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India’s Battery Recycling Infrastructure Gap: A Critical Review for a Circular Economy

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Abstract: India's burgeoning electric vehicle (EV), solar power, and energy storage sectors are accelerating demand for lithium-ion batteries (LIBs), with cumulative critical mineral requirements projected to exceed 250 kilotons between 2024 and 2030. However, formal recycling remains limited—under 5%—while nearly 90% of end-of-life batteries are processed informally through hazardous methods. This review examines India’s current battery waste management ecosystem, identifying enforcement lapses in Extended Producer Responsibility (EPR), infrastructural voids, and the marginalization of informal actors.

It benchmarks India’s challenges against regulatory and industrial models in China, the European Union, and the United States, assessing reverse logistics, policy mandates, and system scalability. Drawing from secondary research and firsthand insights from a battery manufacturing internship, the study outlines the economic opportunity of a $3.5 billion recycling market and the cost advantage of recovered materials—up to 40% savings. It further explores environmental risks and proposes strategic interventions including formal–informal integration, digital tracking mechanisms, and return-based incentives. Advancing LIB recycling is not only critical for sustainability but central to India's resource independence and circular economy aspirations.

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Keywords: *Lithium-Ion, Battery Recycling, India, NMC, LFP, Circular Economy, EPR, E-Waste.*

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I. INTRODUCTION

India is rapidly progressing in its clean energy transition, marked by growth in electric vehicles (EVs), solar power, and Battery Energy Storage Systems (BESS). The numbers are absolutely staggering when you look at the scale of transformation happening. The government targets 500 GW of non-fossil power by 2030 and net-zero emissions by 2070. EV adoption—aiming for 30% penetration in private cars and up to 80% in two and three-wheelers—is driving lithium-ion battery (LIB) demand. During my internship at Waaree Energies, I saw firsthand how LIBs are used in EVs and BESS, where Battery Management Systems (BMS), Energy Management Systems (EMS), thermal management systems, and grid manage storage and distribution of renewable energy. Working there gave me a unique perspective on just how crucial these systems are becoming for India's energy future.

However, this rapid growth is generating massive end-of-life (EoL) battery waste, while India's recycling systems remain largely undeveloped. Only 1% to 5% of end-of-life lithium-ion batteries in India are formally recycled, with the majority handled by the informal sector, posing environmental and safety risks [1]. India's heavy reliance on imports for critical battery materials like lithium and cobalt adds economic vulnerability, with over $5 billion in import exposure projected through 2030.

Effective battery recycling is not just an environmental need—it's a strategic necessity for India's energy goals, resource security, and global leadership in sustainability. This review analyses India's recycling infrastructure, challenges, global case studies, and offers practical recommendations, enriched by insights from my internship experience.

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II. APPROACH

This paper combines in-depth secondary research with experiential learning gained through a hands-on internship at Waaree Energies, a leading battery manufacturer in India. To understand the current state of lithium-ion battery (LIB) recycling, I reviewed government reports, industry white papers, academic publications, and regulatory documents from India and other countries. This helped frame a broad understanding of the technical, economic, and policy dimensions of battery recycling.

Alongside this, I undertook an internship where I closely observed the manufacturing and testing of batteries—particularly NMC and LFP chemistries. I gained exposure to battery management systems (BMS), quality testing procedures, and safety protocols related to handling and assembly. I also witnessed how companies manage end-of-life battery components and the practical challenges they face in terms of logistics, traceability, and material recovery.

By blending academic research with firsthand industry insights, this review offers a grounded perspective on the gaps and opportunities in India’s recycling ecosystem, especially in the context of the country’s clean energy goals.

III. LITERATURE REVIEW

India's lithium-ion battery market is poised for explosive growth, directly translating to a significant increase in end-of-life battery waste. While the initial query suggested a projection of 800 GWh by 2030, other comprehensive reports provide varying but still substantial figures. For instance, a joint report by the India Cellular and Electronics Association (ICEA) and Accenture projects total LIB demand to reach 115 GWh by 2030, with electric vehicle-linked usage expected to grow at a compound annual growth rate (CAGR) of 48% [2]. Other estimates range from 60-65 GWh by ICRA [3] to 132 GWh [4] or 128 GWh by NITI Aayog [5] by the same year. The Central Electricity Authority (CEA) further projects a requirement of approximately 28 GW/108 GWh of Battery Energy Storage System (BESS) capacity by 2030 [6]. This variability in projections, while not undermining the overall trend of massive growth, highlights the inherent uncertainty in forecasting a rapidly evolving market. It suggests that any policy or infrastructure development must be flexible and scalable to accommodate different growth scenarios, ensuring adaptability to consistently high future waste volumes.

