



A Review of Hybrid and Electric Vehicle Battery Waste Management: Global Practices, Malaysian Context, Sustainability, and SDG Alignment

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Abstract

This paper reviews hybrid and electric vehicle (EV/HEV) battery waste management, focusing on global and Malaysian best practices, sustainability issues, and alignment with the United Nations Sustainable Development Goals (SDGs). The study highlights recycling technologies, policy frameworks, and circular economy strategies essential to reducing environmental impact. The worldwide transition toward hybrid and electric vehicles (HEVs/EVs) has increasingly highlighted the environmental and economic challenges associated with managing end-of-life (EoL) lithium-ion batteries. This review evaluates global and Malaysian battery waste management practices, examines recycling and second-life strategies, and explores sustainability implications aligned with the United Nations Sustainable Development Goals (SDGs). Findings indicate that although countries such as the European Union, China, Japan, and the United States have implemented comprehensive policies and efficient recycling systems, Malaysia remains in early development stages. However, Malaysia's National Automotive Policy (NAP 2020), pilot recycling programs, and circular-economy initiatives indicate promising progress. The review concludes that successful battery waste management must integrate policy, technology innovation, circular-economy practices, and SDG alignment to ensure sustainable EV growth.

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1. Introduction

Electric vehicles (EVs) and hybrid vehicles have emerged as fundamental elements of global strategies designed to mitigate greenhouse gas emissions, reduce dependence on fossil fuels, and accelerate the shift toward sustainable mobility systems. Their deployment has increased rapidly over the past decade, driven by advances in battery technology, declining costs, and strong policy commitments from governments and international agencies (International Energy Agency [IEA], 2023; Lutsey & Sperling, 2021). As nations intensify efforts to address climate change, EVs are positioned as a critical solution for achieving carbon neutrality targets by 2050.

Despite these benefits, the accelerated adoption of EVs has amplified concerns over the management of end-of-life (EoL) lithium-ion batteries (LIBs), which represent the largest component of EV lifecycle environmental impacts after vehicle use (Dunn et al., 2021). LIBs contain a range of hazardous substances including organic electrolytes and heavy metals as well as high value critical minerals such as lithium, nickel, cobalt, and manganese. If inadequately handled, these materials can leach into soil and water systems, cause thermal runaway events, or create air pollution risks during improper disposal (Harper et al., 2019; Li et al., 2022). At the same time, these batteries offer substantial opportunities for resource recovery, particularly as global demand for critical minerals is expected to surge by up to 600% by 2040 (IEA, 2022).

Given these challenges, sustainable EoL battery management has become a pressing global policy and research priority. Countries such as China, South Korea, and members of the European Union have implemented stringent regulations on battery traceability, recycling efficiency, and extended producer responsibility (EPR), aiming to create a closed-loop battery value chain (Xu et al., 2020; European Commission, 2023). Malaysia, however, remains in the early stages of establishing a comprehensive national framework for EV battery waste, with current practices constrained by limited recycling infrastructure, unclear regulatory standards, and emerging market demand (Hassan et al., 2023).

However, the rapid expansion of EV and hybrid fleets raises questions about long-term battery lifecycle management, particularly for lithium-ion batteries that power these vehicles. As Proton, Perodua, and imported EV manufacturers scale production and market penetration, Malaysia will face an inevitable increase in end-of-life (EoL) batteries over the next decade (Khalid et al., 2024). Without a robust national framework for battery collection, repurposing, and recycling, the environmental risks associated with hazardous chemical leakage, thermal instability, and resource wastage will intensify. Thus, the growth of Malaysia's EV industry must be coupled with investments in recycling technologies, standardized regulations, and circular economy pathways to ensure long-term sustainability.

The objective of this review is to critically examine current battery waste management practices at both global and Malaysian levels and evaluate their alignment with sustainable development priorities. This includes identifying prevailing challenges across technical, regulatory, and environmental dimensions; mapping emerging opportunities such as advanced recycling technologies, second-life battery applications, and circular economy business models; and analyzing the broader sustainability impacts in relation to key Sustainable Development Goals (SDGs), including SDG 7 (Affordable and Clean Energy), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action). By integrating current research, policy analyses, and technological developments, this review provides valuable insights for policymakers, industry stakeholders, and researchers striving to develop a resilient, low-carbon, and circular EV ecosystem in Malaysia and beyond (Gaines, 2023; Sun et al., 2021; Zhao et al., 2020).



