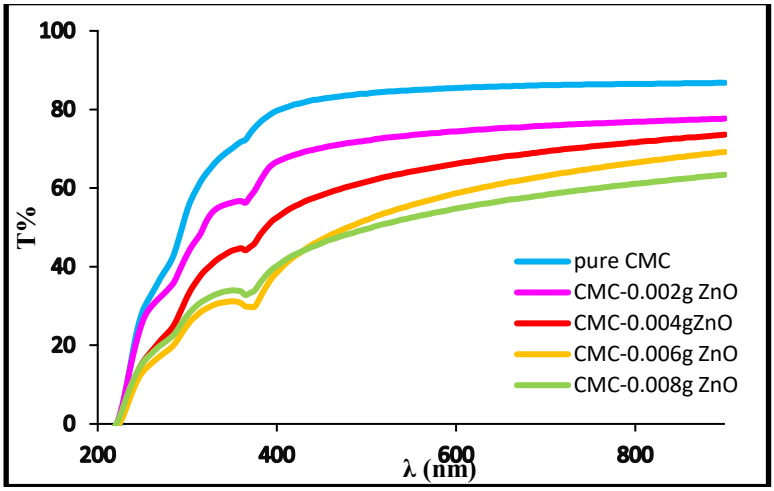


Figure 6. Transmittance spectrum of different ratio of carboxymethyl cellulose / ZnO nano-composite films.

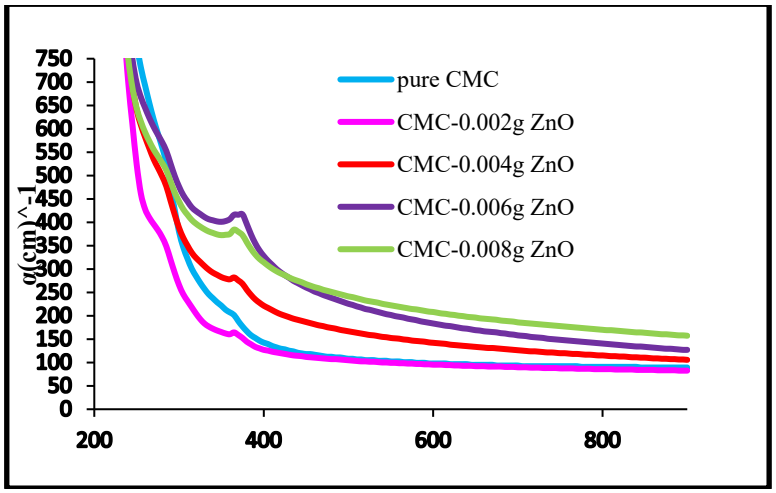


Figure 7. Absorption Coefficient of different ratio of CMC/ZnO nano-composite films.

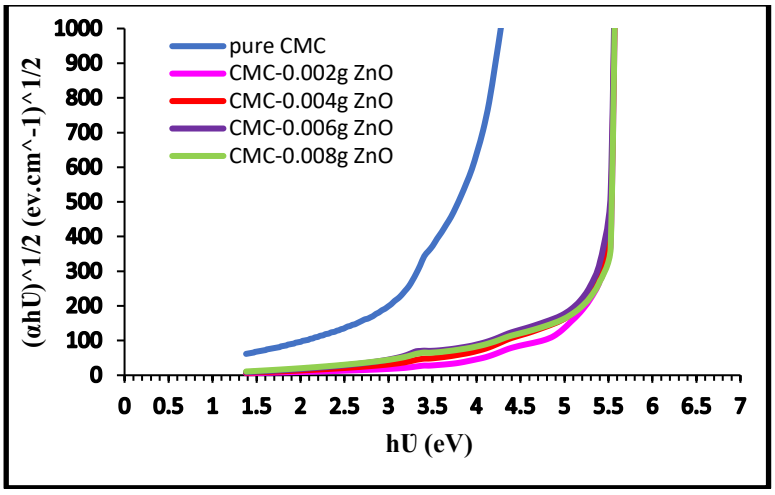


Figure 8. The allowed indirect transition (αhυ)1/2on (hυ) for CMC/ZnO nano-composite films.

