Synthesis of Nanoparticles from E-Waste and Industrial Waste: A Review

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Abstract

Electronic waste (e-waste) and industrial waste represent both environmental burdens and untapped resource streams. Traditional disposal strategies face sustainability challenges due to hazardous components and accumulation rates. A promising alternative is the recovery and reuse of valuable elements to synthesize nanoparticles (NPs) with applications in catalysis, sensors, biomedicine, and energy devices. Eco-friendly alternatives with great selectivity that convert metal ions into NPsare provided by green recovery methods like biohydrometallurgy.This review comprehensively surveys methods for nanoparticle synthesis from e-waste and industrial by-products, characterizes the materials produced, discusses mechanisms, advantages, drawbacks, and identifies research gapsand discovers innovative methods to sustainable metal nanoparticle synthesis from WPCBs and waste Batteries.This review has significant implications since it identifies the synthesis of sustainable metal NPs from WPCBs as a key remedy for the environmental issues associated with e-waste, opening way for environmentally friendly recycling methods and provision of valuable materials for a variety of industrial uses.

Keywords: Green synthesis, E-waste, industrial waste, nanoparticles, recycling, materials recovery.

1. Introduction

Growth in electronic device usage and industrial manufacturing has escalated waste generation. E-waste comprises precious metals namelyZn,Au, Cu, Ag, Cu,Pd, Pt, and rare earths(4,5)industrial wastes include slags, fly ash, and spent catalysts rich in metal oxides(19). Conventional recycling focuses on bulk metal recovery, but recent research explores value addition via nanoparticle production(54).

Nanochemistry is an emerging subdiscipline of chemical and materials science that focuses on the development of innovative methods for producing nanoscale materials smaller than 100 nm(54). Various types of wastes can serve as valuable starting materials for nanoparticle synthesis. Industrial wastes, particularly large quantities of discarded batteries, act as significant sources of metals,namelycopper, zinc, carbon, cobalt, lead, and lithium(36,7). Similarly, e-wasteis recognized as asignificant secondary resource for recovery of valuable metals, including Au, Cu, Pd, Ag,Pt (33,48). Battery waste streams—notably-Zn-C, lead-acid, lithium-ion batteries—haverecognized as rich sources of metal oxides and metallic components that can be converted into functional NPs through thermal, chemical, or green synthesis routes. (63,69)

Because of ever-increasing collection of abandoned devices, e-waste, also recognized as industrial waste or e-waste, is a developing global environmental issue. In 2019, 53.6million metrictons(MT) of e-waste are producingglobal; via 2030, that amount is likely to rise to 74.7million MT.(5,16) Present estimates suggest that e-waste generation is about 52.2million tons annually,having an estimated annual growth rate of 5%(5). E-wastecomprises a variety of complex components, with WPCBs comprising approximately 10% of total e-waste(67) .The high concentration of base metals,namelyCuor tin (Sn), valuable metals,notably,Au, Ag, Pd, or dangerous metals like cadmium (Cd), lead (Pb), nickel (Ni),mercury (Hg),makes WPCBs particularly important(11, 59). Inappropriate processing or disposal of these hazardous constituents posessevere environmental as well as health risks, particularly in regions lacking formal recycling infrastructure (20).

By encouraging the reuse of extracted materials in industrial processes, WPCB recycling helps to significantly reduce total waste output and decrease dependence on fresh raw resources (11, 21, 67).

Numerousapproaches, namely hydrometallurgy, pyrometallurgy, mechanical processing, are frequently employed in sustainable recycling for extractingvaluable metals from industrial and e-waste (21, 59). Because of their distinctive size-dependent physical as well as chemical features and high surface-to-volume ratios, NPshave been ideal for use in advanced energy systems, biomedical sensors, environmental remediation, and catalysis (29, 51,70).