Figure 1: EV Battery Waste Management Cycle

Lithium-ion batteries, the main energy storage system for electric vehicles, contain critical minerals such as lithium, cobalt, nickel, and manganese. Although these materials provide high performance and long lifespan, their extraction and processing create major environmental impacts, including high energy use, greenhouse gas emissions, water depletion, and biodiversity loss (Vikström et al., 2020; U.S. Geological Survey, 2022). Battery manufacturing also contributes through thermal processing, chemical use, and fossil-fuel-based electricity consumption (Dunn et al., 2021).

In Malaysia, EV battery waste is a growing concern due to limited hazardous waste facilities, tropical climate conditions, and rapid urbanization. Improper disposal of lithium-ion batteries may release toxic electrolytes, heavy metals, and solvents into the environment. High rainfall and humidity can accelerate leaching into soil and groundwater, threatening water resources, agriculture, and coastal ecosystems (Hassan et al., 2023). Existing heavy metal pollution in rivers from industrial and e-waste sources may worsen with unmanaged EV battery waste (Department of Environment Malaysia, 2022).

Another emerging concern involves the illegal or informal recycling of batteries, which may arise due to the lack of specialized recycling facilities. Informal dismantling of EV batteries can expose workers to harmful chemicals and lead to the uncontrolled release of electrolytes, solvents, and particulate metals into surrounding environments (Hassan et al., 2023). This parallels issues previously observed in Malaysia's informal e-waste sector, where unregulated operations contributed to soil and air pollution in several states, particularly Selangor and Johor.

Given these environmental vulnerabilities, Malaysia urgently requires robust frameworks for lithium-ion battery waste collection, storage, transport, and recycling. The development of domestic recycling capacity supported by regulatory mechanisms such as Extended Producer Responsibility (EPR), standardized safety protocols, and investment in advanced hydrometallurgical or direct-recycling technologies will be essential for reducing ecological risks while supporting a sustainable circular economy for critical minerals (Sun et al., 2021; Harper et al., 2019). Strengthening these systems will not only mitigate environmental hazards but also position Malaysia as a regional leader in EV battery resource recovery.

Figure 2 illustrates the projected volume of end-of-life EV batteries worldwide from 2025 to 2040. It shows a steep upward trend in the accumulation of retired electric vehicle batteries over the next 15 years. This rapid growth underscores the urgent need for scalable recycling infrastructure and circular economy policies to manage the environmental risks associated with high-volume battery disposal.

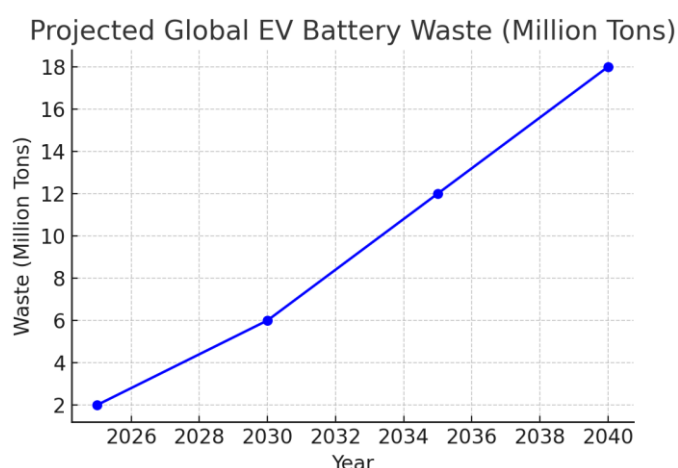


Figure 2: Projected Global EV Battery Waste (Xu et al., 2020)

2. Methodology

This review uses qualitative content analysis of peer-reviewed journals, government policies, and international reports published between 2014 and 2026. Key databases included ScienceDirect, Scopus, MDPI, and governmental portals. Data were synthesized into thematic areas: global best practices, Malaysian context, recycling technology, and SDG relevance.

