RP Current Trends In Engineering And Technology (e-ISSN: 2583-5491)
Vol. 5, No. 1 (January – March 2026) pp. 14–18

RESEARCH PLATEAU
PUBLISHERS

Cite this article: P.P. Poonia, T.N. Shaikh, From battery waste to smart textiles: Green synthesis of graphene and carbon nanoparticles for sustainable materials innovation, *RP Cur. Tr. Eng. Tech.* **5** (2026) 14–18.

Review Article

From battery waste to smart textiles: Green synthesis of graphene and carbon nanoparticles for sustainable materials innovation

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ARTICLE HISTORY
Received: 11 April 2026
Revised: 26 May 2026
Accepted: 27 May 2026
Published: 12 June 2026

KEYWORDS
Graphene nanoparticle;
Carbon nanoparticle;
Recycling; Sustainable;
Smart textile.

ABSTRACT

Green synthesis of graphene and carbon nanoparticles from used alkaline batteries is gaining attention as an eco-friendly recycling strategy. This review highlights environment friendly methods such as electrochemical exfoliation, ultrasonic dispersion, and hydrothermal treatments for converting hazardous battery waste into high-quality carbon and graphene nanomaterials, replacing the harsh chemical methods. Sustainable method practices minimize the chemical inputs, energy consumption, and emissions; life-cycle analysis indicates that these green processes yield significantly lower greenhouse gas emissions, water use, and waste generation than conventional routes. The resulting nanomaterials are integrated into smart textiles to impart multifunctional properties such as conductive fabrics for wearable electronics, antimicrobial, UV-protective coatings, EMI shielding and energy storage capabilities. This approach supports waste reduction and circular economy goals by recycling battery waste into high-performance materials, driving green innovation in advanced functional textiles.

1. Introduction

Alkaline batteries are widely used in low- to moderate-drain household electronic devices such as remote controls, wall clocks, flashlights, toys, and portable radios [1]. They are also commonly used in everyday gadgets like wireless mice, keyboards, and small medical devices due to their long shelf life and stable performance. Alkaline batteries release hazardous products when they are damaged, corroded, or improperly disposed of in landfills or open environments [2]. Used batteries contain toxic heavy metal (Pb, Cd, Co, Ni, Mn, Cu) and organic electrolytes ($LiPF_6$, $LiClO_4$, etc) that leach into soil and water. During degradation, the battery casing breaks down and releases alkaline electrolyte such as potassium hydroxide along with metals like zinc and manganese, which can contaminate soil, ground water, harm plants and poison aquatic organism by disrupting normal biological functions [3]. In human, exposure to toxic products from used batteries particularly heavy metals like manganese and zinc and alkaline electrolytes such as potassium hydroxide can lead to several health disorders. Prolonged exposure to manganese may cause neurological conditions similar to Parkinson's disease, including tremors, memory loss, and impaired motor function (a condition known as manganism). Contact with potassium hydroxide can result in severe skin burns, eye damage, and respiratory issues such as bronchitis or lung irritation [4]. Ingestion or chronic exposure to excess zinc may lead to gastrointestinal disorders like nausea, vomiting, and abdominal pain, as well as disruption of metabolic and immune functions [4]. Additionally, long-term exposure to contaminated water or soil can increase the risk of organ damage and overall toxicity in the human body.

2. Materials and methods – Green extraction protocols

2.1 Battery pretreatment

Recycling batteries turns waste into a resource stream, conserving critical materials and lowering environmental burdens [5]. By recovering cobalt, lithium, nickel, zinc, and more, recycling reduces the need for virgin mining and the associated energy use and emissions [6]. A life-cycle analysis found that battery recycling can cut resource use and environmental impact by roughly 5–30% compared to non-recycled cases [7]. Economic analyses suggest battery recycling can generate multi-billion-dollar value chains in coming decades [8]. However, recycling itself consumes energy and may generate waste streams (e.g. acid effluents) so the net benefit depends on process efficiency. Overall, abundant evidence indicates battery recycling is a key pillar of environmental sustainability and a more circular battery economy [9]. Meanwhile, graphene and carbon nanomaterials are highly valued for their exceptional electrical, thermal and mechanical properties, with applications in energy, sensing and textiles. Converting battery "waste" carbon (graphite rods, electrode powder) into graphene or carbon nanoparticles (CNPs) embodies circular-economy principles [10].