Investigationispresented that conventional cyanide-based leaching presents several limitations, including high toxicity, wastewater generation, and increased operational costs due to the multiple treatment stages involved—searching for more sustainable chemical alternatives is essential(1,40). In recent years, alternative lixiviants, such as thiocyanate, have gained interest as more environmentally friendly alternatives for leaching gold and silver. Thiocyanate is an appropriate choice for sustainable metal recovery methods since it is less toxic, more chemically stable, and uses fewer chemical substances than cyanide.(3, 46)

Biotechnology-based methods like biohydrometallurgy greatly improve metal recovery processes when utilizing aqueous solutions as well as biological metabolites formed by specificmicroorganisms. Bioleaching, in particular, is widely regarded as a green and sustainable technology because it requires low capital investment, is inexpensive to operate, consumes minimal energy, and generates little to no toxic waste compared to conventional chemical leaching methods (27, 52).

Additionally, by combining mechanical separation, chemical treatment, and clean reprocessing procedures, sustainable recycling systems are designed for high recycling efficiency or low environmental emissions (21,39). These approaches effectively separate layers and components of WPCBs, enabling their reuse in multiple industrial applications (67). A notable advancement in this field is synthesis of high-value-added products—such as microstructures and nanomaterials—from metals recovered through WPCB recycling, offering new pathways for waste valorization and circular economy initiatives (2, 12).

With their high "surface-area-to-volume ratio (SA/V)", NPs—which are typically among 1-100nm in size—have distinct chemical,optical,physical, biological properties from their bulk counterparts (29, 51). These unique characteristics have enabled many different usesin medical and biological fields, like medical diagnostics, therapeutics, biosensing, drug delivery, imaging, and the development of antimicrobial or sterilizing surface coatings (26, 53, 70).

Since "electric vehicles (EVs)", portable electronics, energy storage systems were growing rapidly, battery waste is rapid-growing waste source (17, 22). Inappropriate disposal of batteries leads to soil and groundwater contamination as a result of heavy-metal leaching, acid leakage, and the release of toxic organic electrolytes (28, 57). Therefore, valorization of waste batteries through metal recovery and nanoparticle fabrication has emerged as an environmentally and economically promising approach (37, 68). With global shift toward portable electronics and electric mobility, battery consumption has risen exponentially, intensifying the environmental risks posed by toxic components such as heavy metals, corrosive electrolytes, and organic solvents found in spent batteries (18, 58).

Alkaline, Li-ion, zinc-carbon (Zn-C) lead-acid, Ni-metal hydride (NiMH)batteries,have among several kinds of waste batteries (17, 22). These batteries also serve as a significant secondary source of precious and strategic metals,namelylithium (Li), zinc (Zn), manganese (Mn), nickel (Ni), cobalt (Co), and silver (Ag) (58, 68). Recycling of these metals typically involves pre-processing steps such as sorting, crushing, mechanical separation, electrolyte removal, and heat treatment (37). Hydrometallurgical processes employ various leaching agents—including mineral acids (H_2SO_4, HCl, HNO_3), organic acids (citric acid, oxalic acid), and reducing agents (H_2O_2, glucose)—which enable selective metal extraction under low-temperature conditions and can achieve metal recovery efficiencies exceeding 90% (10, 41). Conversely, pyrometallurgical recycling involves high-temperature smelting, roasting, and refining processes to recover valuable metals from spent batteries (34, 64).

Pyrometallurgical method for battery recycling is considered fast and industrially scalable; however, it requires extremely high energy input and is associated with significant CO_2 emissions during smelting and roasting operations (34, 64). In contrast, bioleaching utilizes microorganisms, namely Acidithiobacillus ferrooxidans and Leptospirillum ferrooxidans, to extract metals by biological oxidation, offering an eco-friendly and low-energy alternative; however, the process typically suffers from slow kinetics and longer processing times (25, 42, 66).