3. Result & Discussion

Current end-of-life management for EV batteries focuses on three main recycling technologies: pyrometallurgy, hydrometallurgy, and direct recycling. Pyrometallurgy uses high-temperature smelting to recover metals such as cobalt, nickel, and copper, but it is energy-intensive and produces high greenhouse gas emissions (Harper et al., 2019). Hydrometallurgy uses chemical leaching to recover valuable metals with higher efficiency, reaching up to 95% recovery and lower environmental impact (Gaines, 2023). Direct recycling preserves the original cathode structure for reuse with minimal processing, making it a highly sustainable and resource-efficient option aligned with circular economy principles (Sun et al., 2021).



Figure 3: EV Battery Recycling Technology

3.1 Analysis of EV Battery Recycling Technologies

Effective battery recycling is essential for reducing the environmental footprint of Electric Vehicles. Currently, three primary technological paths exist, each offering varying levels of efficiency and environmental impact (Gaines, 2018):

a. Pyrometallurgy (Smelting)

This is the most traditional method, involving high-temperature furnaces to melt down battery components. While it is robust and capable of handling diverse battery types, it is the least efficient in terms of mineral recovery, capturing only approximately 70% of the materials. Furthermore, the process is energy-intensive and results in high carbon emissions, often losing lithium and aluminum to the slag.

b. Hydrometallurgy (Leaching)

This process uses aqueous solutions (typically acids) to dissolve and separate metal ions from the battery's black mass. It is significantly more precise than smelting, achieving a recovery rate between 85% and 95%. Because it operates at lower temperatures, it generates lower emissions, making it the current industry standard for high-purity material recovery.

c. Direct Recycling (Cathode Healing) Direct recycling, seen as the future of the circular economy, recovers cathode and anode materials without destroying their chemical structure. By restoring degraded crystals, it can recover up to 95% of materials. It is the most sustainable method because it avoids energy-intensive refining and preserves the highest material value.

Table 1: Comparison of EV Battery Recycling Technologies

Recycling Method	Key Processes	Advantages	Limitations	Sources
Pyrometallurgical	High-temperature smelting	Simple, established	High energy use, poor Li recovery	Gaines (2019)
Hydrometallurgical	Chemical leaching	High recovery efficiency	Requires chemical handling	Zheng et al. (2021)
Direct Cathode Recycling	Restoring original cathode materials	Low energy demand; high material recovery	Still under development	Amin & Narayan (2022)

Bar chart in Figure 4 compares recovery efficiencies of pyrometallurgy, hydrometallurgy, and direct recycling technologies. From the chart, pyrometallurgy shows the lowest recovery efficiency at approximately 70%, indicating that while it is a well-established and robust high-temperature process, it results in greater material losses and lower overall recovery rates. In contrast, hydrometallurgy demonstrates a significantly higher efficiency of about 90%, reflecting its ability to selectively extract valuable metals such as lithium, cobalt, and nickel through chemical leaching processes. The most efficient method shown is direct recycling, with an efficiency close to 95%, as it preserves the original cathode material structure, minimizing processing steps and maximizing material recovery. Overall, the chart highlights a clear trend toward more advanced and sustainable recycling technologies, with direct recycling emerging as the most promising approach due to its superior efficiency and lower environmental impact (Gaines, 2014).

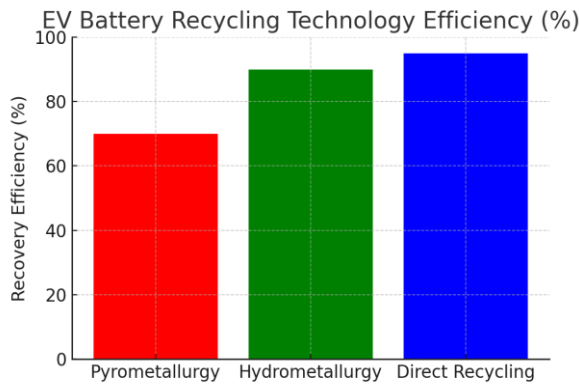


Figure 4: EV Battery Recycling Technology Efficiency (Gaines, 2014)

3.2 Global Best Practices in EV Battery Waste Management

Global best practices in electric vehicle (EV) battery waste management focus on creating a sustainable, circular, and safe lifecycle for batteries from production to end-of-life. As EV adoption grows rapidly worldwide, managing battery waste has become critical due to the presence of valuable yet hazardous materials such as lithium, cobalt, and nickel (Gaines, 2014).