In all cases, spent cells are first safely discharged to remove residual charge. The cells are then dismantled manually or mechanically. For Zn–C primary (dry-cell) batteries, the steel casing is opened and the carbon rod (graphite electrode) is removed [10]. For Li-ion cells, plastic casings are cut away, and cathode/anode foils delaminated. Anode "black mass" (graphite powder, binder, Cu foil) may be separated from cathode [11]. Common pretreatments include sieving or grinding the black mass into fine particles. One study calcined the LIB black mass at 700 °C for 4 h (air) to burn off polymer binders and organics [12]. After grinding or calcination, inert solvents (water, ethanol) are often used to wash away metal salts ($LiPF_6$, $ZnCl_2$) and residual electrolytes. The cleaned graphite/carbon is then dried [12].

2.2 Electrochemical exfoliation

Electrochemical methods have emerged as a green route to graphene. In these, battery-derived graphite rods or powders serve as electrodes in mild electrolytes. Thanh *et al*. recovered Zn–C graphite rods and used them as the anode (with inert cathode) in Na_2SO_4 electrolyte [10]. No strong acids are used, making this safer than Hummers'. Similarly, Suryaprabha *et al*. set up the graphite rod from spent Zn–C battery as both anode and cathode for anodic exfoliation in dilute acid (e.g. 0.25 M H_2SO_4) [11].

The exfoliated material (graphene flakes) was collected from the solution. Advantages of electrochemical routes include ambient temperature, water-based electrolytes (Na_2SO_4 or weak H_2SO_4), and avoidance of $KMnO_4$ [10].

2.3 Chemical Oxidation (Hummers-type)

The classic "Hummers" method ($KMnO_4/H_2SO_4$) can be applied to battery carbons, though it uses hazardous reagents. Suryaprabha and Park mixed 3 g graphite (from Zn–C rods) with $NaNO_3$ and 95% H_2SO_4, stirred <50 °C, then slowly added 9 g $KMnO_4$ [12]. After stirring at 20–85 °C for ~1 h and quenching with water and H_2O_2, the mixture was centrifuged and washed (HCl, water) to yield GO [12]. Similarly, Rawat *et al*. processed recovered LIB graphite via modified Hummers: after oxidation they reduced GO with ascorbic acid (a benign reductant) to produce reduced graphene oxide (rGO) [13]. Despite strong chemicals, these methods are widely used due to simplicity.

2.4 Thermal and hybrid methods

Pyrolysis or calcination of battery carbon is another route. For example, Akshay *et al.* (injected example context) annealed spent Li-ion anode powder under inert gas to produce amorphous carbon nanoparticles [13]. In the Rawat *et al*. study, calcination (700 °C, 4 h) of mixed cathode/anode powder removed binders before subsequent leaching [14]. In Zn–C recycling, Belardi *et al.* reported calcining spent dry-cell powder to recover MnO_2 and carbon residues. Such thermal methods yield largely amorphous or partially graphitic carbons [15]. In some hybrid routes, thermal activation is coupled with mild chemical treatment (e.g. digesting ash in acetic acid to liberate carbon). pyrolysis avoids liquid reagents but consumes energy; moderate conditions (500–700 °C) and inert atmospheres minimize combustion of carbon [16].

2.5 Biological methods

There are few reports of purely biological extraction from battery waste. In principle, one could use plant extracts (Polyphenols) or microbes to reduce graphite oxide to graphene [17]. However, battery-derived graphite may contain toxic metals inhibiting biotreatment. No primary studies were found using enzymes or biomass to directly convert battery carbon. Ultrasonic or microwave-assisted exfoliation (in water or ethanol) is another area, but again lacking specific reports for battery feedstock. Where specifics are lacking, protocols default to conventional chemical or electrochemical methods [18].

3. Characterization and nanoparticle properties

After extraction, battery-derived nanocarbons are extensively characterized.