In India, the prevailing methods of battery disposal reveal a stark divide between informal and formal recycling practices, with serious environmental implications. India's battery disposal system is mostly informal and unregulated. Only 1-5% of end-of-life LIBs are formally recycled, while up to 90% are handled by informal collectors using unsafe methods like acid leaching [1], [8], [9]. This causes toxic pollution, harming both the environment and public health.

The informal sector dominates because it solves immediate problems for consumers -- when your phone battery dies, they'll pay you cash and handle all the logistics. The informal sector dominates due to its cost-effectiveness and reach but is also fuelled by low consumer awareness and high GST on formal recycling. While it fills a crucial gap, it also hinders safe recycling and material recovery. A sustainable fix isn't to eliminate it, but to formalize and integrate this network to improve safety while maintaining its reach.

A. Emerging Alternatives to Lithium-Ion Batteries

➢ *Next-Generation Battery Technologies*

➢ *Calcium-Ion Batteries*

These batteries use calcium's unique ability to transfer twice the charge per ion compared to lithium. They could potentially reach energy densities of 2,500 Wh/kg—far higher than today's lithium-ion systems [27]. The main challenge is finding the right electrolytes to work with calcium's larger ionic size [28].

➢ *Potassium-Ion Batteries*

With potassium being much more abundant and cheaper than lithium, these batteries show real promise for large-scale energy storage. They can potentially deliver higher voltage and energy density than current systems [28]. Researchers are now working on making the electrodes and safety systems more reliable [27].

➢ *Organic Flow Batteries*

Instead of using metals, these batteries use organic molecules dissolved in water-based solutions. While their energy density is lower (20-40 Wh/kg), they can cycle almost indefinitely without losing capacity [28]. Their modular design means you can scale up power and energy independently perfect for grid storage [27].

➢ *Advanced Lithium-Sulphur Batteries*

New designs have solved the old problem of rapid degradation. Modern versions can reach 500-600 Wh/kg—nearly double conventional lithium-ion systems [27]. Recent polymer coating breakthroughs have pushed cycle life beyond 1,000 cycles [28].

➢ *Zinc-Air Batteries*

These use oxygen from the air as part of the reaction, achieving remarkable theoretical energy densities of 1,350 Wh/kg. Since they use ambient air, they're much lighter and cheaper [27]. The main challenges are preventing water evaporation and blocking carbon dioxide, which researchers are tackling with better membranes [28].

While these options are promising, most are still pre-commercial and would need parallel development in infrastructure, regulation, and recycling systems to become viable replacements.

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B. Recycling Processes Used

Recycling of lithium-ion batteries (LIBs) primarily relies on three approaches: pyrometallurgy, hydrometallurgy, and direct recycling**.** Pyrometallurgy, or smelting, involves high-temperature treatment to recover metals such as cobalt, nickel, and copper, but it is energy-intensive and often results in lithium and aluminium losses and requires extensive safety infrastructure due to high-temperature operations [29]. Hydrometallurgy**,** which uses acid leaching and solvent extraction, is more selective and efficient, enabling recovery rates above 90% for key materials. However, when carried out informally with rudimentary acid leaching—as is common in India—it poses serious environmental and health risks due to toxic effluents that contaminate soil and groundwater while endangering worker health [30]. Direct recycling is an emerging method that preserves cathode structures for reuse, offering 40-60% energy savings by avoiding re-synthesis of cathode materials compared to conventional processes [31]. While still in early development, direct recycling could prove crucial in India's context, where economic viability and safe recovery are both pressing challenges. Integrating advanced hydrometallurgical methods with innovations in direct recycling would significantly enhance India's ability to bridge its recycling infrastructure gap [29], [30].