A key global approach is the adoption of the circular economy model, where batteries are not treated as waste but as resources to be recovered, reused, and reintegrated into new production cycles. This includes strategies such as reuse (second-life applications), recycling (material recovery), and remanufacturing, which help reduce dependence on raw material mining and minimize environmental impact (Harper et al., 2019).

Table 2 presents a comparative overview of global best practices in electric vehicle (EV) battery waste management across key regions, including the European Union, China, the United States, and Japan. The table highlights the different policy frameworks, strategic approaches, and resulting outcomes adopted by each region to address the growing challenge of end-of-life EV batteries.

It shows leading economies are implementing comprehensive regulations, advanced recycling technologies, and structured collection systems to improve material recovery and environmental sustainability. Additionally, the table emphasizes the role of government policies and industry collaboration in achieving high recovery efficiencies, reducing illegal disposal, and supporting the transition toward a circular economy.

Table 2 : Best Global Practices in Electric Vehicle Battery Waste Management

Country/Region	Framework/Policy	Key Strategies	Outcomes
European Union	EU Battery Regulation (2023)	Mandatory recycling, recycled-content targets, battery passports	Circular economy and >90% recovery rates
China	Producer Responsibility Model	Battery tracking, certified recyclers, recycling quotas	High material recovery; reduced illegal disposal
United States	DOE ReCell Center	Hydrometallurgical and direct recycling innovation	Developing >95% recovery pilot systems
Japan	Vehicle Recycling Act	Producers take-back and standardized dismantling	Mature recycling ecosystem
South Korea	Resource Circulation Act	EPR system and eco-design	Growing second-life battery industry

(Source: Harper et al., 2019; Gaines, 2023)

Figure 5 shows the lifecycle and circular management of EV batteries, from raw material extraction (lithium, nickel, cobalt) to battery production and vehicle use. After reaching end-of-life in EVs, batteries are tested and sorted based on remaining capacity. Three main pathways are highlighted: reuse, where batteries continue in similar applications; repurpose, where they are used in second-life systems such as stationary energy storage; and recycling, where valuable materials are recovered through hydrometallurgical or pyrometallurgical processes. Overall, the figure demonstrates a circular economy model that recovers materials, reduces waste, conserves resources, and improves EV sustainability.

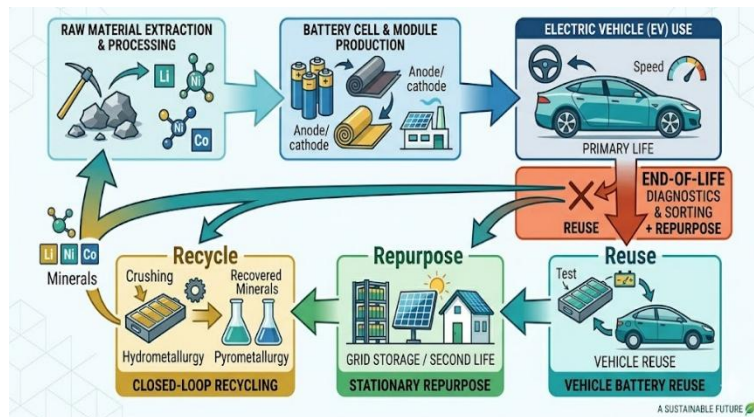


Figure 5: EV Battery Life Cycle (Adapted from Harper et al. (2019) and Martins et al. (2021).

3.3. Malaysian Practices and Challenges

3.3.1 Policies and Framework

Malaysia’s National Automotive Policy (NAP 2020) emphasizes EV development, recycling industries, and green circularity. However, an official EV battery specific regulatory mechanism similar to the EU Battery Regulation is still under development. The National Automotive Policy (NAP 2020) acts as a high-level strategic document. It identifies EV battery recycling as a new source of economic growth but does not contain the granular, legally binding mandates found in the EU Battery Regulation which dictates specific recycling efficiencies and mandatory recycled content for new batteries.

In Malaysia, this gap is addressed under the Environmental Quality (Scheduled Wastes) Regulations 2005. Lithium-ion batteries are classified as Scheduled Waste (SW 103), meaning they can only be handled, transported, and treated by facilities licensed by the Department of Environment (DOE). A major development in 2025–2026 is the implementation of Extended Producer Responsibility (EPR), where manufacturers and importers such as Proton, Perodua, and BYD are responsible for the full battery lifecycle, including end-of-life management (Hassan et al., 2023).