Table 1. The allowed indirect transition for CMC/ZnO films.

Sample	Energy Gap (ev)
pure CMC	5.1
CMC-0.002g ZnO	4.9
CMC-0.004g ZnO	4.8
CMC-0.006g ZnO	4.8
CMC-0.008g ZnO	4.7

5. Conclusion

In this study, composite films of carboxymethyl cellulose (CMC) infused with zinc oxide nanoparticles (ZnO NPs) with varied concentrations (0.002-0.008 g) were formulated by the solution casting technique and characterized by X-ray diffraction (XRD), field emission electron microscopy (FE-SEM), in addition to optical assimilation/transmittance spectroscopic analysis. The results revealed a systematic drop in the indirect photonic energy gap derived from 5.1 electron Volt to 4.9 electron volt with increasing ZnO concentration, which is consistent with the documented literature regarding comparable CMC/metal-oxide nanocomposite systems. These results altogether imply that CMC/ZnO composites are attractive candidates for optical and optoelectronic applications as well as UV-shielding applications, with the option of modifying the band gap by altering the concentration of the doped inorganic phase. Future investigations on crystallite size and Urbach energy calculations are proposed for deepening the quantitative knowledge of the structure-optical property link in this system.

REFERENCES

[1] Yousefi N, Zahedi Y, Yousefi A, Hosseinzadeh G, Jekle M. Development of carboxymethyl cellulose-based nanocomposite incorporated with ZnO nanoparticles synthesized by cress seed mucilage as green surfactant. Int J Biol Macromol. 2024;265.

[2] Salama HE, Abdel Aziz MS. Optimized UV-barrier carboxymethyl cellulose-based edible coatings reinforced with green synthesized ZnO-NPs for food packaging applications. Polym Bull. 2024;81:16733–55.

[3] Zafar A, Khosa MK, Noor A, Qayyum S, Saif MJ. Carboxymethyl Cellulose/Gelatin Hydrogel Films Loaded with