Recycling waste batteries is crucial for both reducing pollution in environment and recovering precious metals that might be used again in high-tech companies (22, 58). Advanced hydrometallurgical and bio-based extraction processes provide high recovery efficiencies while minimizing environmental effectsin contrast totraditional pyrometallurgical routes (25, 37). The recovered metals are widely utilized in new battery manufacturing, catalysis, nanoparticle synthesis, electronics, and environmental remediation, contributing significantly to resource conservation and technological development (17, 68). Strengthening investment in battery recycling technologies promotes a circular economy by reducing dependence on primary raw materials and offering sustainable pathways to meet future energy challenges (34, 64).

Recovery of metal NPs from waste batteries represents a sustainable pathway for waste utilization and advanced materials engineering (37, 58). Modern hydrometallurgical techniques and green synthesis routes—such as plant-mediated, microbial, and organic-acid-assisted reduction—enable high recovery efficiency and improved nanoparticle quality thoughreducing environmental impact (25, 41). Future investigation should prioritize scalable green extraction strategies, energy-efficient metal-to-nanoparticle conversion processes, and standardized protocols to ensure nanoparticle uniformity and purity for industrial applications (17, 68).

NPs derived from e-waste, mainly from waste printed circuit boards (WPCBs), have shown wide applicability across multiple sectors because of their unique physicochemical properties (13, 30). These applications span drug delivery, microelectronics, diagnostics, environmental remediation, catalysis, antimicrobial coatings, and agriculture, where recovered metals such as Cu, Ag, and Au are used to synthesize functional nanomaterials (50, 68). WPCB-derived NPshad demonstrated high catalytic activity and efficiency in degrading toxic dyes and recalcitrant organic pollutants, offering an eco-friendly & cost-effective alternative to wastewater treatment equipment (35, 54).

Recycling waste batteries not only recovers valuable metals,notablymanganese (Mn), lithium (Li), cobalt (Co), Zn, nickel (Ni), lead (Pb), but also enables production of metal or metal-oxide NPs with enhanced functional properties (37, 58).These NPshave useful in several current applications throughelectrical conductivity, catalytic activity, large surface area, optical properties (32, 41). Specifically, NPs derived from waste batteries are increasingly applied in energy storage devices, including high-performance electrodes, pseudocapacitor materials, and hybrid supercapacitors, where they contribute to improved electrochemical performance and sustainability (17, 68).

NPs derived from waste batteries exhibit excellent electrical and chemical sensitivity. For example, ZnO NPs can detect gases such as CO, H_2, and NO_2; MnO_2 NPs are effective for ozone detection; and NiO NPs have been reported for methane sensing (50, 54). Beyond gas sensing, NPs recovered from waste batteries find diverse high-value applications across energy storage, environmental remediation, biomedical technologies, industrial processes (32, 37). Their superior properties—notably large surface area, high catalytic efficiency, optical activity, and excellent electrical conductivity—render them ideal for next-generation technologies (41, 58). Recycling waste batteries into functional NPs not only supports a circular economy but also reduces environmental pollution and promotes sustainable material recovery (17, 68).

In this review, various hydrometallurgical approaches—including acidic and alkaline dissolution—and pyrometallurgical approaches at high temperatures (~1550°C) have been employed to recover zinc (Zn) from spent batteries (41, 58). Thermal nanosizing techniques were applied to simultaneously synthesize ZnO NPs from waste Zn-C batteries, followed by comprehensive characterization using “photoluminescence (PL)”,“X-ray diffraction (XRD)”, “X-ray photoelectron spectroscopy (XPS)”, “Raman spectroscopy”, “Brunauer–Emmett–Teller (BET)” surface analysis,“scanning and transmission electron microscopy (SEM, TEM)", UV–Visible spectroscopy (13, 37). The synthesized ZnO NPshad found to be spherical, having an average size of ~50nm. Optical characterization revealed ultraviolet light absorption at ~388 nm and visible-range photoluminescence, highlighting their potential utility in optical and photocatalytic applications (54, 68).