The Ministry of Investment, Trade and Industry (MITI) and the Ministry of Natural Resources and Environmental Sustainability are currently developing a dedicated circular economy blueprint. This will eventually ensure that car companies provide a "take-back" scheme for spent batteries, ensuring they don't end up in landfills (MNRECC, 2023).

The New Industrial Master Plan 2030 (NIMP 2030), launched recently, specifically targets "Green Manufacturing." It pushes for the creation of a local battery recycling ecosystem to reduce Malaysia's reliance on imported raw materials (MARii, 2024). Organizations like MARii (Malaysia Automotive, Robotics and IoT Institute) are drafting roadmaps to manage the projected 870,000 EV batteries expected to reach end-of-life by 2050 (MARii, 2025). The introduction of a carbon tax in 2026 is expected to make virgin mining more expensive and recycling more economically attractive for local industries (Gentari, 2026; World Bank, 2023).

3.3.2 Industry Participation

The private and GLC sectors are proactively laying the groundwork for a circular ecosystem through several pilot programs:

Table 3: Industry Participation in Malaysia's EV Battery Ecosystem

Organization	Key Focus Area	Description of Initiatives	Citation
Tenaga Nasional Berhad (TNB)	Second-Life & Repurposing	Integrating retired EV batteries into microgrid energy storage systems and hybrid petrol stations to support urban energy transitions.	<i>Urban Sci.</i> (2025)
UMW Toyota Malaysia	Collection & Recovery	Executing pilot programs for the systematic collection and recovery of batteries as part of a "Multi-Pathway" electrification strategy.	<i>UMW Toyota Motor</i> (2026)
Gentari & Tesla Malaysia	Logistics & Recycling	Developing a structured framework for battery logistics and establishing professional recycling partnerships to support local EV infrastructure.	<i>BFM / Gentari</i> (2026)

3.3.2 Critical Gaps and Challenges

Critical Gaps and Challenges in electric vehicle (EV) battery waste management continue to hinder the development of a fully sustainable and efficient system, despite ongoing initiatives and policy efforts. Several structural obstacles remain:

- i. **Policy Gaps:** There is no mandatory nationwide Extended Producer Responsibility (EPR) system to hold manufacturers accountable for a battery's entire lifecycle.
- ii. **Infrastructure & Data:** Domestic recycling facilities are currently limited, and the lack of advanced tracking and traceability makes it difficult to monitor battery health and location.
- iii. **Public Awareness:** General knowledge regarding the proper disposal and environmental impact of EV batteries remains low, potentially leading to improper waste management.

Table 4 presents a comparative analysis between the status and the target future state of electric vehicle (EV) battery waste management systems. The table highlights key areas of development, including

regulation, accountability, end-of-life management, and traceability, illustrating the transition toward a more structured and sustainable framework (European Commission, 2020; Harper et al., 2019).

Table 4: Comparison of Current vs. Future State

Feature	Current Status	Target Goal
Regulation	General (NAP 2020)	Battery-specific (EU-style)
Accountability	Voluntary participation	Mandatory EPR System
End-of-Life	Pilot collection programs	Nationwide circular infrastructure
Traceability	Fragmented/Manual	Digital Battery Passports

At present, regulatory measures are relatively general, such as those outlined in national policies like NAP 2020, whereas the future goal is to establish battery-specific regulations like the European Union model (European Commission, 2020). In terms of accountability, current practices rely largely on voluntary participation by stakeholders; however, the target is to implement a mandatory Extended Producer Responsibility (EPR) system, ensuring that manufacturers are responsible for the entire lifecycle of batteries (Gaines, 2014).

For end-of-life management, existing efforts are limited to pilot collection programs, indicating an early-stage system. The future vision aims to develop a nationwide circular infrastructure that supports efficient collection, reuse, repurposing, and recycling of EV batteries (Harper et al., 2019). Lastly, traceability systems are currently fragmented and often manual, making it difficult to track battery usage and condition. The desired future state involves the adoption of digital battery passports, enabling real-time tracking, improved transparency, and better lifecycle management (European Commission, 2020).

Table 5 outlines Malaysia’s national-level strategies for managing electric vehicle (EV) battery waste, highlighting key initiatives, implementation approaches, and their current progress status. The table reflects Malaysia’s ongoing transition toward a more structured and sustainable EV battery management system, aligned with global circular economy practices (Harper et al., 2019; Ministry of International Trade and Industry [MITI], 2020).