Zinc Oxide Nanoparticles for Sustainable Food Packaging Applications. Polymers (Basel). 2022;14.
[4] Badry R, Sabry NM, Ibrahim MA. Enhancing the structural and optoelectronic properties of carboxymethyl cellulose sodium filled with ZnO/GO and CuO/GO nanocomposites for antimicrobial packaging applications. Sci Rep. 2024;14.
[5] Saadiah MA, Zhang D, Nagao Y, Muzakir SK, Samsudin AS. Reducing crystallinity on thin film based CMC/PVA hybrid polymer for application as a host in polymer electrolytes. J Non Cryst Solids. 2019;511:201–11.
[6] Mazuki NF, Fuzlin AF, Saadiah MA, Samsudin AS. An investigation on the abnormal trend of the conductivity properties of CMC/PVA-doped NH4Cl-based solid biopolymer electrolyte system. Ionics (Kiel). 2019;25:2657–67.
[7] Anjum S, Hashim M, Malik SA, Khan M, Lorenzo JM, Abbasi BH, et al. Recent advances in zinc oxide nanoparticles (Zno nps) for cancer diagnosis, target drug delivery, and treatment. Cancers (Basel). 2021;13.
[8] Raghavendra VB, Shankar S, Govindappa M, Pugazhendhi A, Sharma M, Nayaka SC. Green Synthesis of Zinc Oxide Nanoparticles (ZnO NPs) for Effective Degradation of Dye, Polyethylene and Antibacterial Performance in Waste Water Treatment. J Inorg Organomet Polym Mater. 2022;32:614–30.
[9] Rahman MS, Hasan MS, Nitai AS, Nam S, Karmakar AK, Ahsan MS, et al. Recent developments of carboxymethyl cellulose. Polymers. 2021;13.
[10] Kanikireddy V, Varaprasad K, Jayaramudu T, Karthikeyan C, Sadiku R. Carboxymethyl cellulose-based materials for infection control and wound healing: A review. International Journal of Biological Macromolecules. 2020;164:963–75.
[11] Adler BL, DeLeo VA. Sunscreen Safety: a Review of Recent Studies on Humans and the Environment. Current Dermatology Reports. 2020;9.
[12] Jesus A, Sousa E, Cruz MT, Cidade H, Lobo JMS, Almeida IF. UV Filters: Challenges and Prospects. Pharmaceuticals. 2022;15.
[13] D'Amora U, Dacrory S, Hasanin MS, Longo A, Soriente A, Kamel S, et al. Advances in the Physico-Chemical, Antimicrobial and Angiogenic Properties of Graphene-Oxide/Cellulose Nanocomposites for Wound Healing. Pharmaceutics. 2023;15.
[14] Vyas A, Ng SP, Fu T, Anum I. ZnO-Embedded Carboxymethyl Cellulose Bioplastic Film Synthesized from Sugarcane Bagasse for Packaging Applications. Polymers (Basel). 2025;17.
[15] Madhloom SA. Study of physical properties for silica nanoparticles additive effect into carboxymethyl cellulose polymer (CMC) films. AIP Conf Proc. 2026;70039 May:1–6.
[16] Alharbi KH, Alharbi W, El-Morsy MA, Farea MO, Menazea AA. Optical, Thermal, and Electrical Characterization of Polyvinyl Pyrrolidone/Carboxymethyl Cellulose Blend Scattered by Tungsten-Trioxide Nanoparticles. Polymers (Basel). 2023;15.
[17] Antony, M. F. S., Bara, H. B., Thambidurai, A., Peter, L. S., & Daniel S. In Situ Fabrication of the ZnO-Embedded Carboxymethyl Cellulose Nanocomposite Film for Food Packaging Materials: A Sustainable Approach. ACS Sustain Resour Manag. 2026;3:768–86.
[18] Badry R, El-Nahass MM, Nada N, Elhaes H, Ibrahim MA. Structural and UV-blocking properties of carboxymethyl cellulose sodium/CuO nanocomposite films. Sci Rep. 2023;13.
[19] Abdel-Fattah EM, Elnemr AM, Elsharkawy WB, Fahmy T. Multifunctional PVA–CMC/ZnO–Au Nanocomposite Films with Enhanced UV Shielding, Thermal Stability, and Antibacterial Performance. Polymers (Basel). 2026;18:1–19.
[20] Badry R, El-Nahass MM, Nada N, Elhaes H, Ibrahim MA. Tunable optical and UV-blocking properties of eco-friendly CMC/ZnO nanocomposite films. Sci Rep. 2026;16:1–25.
[21] Saadeldin MM, Salim SJ, Abdelghany KA. Electrical, thermal, optical, and magnetic properties of ZTO nanocomposites in a PVA matrix: functional correlations with non-thermal structural modifications. Discov Nano. 2026;21.
[22] Becheri A, Dürr M, Lo Nostro P, Baglioni P. Synthesis and characterization of zinc oxide nanoparticles: Application to textiles as UV-absorbers. J Nanoparticle Res. 2008;10:679–89.
[23] Yadollahi M, Gholamali I, Namazi H, Aghazadeh M. Synthesis and characterization of antibacterial carboxymethyl cellulose/ZnO nanocomposite hydrogels. Int J Biol Macromol. 2015;74:136–41.
[24] Raj VJ, Ghosh R, Girigoswami A, Girigoswami K. Application of zinc oxide nanoflowers in environmental and biomedical science. BBA Advances. 2022;2.
[25] Radmehr M, Poursattar Marjani A, Akhavan A. Synthesis and characterization of antibacterial CMC/AAc/ZnO nanocomposite superabsorbent using gamma radiation. Sci Rep. 2025;15.

[26] Yousefi F, Mousavi SB, Heris SZ, Naghash-Hamed S. UV-shielding properties of a cost-effective hybrid PMMA-based thin film coatings using TiO2 and ZnO nanoparticles: a comprehensive evaluation. Sci Rep. 2023;13.