C. Challenges in Recycling Infrastructure

India's ambition to lead in clean energy is significantly hampered by substantial gaps in its battery recycling infrastructure, affecting collection, processing, and policy enforcement.

➤ *Low Collection Rates*

Despite the introduction of the Battery Waste Management Rules (BWMR) in 2022, collection rates for end-of-life batteries remain critically low. During my internship, I saw firsthand how complex proper battery handling is -- and most collection points don't have this capability. For instance, approximately 39% of consumer electronics batteries are not collected. A major hurdle is the lack of a well-defined infrastructure and reverse logistics mechanism for safe and formal collection [10]. This issue is particularly acute in rural and semi-urban regions, where designated collection centres or drop-off points are scarce, severely limiting consumer participation and making collection targets unrealistic [11].

➤ *Informal/Unregulated Recyclers*

As previously highlighted, the informal sector handles a vast majority of battery waste, accounting for nearly 90% of India's battery waste. The problem isn't that these informal workers are lazy or careless -- they're incredibly resourceful and entrepreneurial. While efficient in collection due to its widespread reach and cost-effectiveness, its practices are largely unscientific and unsafe. These include rudimentary methods like acid leaching that release toxic pollutants, contaminate soil and groundwater, and compromise worker safety [4]. The exclusion of these informal workers from the formal system leads to missed opportunities for material recovery and exacerbates environmental degradation [11]. This situation creates a paradox: the informal sector fills a critical collection gap but creates severe downstream problems.

➤ *Policy Enforcement Gaps*

India's 2022 Battery Waste Management Rules introduced Extended Producer Responsibility (EPR), but enforcement remains weak. The policy does not distinguish between large and small producers, making compliance uneven. Monitoring is minimal, with reliance on self-reporting and a non-functional audit system. Informal recyclers, despite playing a dominant role in collection, remain excluded, leading to unsafe practices. Consumer awareness is low, and there are no incentives for returning used batteries. Recyclers also lack technical guidance, and the absence of a recycled content mandate reduces the economic appeal of formal recycling. During my internship at Waaree Energies, I observed how effective EPR systems require robust supply chain tracking mechanisms—such as a "Battery Aadhar"—which are currently missing in India [12].

Table 1: Key Policy Gaps in India's Battery Waste Management Rules (BWMR 2022) [11]

Policy Gap	Description/Consequence
No Differentiation Among Producer Categories	Treats all producers, similarly, burdening small businesses and creating loopholes for large corporations.
Limited Monitoring and Weak Enforcement	Relies on self-declared figures with rare inspections; minimal follow-up on non-compliance; EPR audit module inoperable.
Infrastructure Gaps in Reverse Logistics	Inadequate collection centres, especially in rural areas, limiting consumer participation and making collection targets unrealistic.
No Formal Inclusion of Informal Recyclers	Excludes a significant workforce, perpetuating unsafe practices and wasting potential for efficient material recovery.

Low Consumer Awareness and Zero Incentives	Most consumers are unaware of proper disposal methods; no rewards for returning batteries, leading to improper disposal.
Inadequate Guidance on Recycling Technology	Lack of clear benchmarks for handling various battery types can lead to substandard or hazardous recycling techniques.[16]
Absence of Recycled Content Mandates	No requirement for using recycled materials in new batteries, weakening demand for secondary raw materials and making formal recycling less viable.[16]

D. Small players in Indian Recycling Landscape

An important component of India's battery recycling ecosystem is the growing presence of small and mid-sized players, whose contributions, technologies, and scalability challenges provide insight into the broader industry's current limitations and opportunities. Despite these systemic challenges, I'm genuinely optimistic about some impressive Indian companies that are making real progress. A few formal Indian recyclers are emerging and developing advanced capabilities. Companies like Attero Recycling, BatX Energies, and Lohum are pioneering efforts in this nascent industry [4].

Attero Recycling, one of India's leading e-waste and lithium-ion battery recyclers, is both R2-certified and affiliated with the Central Pollution Control Board (CPCB). It employs globally patented technology with a reported recycling efficiency of over 98%, capable of recovering critical raw materials like lithium, cobalt, and nickel [13]. In FY2025, the company processed more than 15,000 tons of lithium-ion batteries and has ambitious plans to scale this to 50,000 tons. To support this growth, Attero is investing INR 100 crore to expand its rare earth element (REE) recycling infrastructure to a capacity of 30,000 tons [14].