2. Experiment

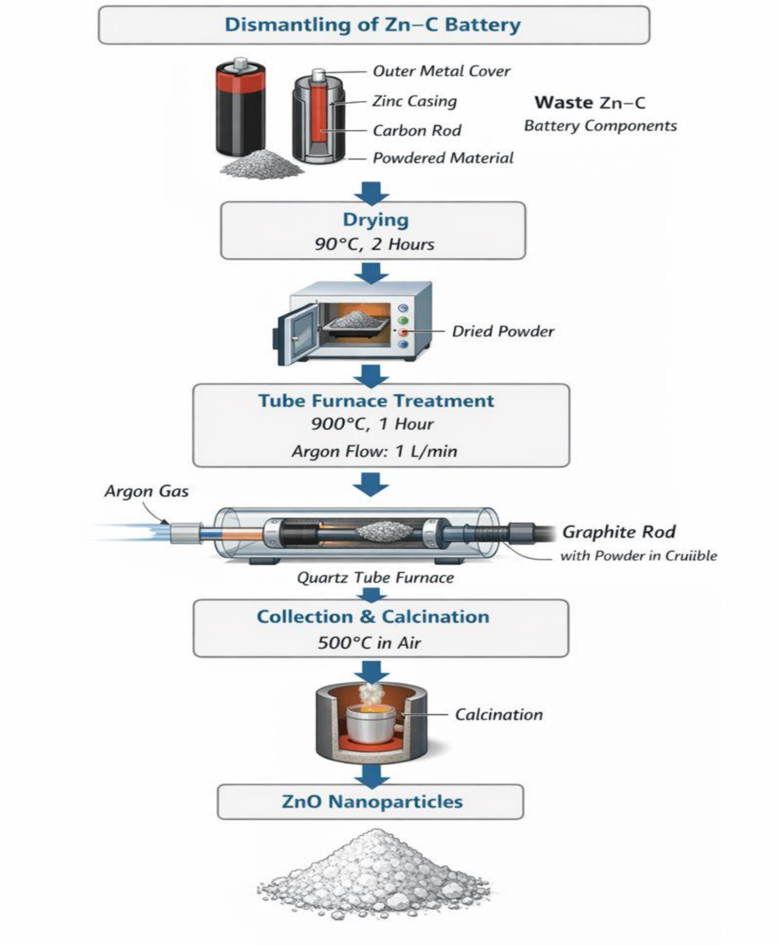
Waste Zn–C batteries were manually dismantled to separate their individual components, including external metal cover, metal caps, zinc casing, carbon rods, or the powdered electrode materials (17, 37).In commercial batteries, the powdered mixture, which has been packed between the carbon rod or zinc casing, serves as the positive electrode, while zinc casing functions as the negative electrode (41, 68). Zinc chloride now in battery acts as the electrolyte, facilitating ionic conduction during battery operation (58, 13). Effective recovery and valorization of metals and metal-oxide NPs from spent Zn–C batteries requires understanding their composition and arrangement.

The powdered electrode material—wetted with electrolyte and containing zinc and manganese compounds—was collected and used as the raw precursor for ZnO nanoparticle synthesis (54,41). The powdered material was first oven-dried at 90°C for 2hours to eliminatemoisture, ensure uniform thermal decomposition, which is a critical step for achieving controlled nanoparticle size and morphology during subsequent synthesis processes (13, 68). Proper drying and thermal pre-treatment of the electrode powders enhances the quality and crystallinity of ZnO NPs obtained from waste batteries.

A horizontal quartz tube furnace (length:1000mm, diameter:45mm) equipped with a controlled gas supply system and a graphite sample holder was employed for the thermal synthesis process (54, 13). High-purity argon gas has beenconstantly supplied to flow at rate of 1L/min to keep an inert atmosphere, which prevents unwanted oxidation and ensures uniform thermal decomposition during the heating of the electrode material (41,68). The utilization of an inert gas environment is critical in achieving high-purity ZnO NPs with controlled morphology and crystallinity from waste battery precursors.