Morphology: TEM and SEM reveal shapes: graphene appears as thin layered flakes (few nanometers thick, micrometers wide) while carbon nanoparticles appear as irregular or roughly spherical particles (~5–100 nm) [14].

Crystallinity: XRD identifies graphitic structure: typical GO/rGO shows a (002) graphite peak near 26.5°, whereas GO shows a new (001) peak ~11–12° (layer spacing ~0.8 nm) [12]. For example, after oxidation of battery graphite, Suryaprabha and Park found the 002-graphite peak disappeared and a GO (001) peak at 11.6° emerged.

Raman: Characteristic G-band ($\approx 1580\ cm^{-1}$) and disorder D-band ($\approx 1350\ cm^{-1}$) are used. Fresh graphite has low D/G intensity; oxidation increases the D peak. Many studies report D/G ratios: battery-GO materials often have D/G ~0.5–1.0, indicating defects and small domain size, while more crystalline graphene have D/G ~0.1–0.5 [19].

Surface chemistry: FTIR and XPS detect oxygen-containing groups on GO (–OH, –COOH, epoxy). XPS C1s spectra show C–C (sp^2) vs C–O and C=O peaks, confirming partial oxidation. Ascorbic reduction typically lowers the C–O signal [10].

Surface area: BET analysis usually gives hundreds m^2/g. For example, Nazari *et al.* reported battery-derived graphene with higher specific surface area than commercial graphite. Graphene materials can exceed 300–500 m^2/g, while carbon nanoparticles from pyrolysis might have < 200 m^2/g [20].

Thermal stability: TGA shows weight loss from labile oxygen groups; GO loses ~20–30% mass by 200–400 °C, whereas rGO/CNPs are more stable [21]. Aleksandrzak *et al.*, data confirm that "green" processed materials from batteries exhibit similar structures to conventional GO/rGO, albeit with some residual heteroatoms (from electrolytes or sludge).

In summary, battery-derived graphene is essentially few-layer graphene or rGO with high surface area and relatively low defect densities (D/G ~0.1–0.3 in many reports) [10]. Typical thickness is a few layers (~1–5 nm) and lateral size can be microns depending on exfoliation. Carbon nanoparticles from thermal routes are mostly amorphous with sp^2/sp^3 mix, lower graphitic order, D/G ~0.5–1 [19]. Functional groups (–OH, –COOH) are present on all, enabling dispersion and grafting.

Fig. 1 shows the schematic flowchart illustrating the sustainable conversion of discarded battery cells into graphene-based carbon materials and their integration into functional smart textiles through green processing routes [22].

