

Sustainable hydrothermal synthesis and characterization of carbon-ZnO nanocomposites from discarded dry cell batteries for prospective antimicrobial applications

Hari Murthy ^a, Khushi N ^a, Aghal Pravin ^a, P Baraneedharan ^b, Sourav Roy ^{a,*}

^a Department of Electronics and Communication Engineering, School of Engineering and Technology, CHRIST University, Kanminike, Bengaluru – 560074, Karnataka, India

^b Centre for Excellence in Photonics and Nanotechnology, Saveetha Engineering College, Thandalam, Chennai – 602105, Tamil Nadu, India

* Corresponding author: sourav.roy@christuniversity.in

Abstract.

Spent dry cells get disposed irresponsibly in landfills creating an environmental concern. This work investigates the reuse of battery-derived carbon as a sustainable dopant in ZnO nanocomposites synthesized via a hydrothermal method. X-ray diffraction confirms the presence of hexagonal wurtzite ZnO nanocomposites with an average crystallite size of ~19.5 nm. Scanning electron microscopy and electron diffraction studies revealed spheroidal particles with agglomerates of $\sim 140 \pm 39$ nm with trace carbon incorporation alongside Zn and O. UV–visible spectroscopy exhibited a characteristic absorption peak at ~356 nm, with an optical bandgap between 3.12–3.15 eV. Empirical bandgap–refractive index relations (Moss, Ravindra, Herve–Vandamme, Kumar–Singh, Annani) gave an average value of ~2.44. The study demonstrates a circular economy approach for converting waste dry-cell battery carbon into functional ZnO dopants, supporting the future development of printable ZnO-based inks for direct ink writing applications in healthcare.

Keywords: zinc oxide, carbon incorporation, dry cell, waste battery recycling, hydrothermal, nanocomposites, sustainability, circular economy.

1. INTRODUCTION

ZnO is a wide band n-type semiconductor with a bandgap of 3.37-3.4 eV [1], and its unique electronic, optical, photochemical, and magnetic properties make it suitable for various applications [2]. Several methods have been investigated for synthesizing ZnO nanostructures, among which the most straightforward, scalable, and energy- and cost-efficient method for growing ZnO nanostructures is the hydrothermal method [3].

Electronic waste (e-waste) generation has increased exponentially, with recent UN reports projecting global e-waste to reach 74.7 million metric tons by 2030. Batteries account for a substantial fraction of this waste, with more than 300,000 tons produced annually worldwide since 2002 [4]. Zinc-carbon and alkaline batteries are among the most widely used primary cells, consisting of porous carbon powder and graphite rods combined with MnO₂ cathodes, enclosed within a zinc casing that also functions as the negative electrode. Their disposal poses a significant environmental and health risk due to heavy metals, reactive salts, plastics, and organic compounds [5]. The recovery and reuse of porous carbon from spent batteries remain challenging because of MnO₂ contamination associated with ion transfer layers [6]. Discharged alkaline cells provide a low-cost and environmentally sustainable source of activated carbon, supporting circular economy practices through waste reduction, lower CO₂ emissions, and resource-efficient material recovery. Metal oxide–carbon nanocomposites have attracted considerable interest for applications in photocatalysis, electrochemical sensing, and wearable electronics because of their high sensitivity and multifunctional properties. Carbon doping can improve electrical conductivity [7], visible light absorption, electrochemical and thermal capabilities, and corrosion resistance [8]. Incorporating carbon into ZnO nanostructures offers an effective strategy for tailoring optical and functional characteristics. However, reports on the utilization of waste battery-derived carbon as a dopant source remain limited. The present study addresses this gap through the hydrothermal synthesis of carbon-incorporated ZnO nanoparticles using carbon recovered from discarded dry-cell batteries. Their structural, morphological, and optical properties are systematically investigated to evaluate their suitability for future ink-based antimicrobial and printable electronic applications.

2. MATERIALS AND METHODS

Duracell® alkaline batteries were selected because of their higher charge storage capacity and ready availability. The process for the carbon extraction is shown in Figure 1(a). The extraction process was previously discussed by Kumar et al. [9]. Zinc nitrate hexahydrate and sodium hydroxide pellets were used as precursors, while PVA was added as stabilizer. The synthesis of ZnO nanocomposites with different molar ratios of carbon was performed using the hydrothermal method is shown in Figure 1(b). Different concentrations of PVA ranging from 0.5–2.5 g/lit and carbon doping ranging from 0–2.5 mg/lit were investigated.