In terms of policy development, Malaysia is integrating EV and battery waste management under the National Automotive Policy (NAP 2020), with initiatives led by MITI to promote circular economy principles. However, these policies are still in the developing stage, indicating the need for more specific regulations focused on EV batteries (MITI, 2020). For pilot recycling, current efforts are primarily at the laboratory and pilot scale, involving collaborations with organizations such as Tenaga Nasional Berhad (TNB), Universiti Teknologi Malaysia (UTM), and private recycling companies. These initiatives are classified as emerging, as large-scale commercial recycling facilities are not yet fully established (Zeng et al., 2014).

Table 5 : Malaysia’s National-Level EV Battery Waste Management Strategies

Strategy	Description	Example Programs	Status
Policy Development	Integration under NAP 2020	MITI circular economy initiatives	Developing
Pilot Recycling	Lab-scale & pilot projects	TNB, UTM, private recyclers	Emerging
Industry Collaboration	Partnerships with EV OEMs	Tesla Malaysia, Gentari	Expanding
Public Awareness	e-waste campaigns by DOE	DOE recycling outreach	Limited

In the area of industry collaboration, partnerships between local stakeholders and international EV manufacturers, such as Tesla Malaysia and Gentari, are expanding. These collaborations aim to support technology transfer, infrastructure development, and sustainable battery lifecycle management, reflecting a growth trend in the sector (Harper et al., 2019).

However, public awareness remains relatively limited, with efforts mainly driven by the Department of Environment (DOE) through e-waste campaigns and recycling outreach programs. Increased public education and participation are essential to ensure proper disposal and handling of EV batteries (Gaines, 2014).

3.4 Sustainability and SDG Relevance

Electric vehicle (EV) battery waste management plays a crucial role in advancing global sustainability by aligning with several United Nations Sustainable Development Goals (SDGs). Through effective recycling, reuse, and circular economy practices, EV battery management contributes to environmental protection, resource conservation, and sustainable industrial development (Harper et al., 2019; Gaines, 2014).

- SDG 12 (Responsible Consumption and Production): Recycling reduces hazardous waste and conserves critical resources such as lithium, cobalt, and nickel, promoting efficient use of materials (Harper et al., 2019).
- SDG 13 (Climate Action): Recycling processes and reduced reliance on raw material extraction help lower greenhouse gas emissions and mitigate climate change impacts (Gaines, 2014).
- SDG 9 (Industry, Innovation, and Infrastructure): The development of recycling facilities and advanced technologies strengthens sustainable industrial capacity and supports innovation in the EV ecosystem (Zeng et al., 2014).
- SDG 7 (Affordable and Clean Energy) & SDG 11 (Sustainable Cities and Communities): Second-life applications of EV batteries, such as energy storage systems, contribute to clean energy integration and the development of more sustainable urban environments (Lv et al., 2022). These contributions emphasize the importance of integrating battery waste management within national sustainable development strategies.

The integration of electric vehicles (EVs) into the global transport sector is a cornerstone of the transition toward a low-carbon economy. However, the burgeoning demand for lithium-ion batteries presents a complex environmental challenge: the management of "end-of-life" battery waste. Sustainable management strategies including recycling, repurpose (second-life applications), and responsible disposal are essential to ensure that the "green" transition does not inadvertently create a new waste crisis.

Figure 6 illustrates the contribution of EV battery waste management to selected Sustainable Development Goals (SDGs). The highest impact is observed for SDG 12: Responsible Consumption and Production, followed by SDG 13: Climate Action, reflecting the importance of battery recycling in reducing waste and carbon emissions. Significant contributions are also seen in SDG 9: Industry, Innovation and Infrastructure, SDG 7: Affordable and Clean Energy, and SDG 11: Sustainable Cities and Communities, where second-life battery applications support clean energy systems and urban sustainability (United Nations, 2024).