Dried powder has beenemployed in a ceramic crucible, mounted on a graphite rod, and carefully inserted into the hot zone of the quartz tube furnace (54, 13). The furnace temperature was maintained at 900 °C for 1 hour, enabling thermal reduction and sublimation of zinc-containing compounds (41, 37). A greyish solid deposit formed near the gas outlet, which was collected as it contained zinc-rich vapors condensed during the process. This step is critical for manufacture of high-purity ZnO NPs with controlled morphology and crystallinity from waste Zn–C battery powders (68, 58).

To obtain phase-pure ZnO, the collected greyish powder was subjected to a post-calcination step at 500 °C in air (54, 37). This heat treatment effectively removed residual hydroxide and carbonate impurities and converted the thermally produced zinc compounds into crystalline ZnO NPs with improved structural and optical properties (13, 68)**.** Post-calcination is a critical step in achieving high-purity ZnO suitable for applications in catalysis, optics, and electronics (41, 58).



An overall flow diagram to synthesize ZnO from a spent Zn-C battery

Characterization

Using modern characterization methods, morphological, structural, chemical, optical characteristics of produced ZnO NPshave been systematically examined. A Cu Kα radiation source (λ=1.5406Å) operating at 45kV or 40mA has beenemployed for XRD, and diffraction patterns have been acquired in a 2θ range of 10°–100° (47, 60). The obtained XRD profiles were indexed and phase-identified using “X’Pert HighScore Plus software (version 4.7)”, consistent with standard procedures adopted in ZnO crystallographic studies (43). The surface chemical composition or oxidation states have been further examined utilizing XPS, ESCALAB 250Xi, Thermo Scientific, UK,under standard operating conditions with a 500 µm spot size, following well-established XPS analysis protocols for ZnO nanostructures (9, 6).

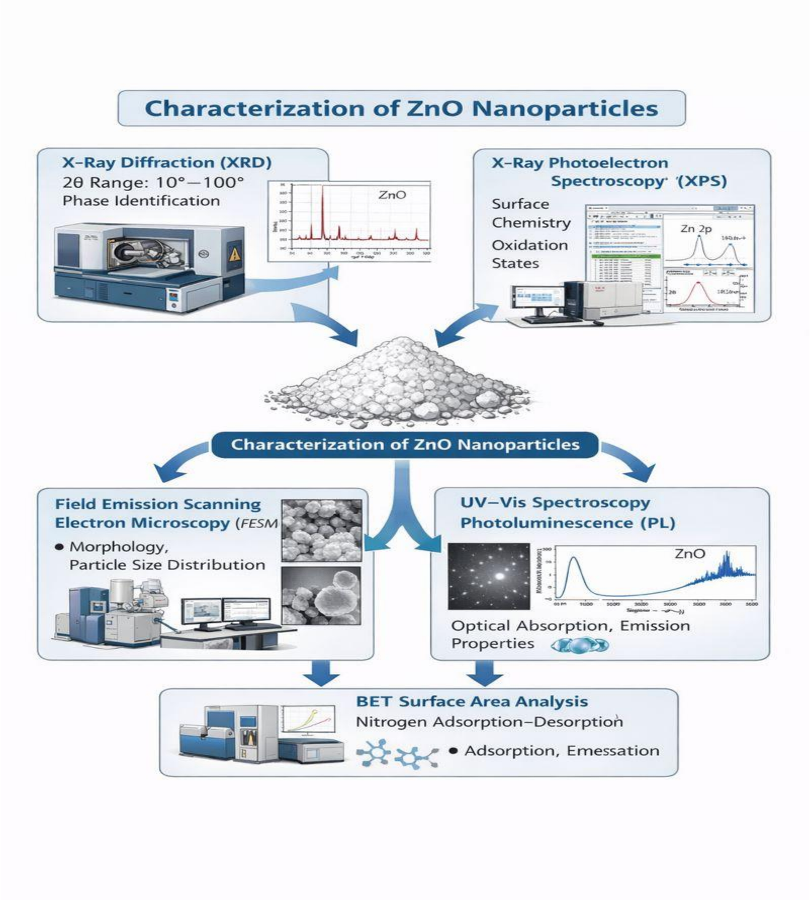
Table 1.