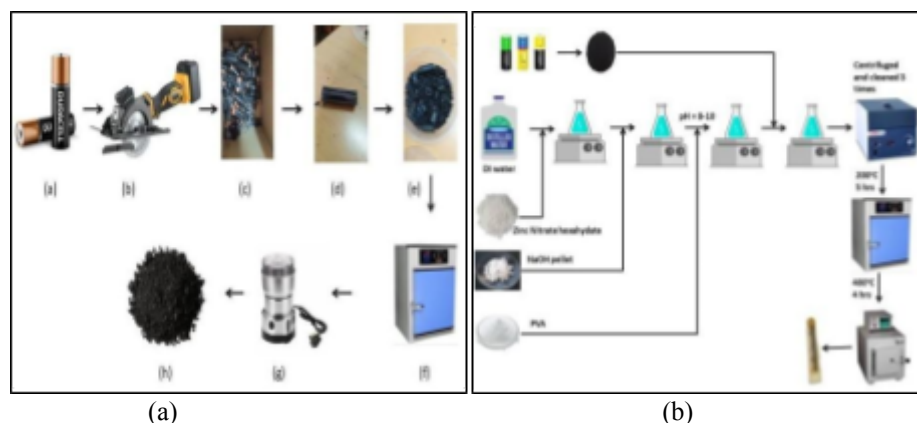


Figure 1. (a) Schematic representation on the method for (a) carbon extraction from batteries, and (b) ZnO-C nanocomposite synthesis method.

Crystallographic phase analysis was carried out using a Rigaku SE X-ray diffractometer operated at 40 kV and 50 mA with CuK α radiation and a step size of 0.01°. Diffraction patterns were recorded over a 2θ range of 5°–70°, with a counting time of 0.5 s per step across 3496 steps, resulting in a total scan duration of 1805 s. Surface morphology and compositional investigations were performed using a Hitachi SU3500-A scanning electron microscope integrated with an Oxford X-max silicon drift EDX detector, operated at an accelerating voltage of 15 kV and a working distance of 7 mm. Optical absorption characteristics were evaluated using a double-beam UV–visible spectrophotometer (V-740, Jasco, Tokyo, Japan) equipped with Deuterium and Xenon Arc light sources and a silicon photodetector. Measurements were obtained using a 10 mm path length micro-UV cell over the wavelength range of 200–850 nm.

3. RESULTS AND DISCUSSION

The XRD exhibits good agreement with the wurtzite phase of hexagonal ZnO, according to JCPDS Card No. 36–1451. The incorporation of carbon does not measurably distort the ZnO lattice, possibly due to the low concentration of carbon present in the samples (as shown in EDX). The lattice constants were determined to be $a=b=3.22\text{Å}$ and $c=5.17\text{Å}$. The c/a ratio is 1.6 which is close to the ideal wurtzite value (~ 1.611 – 1.633) [10], with the Zn–O bond length around $\sim 1.96\text{Å}$ [11]. The volumes of the hexagonal Wurtzite primitive cells of the ZnO was found to be 46.44Å^3 [12]. The average crystal size was calculated using Debye–Scherrer formula to be $\sim 19.5\text{nm}$. Figure 2(b) shows the SEM micrograph showing the ZnO nanocomposites with a spheroidal morphology, smooth edges, and agglomeration, with an average diameter of around $140\text{nm} \pm 39\text{nm}$. EDX data reveal that Zn and O are major components, with trace amount of carbon. No other impurities were observed during the analysis.

The absorbance of the nanocomposites was measured in the range of 200–800nm. The absorption spectra of ZnO with varying carbon concentrations are shown in Figure 3(a) with a peak absorbance at $\sim 356\text{nm}$, as reported in literature [13]. Carbon concentration does not significantly affect the peak UV absorption edges due to its trace presence. The bandgap of the samples was determined using Tauc plot, and found to be in the range of 3.12–3.15 eV. (Figure 3(b)) [14]. These values were slightly lower than those of bulk ZnO due to smaller particle size and defect density, leading to quantum confinement effects in agglomerations and smaller particles [13]. The estimated E_{CB} (energy-conduction band) and E_{VB} (energy-valence band) are -0.285eV and $+2.865\text{eV}$, respectively [15]. The refractive indices were calculated to be about 2.44 (Figure 3(c)) using the E_g values

obtained earlier and models, such as Moss, Reddy-Ahmed, Ravindra, Herve and Vandamme, Kumar-Singh, and Annani et al. [16], which is close to that of bulk ZnO ($n \sim 2$ at 600 nm [17]).