BatX Energies spearheads an innovative, eco-conscious approach to LIB recycling, promoting sustainability and resource efficiency. Their proprietary "Net Zero Waste, Zero Emissions" process extracts high-quality materials like lithium, cobalt, nickel, and manganese from used LIBs, including manufacturing rejects, with a focus on supporting India's EV sector and reducing import dependence. They aim for a 90% recovery rate by 2027 [15].

PolyProtic is also involved in developing processing and specific chemicals for rechargeable batteries and reclaiming metals from e-waste and batteries, indicating a focus on technological solutions for recycling [16].

While these players exist and demonstrate India's technological capability for advanced LIB recycling, they currently operate at limited capacity. The primary challenge is not a complete lack of know-how, but rather the inability to scale these operations due to high capital costs, limited policy support, and insufficient collection mechanisms [4]. India's current formal recycling capacity is estimated at around 60,000 tonnes annually, with only 50% of this converted into 'black mass' for mineral extraction [17]. This points to a disconnect between innovation at the individual company level and systemic infrastructure support.

E. International Regulatory Approaches

➢ *Comparative Study – Other Countries*

Examining international approaches to battery recycling offers valuable lessons for India, highlighting diverse strategies and their effectiveness.

- *China's Take-Back Rules*

China has demonstrated a long-standing commitment to EV battery recycling, implementing policies and standards for over a decade [18]. The nation has introduced an action plan to promote EV battery recycling and established over 10 national standards by the end of 2024 [18]. Significant progress includes the presence of approximately 150 qualified recycling companies and over 10,000 recycling service outlets, indicating a widespread collection and processing network [18].

Recent proposals include stricter recovery rate requirements, such as 90% for lithium and 98% for nickel, cobalt, manganese, copper, aluminum, and rare earth metals [19]. Environmental standards are also being tightened, with caps on energy consumption for lithium carbonate production, high fluorine emission recovery rates, and stringent wastewater recycling requirements [19]. China employs a "whitelist" system for approved recyclers, aiming to consolidate the industry and constrict the unregulated market [19]. Despite these robust efforts, challenges persist, including insufficient regulation and illicit processing by unqualified companies, which can still lead to environmental pollution and safety hazards [18].

- *EU's EPR Frameworks*

The European Union has probably the most sophisticated approach to battery recycling anywhere in the world. It has established a comprehensive and binding legal framework through Regulation (EU) 2023/1542, which entered into force in August 2023, governing the entire lifecycle of batteries across all member states [20]. This framework mandates Extended Producer Responsibility (EPR), requiring manufacturers, importers, and sellers to manage the environmental impact of their products, including collection, recycling, and safe disposal [20].

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Key EPR obligations, enforceable from August 2025, include producer registration, financial responsibility for waste battery collection, treatment, and recycling, and stringent labeling requirements. These labels must feature a cross-out wheeled bin symbol, an indication of battery chemistry, and a QR code for digital product information, enhancing transparency for consumers and recyclers [20]. The regulation also mandates carbon footprint disclosure for EV, industrial, and Light Means of Transport (LMT) batteries from 2025, and sets minimum recycled content targets from 2031 (e.g., 16% cobalt, 6% lithium and nickel) [20]. A significant innovation is the mandatory digital battery passport from 2027 for EV, industrial, and LMT batteries, providing performance, composition, and sourcing information accessible via QR code [20]. Furthermore, portable batteries must be designed for easy replacement by end-users from 2027, and restrictions on the export of hazardous battery waste to non-OECD countries will apply from March 2025 [20].

- *US Private Sector Models (e.g., Redwood Materials)*

The United States showcases a strong private sector-driven approach to battery recycling, with companies like Redwood Materials leading the way in establishing a closed-loop supply chain for electric vehicles and clean energy products [21]. Redwood Materials focuses on recycling lithium-ion batteries and producing battery materials, such as anode copper foil and cathode active materials, for new battery manufacturing [21].