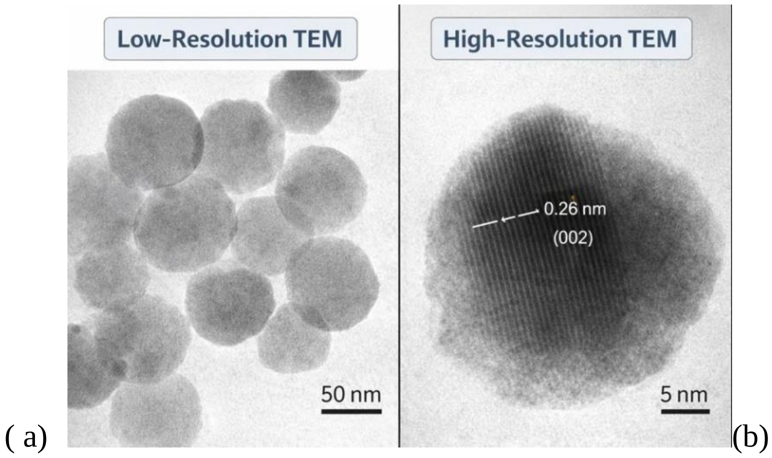
XPS results showing the elements with binding energy (BE) and atomic % of the synthesized ZnO nanoparticles:

Name	Start BE	Peak BE	End BE	FWMH eV	Atomic %	References
O1sA	534.79	530.36	526.69	1.4	26.53	Moulder et al.[1]
O1sB	534.79	531.56	526.69	1.4	13.63	Moulder et al.[1]
O1sC	534.79	532.68	526.69	1.39	3.61	Moulder et al.[1]
C1sA	294.99	284.80	281.39	1.49	6.84	Moulder et al.[1]
C1sB	294.99	286.47	281.39	1.49	2.12	Moulder et al.[1]
C1sC	294.99	287.80	281.39	1.49	0.62	Moulder et al.[1]
C1sD	294.99	289.30	281.39	1.49	1.58	Moulder et al.[1]
Zn2p3	1026.49	1021.87	1017.49	1.9	29.96	Moulder et al.[1]

“Field emission scanning electron microscopy (FESEM, FEI Nova NanoSEM450)”or“transmission electron microscopy (TEM, JEOL JEM-1400)”wasemployed to analyze morphological characteristics and particle size distribution of produced ZnO NPs.FESEM imaging was performed after sputter-coating the NPs with a thin platinum layer to enhance surface conductivity, following standard procedures for metal-oxide nanomaterials (56, 60). For TEM analysis, the NPshave been ultrasonically spread in ethanol, suspension was drop-cast onto holey C-coated Cu-grids; “selected area electron diffraction (SAED)” patterns have recorded to validate crystallinity and lattice structure, consistent with prior ZnO nanostructure research (He et al., 2015; Wu et al., 2017). Using N-adsorption–desorption analysis ,“Brunauer–Emmett–Teller (BET)” technique, which is often used to characterize ZnO nanopowders and porous oxide materials, the textural characteristics, including specific surface area, were assessed (43, 62).

UV-Vis spectroscopy had beenemployed to examine optical absorption characteristics of produced ZnO NPs. The NPs were ultrasonically dispersed in ethanol, and absorption spectra have been noted in a 1mm path-length quartz cuvette over the wavelength range of 600–200 nm, following standard protocols for ZnO nanomaterials(62, 61). As per the known PL characterization of ZnO NPs, photoluminescence (PL) measurements were conducted utilizing a Renishaw inVia Raman spectrometer fitted with a 15× objective lens and a 325 nm near-UV excitation source to examine defect-related emission behavior (14, 13). The PL spectra provide insights into oxygen vacancies, zinc interstitials, and other intrinsic defects commonly observed in thermally synthesized ZnO nanostructures (47).