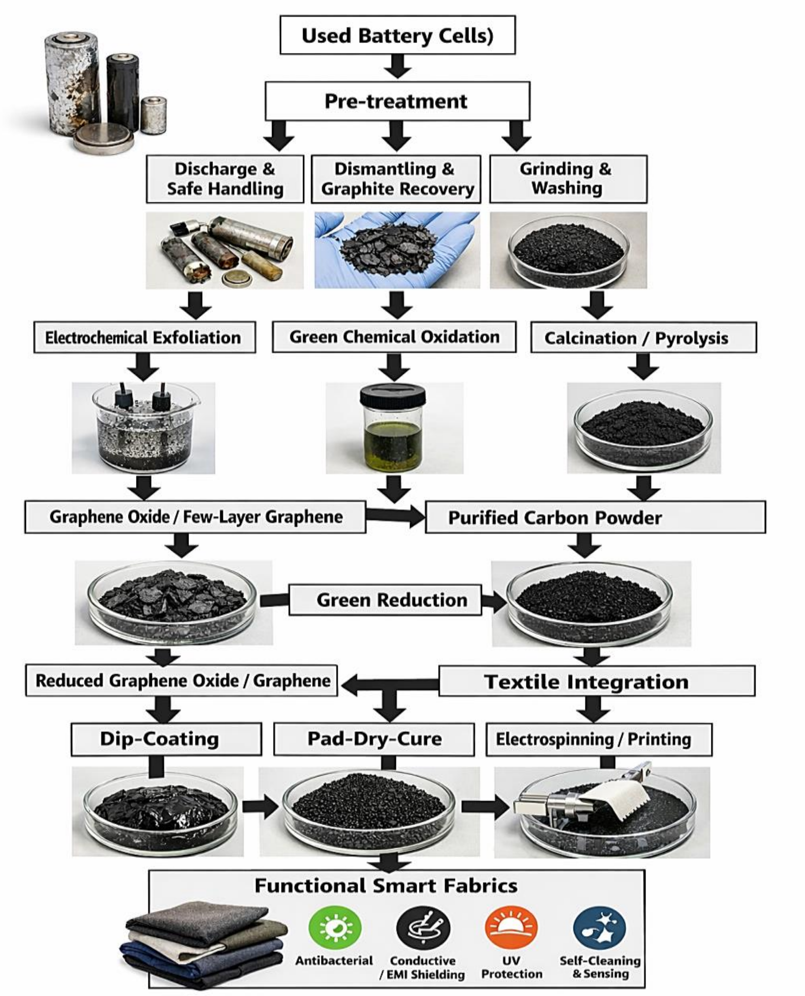

Figure 1: Schematic flowchart illustrating green recycling of used battery cells into graphene/carbon nanomaterials for smart textile applications.

4. Textile applications

The application of carbon nanoparticles (CNPs) and graphene-based nanomaterials onto textile substrates is primarily achieved through surface functionalization and bulk incorporation techniques designed to ensure durability, uniform dispersion, and strong fibre–nanomaterial interaction [23]. Among the most widely adopted approaches, dip-coating and pad–dry–cure finishing enable scalable deposition of aqueous nanoparticle dispersions onto cotton, polyester, and blended fabrics, where electrostatic attraction, hydrogen bonding, and van der Waals interactions promote adhesion to fibre surfaces [24]. In situ reduction of graphene oxide directly on textiles using green reducing agents such as ascorbic acid further enhances coating stability by forming reduced graphene oxide networks anchored to the fibre matrix [25]. Alternatively, electrospinning and melt blending allow incorporation of carbon nanomaterials within polymeric fibres, producing conductive and mechanically reinforced composite filaments [26]. Layer-by-layer assembly and screen printing have also emerged as precise strategies for constructing multifunctional coatings with controlled thickness and patternability [27]. These processing routes collectively enable the fabrication of smart textiles exhibiting durable electrical conductivity, antimicrobial activity, UV shielding, thermal regulation, and sensing capability, while maintaining breathability and mechanical flexibility essential for wearable applications [27].

Conductivity and electronic textiles

Coated textiles become electrically conductive. Reported sheet resistances vary widely depending on loading. For example, GF/PPy/Ag-coated cotton achieved ~7.2 Ω/sq (very conductive), whereas RGO–Cu/cotton was ~6.4 kΩ/sq (higher by 10^3) [19]. Increased graphene loading (by multiple dips) systematically lowers resistance. These conductive fabrics can serve as electrodes and sensors [11]. Suryaprabha *et al.* built a Zn-ion hybrid supercapacitor using a GO-Ag/cotton electrode and Zn foil from batteries; it delivered 140 F/g at 0.5 A/g and retained energy storage under flexing. Graphene textiles also exhibit electroluminescence and can power wearable LEDs.

Electromagnetic interference (EMI) shielding

Several studies report high shielding efficiency from graphene-coated fabrics. In Suryaprabha and Park's cotton-GO-Ag samples, an EMI SE up to ~79 dB (at ~5% GO loading) was measured in the 8.2–12.4 GHz band [12]. Even without metals, GO/cotton showed tens of dB shielding. The high conductivity and multiple reflections in the fabric contribute. Such values far exceed the 20–30 dB needed for commercial shielding, suggesting battery-graphene fabrics are promising for protective garments [28].

Thermal/Joule heating

The coatings enable rapid heating under voltage. The GO-Ag cotton reached 117.8 °C within 35 s at 5% GO loading. Graphene's high thermal conductivity and the fabric's resistive losses yield efficient conversion to heat. This property is exploited for de-icing garments or self-heating textiles [12].