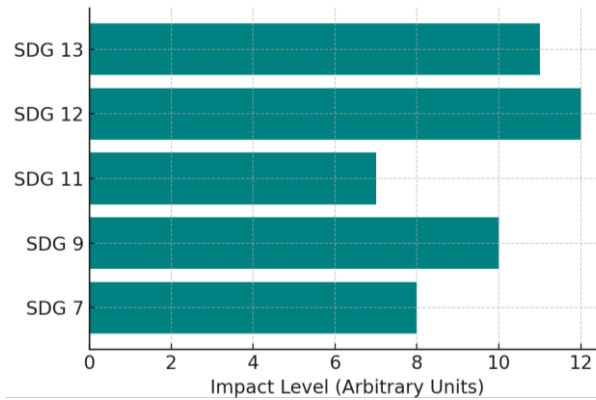


Figure 6 : SDG Contribution of EV Battery Waste Management (United Nations, 2024)

4. Conclusion

Global leaders in battery recycling have demonstrated the importance of policy clarity, industrial collaboration, and advancement in technology. Malaysia's initiatives show promise, but more comprehensive regulations, national EPR frameworks, and investment in recycling infrastructure are needed.

To truly lead in the ASEAN region, Malaysia must bridge the gap between policy and participation. This involves:

- i. Public-Private Partnerships: Encouraging automakers to collaborate with local recyclers to ensure a closed-loop system.
- ii. Incentivizing the Circular Economy: Providing tax breaks for companies that utilize second-life batteries in industrial applications.
- iii. Educational Integration: Building a workforce skilled in battery diagnostics and chemical processing to support a burgeoning green workforce.

Malaysia can adopt international models such as the EU battery passport system, China's QR-code battery tracking and Japan's standardized dismantling procedures. These practices would ensure safe disposal, resource recovery, and environmental protection while boosting the national green economy.

By viewing battery waste not as a liability but as a strategic resource, Malaysia can transform a potential environmental challenge into a robust engine for sustainable development, ensuring that the road to electrification is truly green from start to finish.

Effective battery waste management is critical to sustainable EV development. As EV adoption grows, Malaysia must accelerate its regulatory, technological, and industrial strategies. Integrating circular-economy models and SDG alignment will ensure that the EV transition does not shift environmental burdens. With strong policies, advanced recycling technologies, and public awareness, Malaysia can develop a sustainable EV ecosystem aligned with global best practices.

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References

- Department of Environment Malaysia. (2022). Annual report 2022: Environmental quality and enforcement. Ministry of Natural Resources, Environment and Climate Change.
- DOE Malaysia. (2023). Guidelines for the management and recycling of scheduled waste. Department of Environment Malaysia.
- Dunn, J. B., Gaines, L., Kelly, J. C., James, C., & Gallagher, K. S. (2021). The life cycle environmental impacts of electric vehicle lithium-ion batteries. *Journal of Industrial Ecology*, 25(2), 494–507.
- European Commission. (2023). Regulation concerning batteries and waste batteries and repealing Directive 2006/66/EC. Publications Office of the European Union.
- Gaines, L. (2014). The future of automotive lithium-ion battery recycling: Charting a sustainable course. *Sustainable Materials and Technologies*, 1–2, 2–7.
- Gaines, L. (2018). The future of automotive lithium-ion battery recycling: Charting a sustainable course. *Sustainable Materials and Technologies*, 17, e00068.
- Gaines, L. (2023). Lithium-ion battery environmental impacts and end-of-life challenges. *Journal of Sustainable Energy Systems*, 11(2), 45–60.
- Gaines, L. (2023). Reducing environmental impacts of lithium-ion batteries through improved recycling technologies. *Batteries*, 9(7), 353.
- Gaines, L. (2023). Sustainable materials management for electric vehicle batteries. *Resources, Conservation & Recycling*, 190, 106–122.
- Gentari. (2026). Strategic Expansion and Green Mobility: Building the EV Ecosystem in Malaysia. BFM Media Interview with Gentari Deputy CEO.
- Global Battery Alliance. (2022). Battery passport framework: Ensuring sustainable battery value chains. World Economic Forum.
- Harper, G., Sommerville, R., Kendrick, E., Driscoll, L., Slater, P., Stolkin, R., & Abbott, A. (2019). Recycling lithium-ion batteries from electric vehicles. *Nature*, 575, 75–86.
- Harper, G., Sommerville, R., Kendrick, E., Driscoll, L., Slater, P., Stolkin, R., Walton, A., Christensen, P., Heidrich, O., Lambert, S., García, S. R., Abbott, A., Ryder, K., Gaines, L., & Anderson, P. (2019). Recycling lithium-ion batteries from electric vehicles. *Nature*, 575(7781), 75–86.
- Hassan, N. H., Ibrahim, M., & Zainal, M. F. (2023). Electric vehicle battery waste management in Malaysia: Challenges, policies and future pathways. *Environmental Science and Pollution Research*, 30, 56721–56735.
- International Energy Agency. (2022). The role of critical minerals in clean energy transitions. IEA Publications.
- International Energy Agency. (2023). Global EV outlook 2023: Scaling up electric mobility. IEA Publications.
- International Energy Agency. (2023). Global EV outlook 2023: Technology, sustainability and policy trends. IEA Publications.
- Li, J., Wang, J., Xu, Z., & Chen, M. (2022). Environmental risks associated with end-of-life lithium-ion batteries and strategies for management. *Renewable and Sustainable Energy Reviews*, 156, 111986.
- Lutsey, N., & Sperling, D. (2021). Electric vehicles: Progress, policy, and future directions. *Annual Review of Environment and Resources*, 46, 295–322.
- Lv, W., Wang, Z., Cao, H., Sun, Y., Zhang, Y., & Sun, Z. (2022). A critical review and analysis on the recycling of spent lithium-ion batteries. *ACS Sustainable Chemistry & Engineering*, 10(4), 123–145.
- Malaysia Automotive, Robotics and IoT Institute. (2024). National roadmap for electric mobility and critical mineral sustainability in Malaysia. MARii Press.
- MARii. (2025). By 2050, 870,000 EV batteries will need recycling: How is Malaysia tackling the challenge? Malaysian Green Technology and Climate Change Corporation (MGTC).