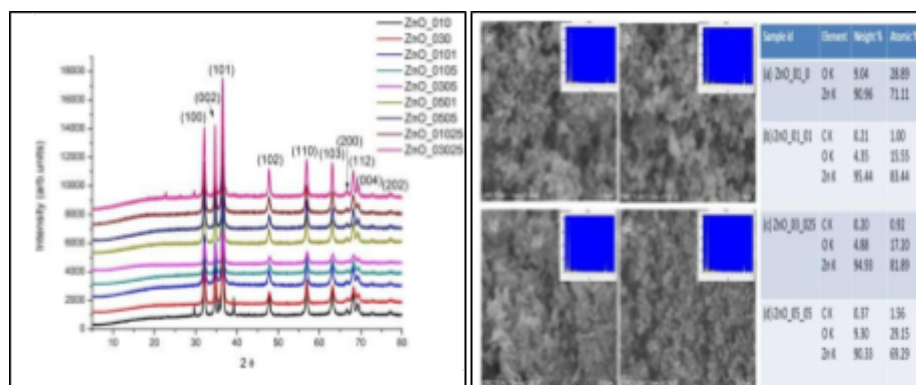


Figure 2. (a) XRD patterns of synthesized composites exhibit distinct ZnO peaks confirming the wurtzite structure, (b) SEM-EDX images provide a representative idea on the spherical and agglomerated nature of the nanocomposites formed along with their composition.

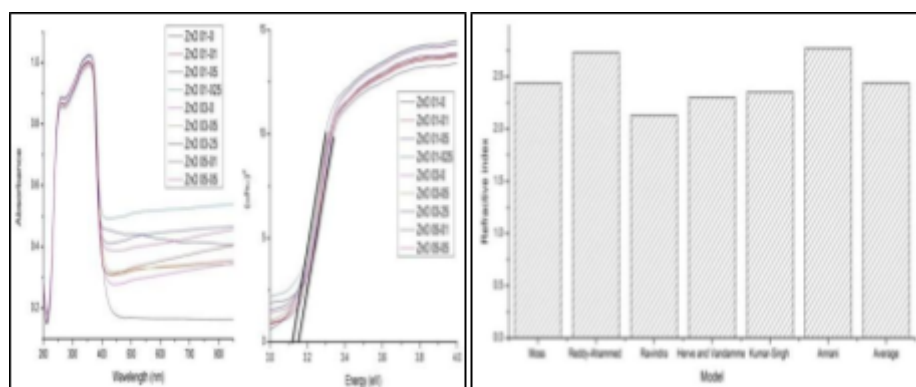


Figure 3. (a) UV-vis absorption spectra show a peak absorbance at ~ 356 nm. (b) Tauc plot analysis from the UV-Visible data suggests a bandgap of 3.12-3.15 eV. (c) Comparison of the refractive indices obtained from various models show an empirical refractive index of ~ 2.44 .

4. CONCLUSION

ZnO nanoparticles were synthesized via a hydrothermal route and incorporated with carbon derived from waste dry-cell batteries without altering the ZnO crystal structure, as confirmed by XRD. SEM and EDX analyses revealed agglomerated ZnO particles with successful carbon incorporation. UV-visible spectroscopy showed an absorption peak at ~ 356 nm, corresponding to a bandgap of ~ 3.12 – 3.15 eV, with minimal variation across carbon loadings and close agreement with literature values. The calculated valence and conduction band energy levels also aligned with reported data. Refractive index values estimated using the Moss, Ravindra, Herve-Vandamme, and Kumar-Singh models showed good agreement, with an average value of ~ 2.44 . Although the current carbon concentration minimally affects intrinsic optical properties, the study demonstrates a scalable approach for valorizing battery waste into functional semiconductor nanostructures, with potential applications in antimicrobial coatings and printable inks for flexible and rigid sensing platforms.

5. FUNDING

This work was supported by the CHRIST University Seed Money Scheme under the grant numbers SMSET-EC-2503, SMET-2102 and SMSEA-2405.