Antibacterial activity

Graphene materials inherently show some antibacterial effect (physical disruption of membranes, oxidative stress). Battery-graphene fabrics have been demonstrated to kill pathogens. For instance, kumar *et al* reported that a GF/PPy/Ag-coated cotton fabric exhibited ~27 mm wide inhibition zones against both *E. coli* and *S. aureus*. The synergy of Ag nanoparticles and graphene's sharp edges likely contributes. In general, graphene/GO alone gives moderate activity (especially under light), and metal-decorated versions are highly potent [29].

UV protection

Graphene and GO absorb UV light strongly. Durability studies show significant improvements in UV blocking. Bhattacharjee *et al*. reported a GO–Cu/cotton fabric with UPF ~46.5, a major gain over bare cotton. This is due to UV absorption by the dense sp^2 network. Typical measured UPFs in graphene fabrics range from 10–80 depending on loading and thickness [19].

Mechanical reinforcement and hydrophobicity

Graphene coatings also affect fabric mechanics. Many authors note a modest increase in tensile strength and stiffness due to graphene's rigidity and strong interfacial bonding. Hydrophobicity is enhanced; the RGO–Cu fabric exhibited higher water contact angles and repelled stains better than untreated cotton [30].

Dye adsorption/filtration

Some battery-graphene materials have been tested as adsorbents. Qiao *et al*. used GO from spent batteries to adsorb Pb^{2+} from water. GO can quickly and effectively adsorb methylene blue, which also exhibits thermal stability. The maximum adsorption capacity and removal rate are about 833.11 mg/g and 99.95%, respectively [31].

Durability and washability

A critical metric for wearable textiles is resistance to washing. Coupling strategies improve this: Bhattacharjee's GO–Cu cotton retained a sheet resistance of ~16.7 kΩ/sq after 20 industrial wash cycles (versus 6.4 kΩ/sq fresh). Similarly, GO-coated fabrics often show <50% increase in resistance after 5–10 home-wash cycles. The loss is attributed to mechanical stress and partial removal of coating, but moderate binding (via silanes or polymers) helps. Overall, most studies report "excellent" washing durability, though systematic quantification remains sparse [19].

Safety/toxicity considerations

While these applications are promising, environmental and health impacts must be addressed. Graphene and GO are generally considered biocompatible at low doses, but sharp edges and reactive groups can harm cells in high concentrations [32]. Metallic residues (from batteries or added Ag/Cu) are known antimicrobials but toxic to aquatic life. No long-term leaching studies have been reported for these textiles. LCA insights (e.g.) suggest by Lin *et al.* when compared to virgin graphene production, battery upcycling reduces greenhouse and acidification footprints. However, formal safety assessments (ecotoxicity of wash-off effluent, chronic exposure of wearers) are needed.

5. Summary

Spent battery cells, notably Zn–C and Li-ion, are viable carbon sources for graphene and carbon nanoparticle production via greener methods. Electrochemical exfoliation in neutral salts and thermal-biological hybrid routes complement traditional chemical oxidation. The resulting nanomaterials possess desirable properties (high surface area, conductivity, tunable functionality) suitable for textile enhancements. Coated fabrics demonstrate multi-functional performance: electrical conduction, EMI shielding, thermal management and biocidal activity. Most studies use Hummers or energy-intensive steps; truly *green* processes (plant extracts, UV oxidation, sub-ambient exfoliation) are under-explored. Environmental impact of residual battery metals in nanomaterials needs study. Future work should standardize durability tests and quantify wash-off of nanomaterials. In summary, the "waste-to-wearables" concept has demonstrated technical promise, but robust, scalable green processes and comprehensive life-cycle analyses are needed. Integrating battery-recovered carbon into textiles can advance circular economy goals, yet optimization of synthesis, performance, and safety will require further interdisciplinary research.

Authors' contributions

All authors contributed equally to the conception, design, experimental work, data analysis, interpretation of results, and preparation of the manuscript. All authors reviewed and approved the final version of the manuscript for publication.

Conflicts of interest

The author declares no conflict of interest.

Funding

This research received no external funding.

Data availability

No new data were created.

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