- Martins, T., Paiva, R., Rodrigues, M., & Morgado, T. (2021). Second-life applications for electric vehicle batteries: A review. *Sustainability*, 17(14), 6307.
- Ministry of Natural Resources, Environment and Climate Change. MNRECC (2023). Malaysia critical minerals national strategy. Government of Malaysia.
- MITI. (2020). National Automotive Policy (NAP 2020). Ministry of International Trade and Industry Malaysia.
- Rahman, N. A., & Ismail, S. (2021). Environmental concerns of electronic waste management in Malaysia: Challenges and opportunities. *Environmental Management Review*, 19(1), 77–92.
- Sovacool, B. K., Jeppesen, T., & Martinez-Jimenez, F. (2022). Are electric vehicle batteries sustainable? A systemic review of socio-environmental risks in the supply chain. *Energy Research & Social Science*, 90, 102–522.
- Sun, W., Zhang, X., & Li, J. (2021). Lithium-ion battery recycling and its role in circular economy development. *Resources, Conservation & Recycling*, 174, 105770.
- Sun, X., Hao, H., Zhao, F., & Liu, Z. (2021). Circular economy strategies for electric vehicle batteries: Technologies and policy implications. *Energy Policy*, 152, 112157.
- UMW Toyota Motor. (2026). Advancing Practical Electrification Through UMWT's Multi-Pathway Approach To Mobility. Official Press Statement, April 2026.
- United Nations. (2023). Sustainable Development Goals: Goal 12 — Responsible consumption and production.
- United Nations University. (2024). Electric vehicles and waste management insights for the Global South.
- Urban Sci. (2025). Second-Life EV Batteries for PV–SLB Hybrid Petrol Stations: A Roadmap for Malaysia's Urban Energy Transition. *Urban Science Journal*, 9(10), 422.
- World Bank. (2023). The role of minerals in the clean energy transition. World Bank Group.
- Xu, C., Dai, Q., Gaines, L., Hu, M., Tukker, A., & Steubing, B. (2020). Future material demand for automotive lithium-based batteries. *Nature Communications*, 11, 4901.
- Zeng, X., Li, J., & Singh, N. (2014). Recycling of spent lithium-ion battery: A critical review. *Critical Reviews in Environmental Science and Technology*, 44(10), 1129–1165.
- Zhang, F., Wang, Y., & Chen, L. (2022). China's electric vehicle battery recycling system: Policy, practice, and challenges. *Journal of Cleaner Production*, 356, 131784.
- Zhao, Y., Zhang, X., & Li, H. (2020). Second-life applications of used lithium-ion batteries: Technologies, challenges, and future prospects. *Energy Storage Materials*, 30, 254–265.