The company boasts high material recovery rates, often exceeding 95% for critical metals like nickel, cobalt, lithium, and copper, utilizing innovative hydrometallurgical refinement processes. What's impressive is how they've created partnerships with major industry players—Redwood Materials has forged partnerships with Panasonic, Ford Motor Company, and Amazon, and has launched used battery collection programs, demonstrating a collaborative approach to reverse logistics [21]. Significant private investments and expansion plans are underway, including the development of production facilities with ambitious capacity targets of 100 GWh by 2025 and 500 GWh by 2030 [21]. Notably, Redwood also focuses on repurposing used battery packs into modular energy storage systems, maximizing value before the final recycling stage [21].

IV. KEY LESSONS FOR INDIA

Comparative analysis shows a clear global shift toward stricter, more integrated battery recycling policies—from China's early take-back rules to the EU's legally binding lifecycle approach. Success in these regions stems not just from regulation, but from promoting private-sector innovation alongside it, where policy drives demand and innovation meets it.

- *Comprehensive Frameworks***:** The EU and China offer strong examples of end-to-end regulatory systems.
- *Recycled Content & Traceability:* Mandates like those in the EU ensure market demand and accountability across the supply chain.
- *Support for Formal Recyclers:* China's whitelist model and U.S. investment-driven strategies show how incentives and clarity can scale the formal sector.
- *Efficient Collection Systems***:** China's extensive reverse logistics network highlights the need for widespread and accessible collection points.
- *R&D Focus***:** Companies like Redwood Materials prove how innovation, backed by policy or funding, can boost recovery rates and reduce dependence on virgin materials.

V. ECONOMIC AND ENVIRONMENTAL IMPLICATIONS.

The lack of a robust battery recycling infrastructure in India carries significant economic and environmental consequences but also presents a substantial opportunity for national growth and sustainability.

India's reliance on imports for critical LIB materials is a major economic vulnerability. Cumulative demand for materials like lithium, cobalt, nickel, and manganese is projected to exceed 250 kilotons between 2024 and 2030, translating to an import exposure of over $5 billion [22]. In 2022 alone, India imported 617 million units of LIBs for USD 1.8 billion [9]. This heavy dependence on foreign sources for essential battery components underscores a significant outflow of capital and exposes the nation to global supply chain volatilities and price fluctuations.

In stark contrast, establishing a robust domestic recycling industry presents a substantial economic opportunity. Reports suggest that lithium-ion battery recycling could spark an industry worth $3.5 billion by 2030 with the right policy steps [23]. This economic potential is not merely a cost of environmental compliance but a significant economic catalyst capable of generating a multi-billion-dollar industry, creating jobs—estimated between 27,000 to 41,000 by 2030 [1]—and reducing strategic import dependencies [1]. Furthermore, studies indicate that the overall cost of producing cathode active material from recycled battery materials can be 48% lower than from virgin materials [24], highlighting the economic viability and efficiency gains of recycling. This makes recycling an attractive proposition for strengthening resource security and economic resilience.

It is important to consider environmental damage from improper disposal. Improper disposal of LIBs—through landfilling or informal methods—poses serious environmental and health risks. LIBs contain hazardous metals like lithium, cobalt, and nickel that can combust or leach into soil and water, contaminating ecosystems. NMC batteries, in particular, risk thermal runaway if mishandled, potentially causing fires and toxic emissions. Informal recycling methods, such as acid leaching, release harmful pollutants, endangering both workers

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and communities. These practices also lead to economic losses from wasted resources and rising public health and remediation costs [5].

Recycling is India's only viable domestic source of critical minerals like lithium. When refined to battery-grade purity, recovered materials support new battery production and help close the loop toward a circular economy. Recycling reduces reliance on mining and cuts carbon emissions by up to 60% versus raw extraction. By 2040, it could lower primarily supply needs for key minerals by 10%, demonstrating how environmental protection and economic efficiency go hand in hand [24].