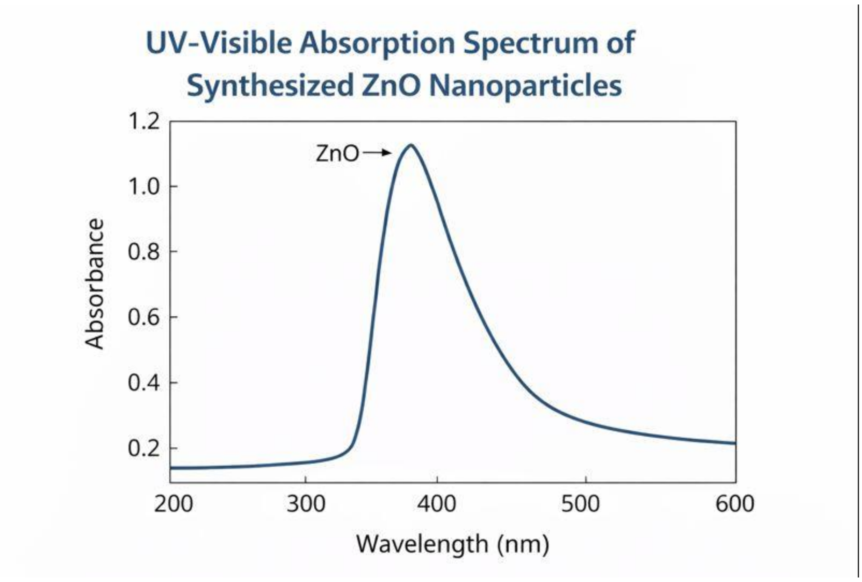




(a) Low (**b**) High resolution TEM images displaying the morphology of ZnO NPs.

Table 2. Structural parameters of synthesized ZnO nanoparticles calculated from XRD spectra :

Assigned Miller Indices (hkl)	**Calculated d Spacing (nm)**	**Observed d Spacing (nm)**	**Particle Size (nm)**	**References**
100	0.285	0.281	27.93	Farzana et al.[15]
002	0.262	0.260	28.12	Farzana et al.[15]
101	0.249	0.248	28.06	Farzana et al.[15]
110	0.163	0.162	26.43	Farzana et al.[15]



The excitonic absorption peak of ZnO NPshas been observed at ultraviolet region ~388 nm (3.2 eV).

3. Result &Conclusion

The currentresearch reports the successful synthesis and detailed categorization of ZnO NPs obtained from consumed Zn–C batteries using a thermal nanosizing approach. The as-synthesized ZnO NPs exhibited a predominantly spherical morphology with an average particle size below 50nm, as confirmed via TEM and FESEM analyses, consistent with earlier reports on thermally derived ZnO nanostructures (23, 56). Structural and compositional characterization through XRD, XPS, and SAED verified the formation of phase-pure, crystalline ZnO with well-defined lattice features, aligning with typical diffraction and surface chemistry characteristics of ZnO NPs (13, 68, 6). Optical studies revealed a strong UV absorption peak near 388 nm in the UV–Vis spectrum, while photoluminescence (PL) measurements showed visible emission associated with intrinsic defect centers namely oxygen vacancies or zinc interstitials, as widely reported in ZnO nanomaterials synthesized via thermal routes (14, 38, 47).

Overall, synthesized ZnO NPs exhibit strong potential for various optical and optoelectronic applications due to their tunable bandgap, defect-mediated photoluminescence, and high exciton binding energy, as widely documented in ZnO-based nanomaterials (47, 14). Importantly, utilization of waste Zn–C batteries as a precursor offers a cost-effective as well as environmentally sustainable route for nanoparticle synthesis, aligning with circular economy strategies and green recycling approaches that convert battery waste into high-value functional materials (13, 30). This valorization pathway not only decreases environmental burden relatedto hazardous waste accumulation but also provides a technologically viable method for recovering metal-rich resources for nanomaterial production (68, 58).

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