6. REFERENCES

- [1] Y. M. Hasseb Elsayed *et al.*, 'Characterizations of ZnO Nanoparticles Green Synthesized using Flaxseeds Extract for Biomedical Applications', *Trends Sci*, vol. 21, no. 8, p. 7923, Jun. 2024, doi: 10.48048/tis.2024.7923.
- [2] V. D. Wankhade, R. B. Pedhekar, V. S. Kalyamwar, V. R. Hiranwale, and S. P. Patil, 'Formation of Nanocrystalline ZnO-TiO₂ Hybrid Oxides through Hydrothermal Route', *NHC*, vol. 48, pp. 1–10, Nov. 2025, doi: 10.4028/p-RWVFV9b.
- [3] S. W. Suciayati, P. Manurung, J. Junaidi, and R. Situmeang, 'Optical and Crystal Structure Properties of ZnO Nanoparticle Synthesized through Biosynthesis Method for Photocatalysis Application', *Indones. J. Chem.*, vol. 24, no. 1, p. 125, Feb. 2024, doi: 10.22146/ijc.84796.
- [4] J. Jan, C.-L. Chang, and S. Chang, 'Preparation of Mn/TiO₂ catalysts using recovered manganese from spent alkaline batteries for low-temperature NH₃-SCR', *Journal of Hazardous Materials*, vol. 472, p. 134497, Jul. 2024, doi: 10.1016/j.jhazmat.2024.134497.
- [5] S. Seemab, S. Muhammad, S. Nawaz, S. Ahmad, R. Ullah, and A. Khan, 'Exploring the adsorption potential of waste graphite obtained from spent dry cells for Congo red dye from aqueous solutions', *Chemical Engineering Science*, vol. 306, p. 121224, Mar. 2025, doi: 10.1016/j.ces.2025.121224.
- [6] Md. Sahadat Hossain, S. Tabassum, S. Khan, D. Islam, and S. Ahmed, 'Extraction of carbon and preparation of activated carbon from waste dry cell battery', *Carbon Trends*, vol. 17, p. 100406, Dec. 2024, doi: 10.1016/j.cartre.2024.100406.
- [7] W. Habib, A. Saji, F. Paul, P. R. Markapudi, C. Wilson, and L. Manjakkal, 'Flexible electrochemical capacitors based on ZnO-carbon black composite', *Results in Engineering*, vol. 25, p. 104510, Mar. 2025, doi: 10.1016/j.rineng.2025.104510.
- [8] A. U. Kumar, T. Saha, S. Prasad, and P. Gadige, 'ZnO/carbon black nano-heterostructures for ultrafast ethanol detection with n to p-type switching at room temperature', *Appl. Phys. A*, vol. 131, no. 4, p. 312, Apr. 2025, doi: 10.1007/s00339-025-08419-9.
- [9] N. Kumar, M. Koohestani, S. Roy, and H. Murthy, 'Sustainable X-Band Microwave Absorber Using Tea Waste and Recycled Carbon Composites', in *2025 19th European Conference on Antennas and Propagation (EuCAP)*, Stockholm, Sweden: IEEE, Mar. 2025, pp. 1–4. doi: 10.23919/EuCAP63536.2025.11000026.
- [10] H. Abdulelah, 'Simple method for calculation hexagonal lattice parameter (a and c) system of ZnO nanorod via x-ray analysis: review', *IPTEKS*, vol. 2, no. 1, pp. 27–32, Mar. 2025, doi: 10.61796/ipteks.v2i1.390.
- [11] M. Mohammadzakeri, S. Jamehbozorgi, M. D. Ganji, M. Rezvani, and Z. Javanshir, 'Toward functionalization of ZnO nanotubes and monolayers with 5-aminolevulinic acid drugs as possible nanocarriers for drug delivery: a DFT based molecular dynamic simulation', *Phys. Chem. Chem. Phys.*, vol. 25, no. 32, pp. 21492–21508, 2023, doi: 10.1039/D3CP01490H.
- [12] E. A. Araújo Júnior *et al.*, 'Synthesis, growth mechanism, optical properties and catalytic activity of ZnO microcrystals obtained via hydrothermal processing', *RSC Adv.*, vol. 7, no. 39, pp. 24263–24281, 2017, doi: 10.1039/C7RA03277C.
- [13] A. N. Abdulqodus *et al.*, 'Green synthesis of ZnO nanoparticles: effect of pH on morphology and photocatalytic degradation efficiency', *Appl. Phys. A*, vol. 131, no. 9, p. 720, Sep. 2025, doi: 10.1007/s00339-025-08874-4.
- [14] A. Hussain, S. Fiaz, A. Almohammed, and A. Waqar, 'Optimizing photocatalytic performance with Ag-doped ZnO nanoparticles: Synthesis and characterization', *Heliyon*, vol. 10, no. 15, p. e35725, Aug. 2024, doi: 10.1016/j.heliyon.2024.e35725.
- [15] B. Abebe, N. K. Gupta, and D. Tsegaye, 'A critical mini-review on doping and heterojunction formation in ZnO-based catalysts', *RSC Adv.*, vol. 14, no. 25, pp. 17338–17349, 2024, doi: 10.1039/D4RA02568G.
- [16] A. I. Abdel-Salam, T. S. Soliman, A. Khalid, M. M. Awad, and S. Abdallah, 'Effect of reduced graphene oxide on the structural and optical properties of ZnO nanoparticles', *Materials Letters*, vol. 355, p. 135465, Jan. 2024, doi: 10.1016/j.matlet.2023.135465.
- [17] S. Maqsood *et al.*, 'Assessment of different optimized anti-reflection coatings for ZnO/Si heterojunction solar cells', *Ceramics International*, vol. 49, no. 23, pp. 37118–37126, Dec. 2023, doi: 10.1016/j.ceramint.2023.08.313.