Table 2: Economic and Environmental Benefits of LIB Recycling in India

Benefit Category	Key Metrics/Data
Economic Value	Potential to become a $3.5 billion industry by 2030.[23]
Import Reduction	Reduces over $5 billion import exposure for critical minerals (2024-2030).[22]
Job Creation	Potential to create 27,000-41,000 jobs by 2030.[1]
Cost Savings	Cathode active material production cost can be 48% lower than from virgin materials.[24]
Carbon Emission Reduction	Up to 60% lower carbon emissions compared to virgin material production.[24]
Pollution Prevention	Prevents soil and groundwater contamination from hazardous battery components.[5]
Resource Recovery Efficiency	Advanced recyclers achieve over 98% material recovery rates.[13]

A. Global Innovations and Emissions Impact

➢ *Real World Environment Benefits*

A major Stanford University study using data from North America's largest battery recycling facility gives us precise numbers on recycling's environmental benefits—and they're impressive [26].

- *Dramatic Emissions Reductions*

Battery recycling cuts greenhouse gas emissions by 58-81% compared to mining new materials. For manufacturing scrap, the benefits are even better—recycling produces only 19% of the emissions that mining does [26]. That translates to avoiding 2.7-4.6 kg of CO_2 for every kilogram of battery material recycled [25].

- *Water and Energy Savings*

Recycling uses 72-88% less water and 77-89% less energy than mining virgin materials [26]. Manufacturing scrap recycling is even more efficient, needing just 12% of the water and 11% of the energy required for new mining [26]. For India, facing both water shortages and energy challenges, these savings are crucial.

- *Transportation Revolution*

Here's a striking comparison—mining and refining battery metals involves shipping materials an average of 35,000 miles (that's like going around the world 1.5 times) [26]. Recycling? Just 140 miles on average from collection to processing [26]. For India, this means massive transportation emission cuts through domestic recycling.

- *Why Location Matters*

The environmental benefits depend heavily on where recycling happens. Facilities powered by coal see smaller climate benefits, while those using clean energy maximize environmental gains [26]. India's growing renewable energy sector positions it well to achieve optimal recycling benefits.

- *Industry Growth*

Global recycling capacity is exploding—from 1.6 million tons annually today to over 3 million tons expected soon [25]. This growth is driven by stricter environmental rules and the first wave of EV batteries reaching retirement age [25].

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VI. RECOMMENDATIONS FOR INDIA

➢ *Building Effective Collection*

India needs collection systems more convenient and economically attractive than informal alternatives. Collection facilities need temperature-controlled storage, fire suppression, and trained staff understanding different battery chemistry safety requirements.

Economic incentives are essential. Deposit-refund systems and trade-in programs offering new battery discounts for old ones can leverage commercial relationships. Multiple channels needed: manufacturer take-back, retailer collection, municipal centres, and specialized services.

➢ *Investment Incentives*

Tax credits for recycling facilities, accelerated depreciation for equipment, and subsidized financing can overcome high capital barriers. Research partnerships between companies and institutions like CSIR-NML can accelerate technology transfer.

Skill development is crucial since recycling requires sophisticated technical knowledge. Training programs need multiple levels, from technicians to engineers. Government procurement prioritizing recycled materials creates demand certainty justifying investment.

➢ *Public Awareness*

Many people don't realize used batteries contain valuable materials or understand proper disposal. Mobile applications helping locate collection points and track environmental impact can make participation convenient. Educational institutions should integrate recycling into curricula and build environmental awareness.

Community engagement through local organizations can build social norms supporting proper disposal. When recycling becomes community pride and environmental responsibility, compliance increases significantly.

➢ *Public-Private Partnerships*

Partnerships can leverage government regulatory authority with private sector efficiency. Government should focus on standards, regulations, and market incentives. Private sector should handle operations, technology development, and market creation.

Performance-based contracts specifying collection targets, recovery rates, and environmental standards while allowing operational flexibility. Blended finance combining grants, loans, and private investment can reduce risks while ensuring returns.

VII. CONCLUSION

India’s growing demand for lithium-ion batteries—driven by EVs and renewable energy—makes a circular battery economy essential. Without strong recycling infrastructure, the country risks environmental damage and continued reliance on imported critical minerals.

This challenge is also an opportunity. With the right policies mandating recycled content, digital traceability, support for formal recyclers, and integration of informal workers, India can lead in sustainable battery management. Collaboration between government, industry, academia, and citizens is key.

Insights from my internship at Waaree Energies reinforced the importance of practical, scalable solutions rooted in real-world challenges. A circular battery economy is not just desirable—it is vital for India’s clean energy future.

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