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Predictive Modeling of End-of-Life Electric Vehicle Battery Volumes and Environmental Impact in Sri Lanka

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***Abstract*—Sri Lanka's electric vehicle (EV) fleet has grown through a volatile policy history: a tax-concession-driven boom in 2015, a sharp decline after the 2018 budget reforms, near-total suspension under the 2020–2025 vehicle import ban, and an explosive rebound after the ban was lifted in February 2025. This paper develops a quantitative forecast of end-of-life (EOL) EV battery volumes and associated environmental risk for Sri Lanka, using Weibull survival models combined with Material Flow Analysis (MFA), run separately for Motor Cars and Motor Cycles and resolved by battery pack model and cathode chemistry. Using Department of Motor Traffic (DMT) registration data for 2012–2025 and pack-level lifetime parameters adapted to Sri Lanka's hot climate, the model projects EOL battery volumes and hazardous material load through 2040 under three end-of-life management scenarios. Results show that Motor Cycles dominate unit counts (about 96% of retiring batteries by 2040), while Motor Cars carry 82% of the hazardous load of vehicles already registered; once projected registrations are included, Motor Cycles carry 54% of the hazardous load and about half of the 2025 car cohort remains in service in 2040. The first wave, already under way since about 2018, consists mainly of manganese-rich Nissan Leaf packs, and lithium iron phosphate (LFP) becomes the majority of retiring mass from 2031. Cumulative hazardous material released under Business-as-Usual conditions is projected at approximately 4,425 metric tons by 2040 (3,067–6,041 t across lifetime cases), falling by 85% under an Aggressive Intervention scenario. The paper concludes with policy recommendations for Sri Lanka's Central Environmental Authority and Department of Motor Traffic.**

***Index Terms*—electric vehicle batteries, end-of-life management, Weibull distribution, material flow analysis, Sri Lanka, environmental impact assessment.**

I. Introduction

The rapid global expansion of electric vehicle (EV) adoption has been accompanied by a parallel surge in lithium-ion battery production and, consequently, an emerging wave of battery retirements. Lithium-ion traction batteries are retired once degradation makes them unsuitable for vehicle use, and without collection and processing they release cobalt, nickel, manganese, lithium salts and flammable fluorinated electrolytes into waste streams.

Sri Lanka has seen a marked, but highly volatile, increase in electric vehicle and electric two-wheeler registrations over the past decade. Department of Motor Traffic (DMT) data show that electric Motor Car registrations peaked in 2015 under since-withdrawn tax concessions, declined sharply after the 2018 budget reforms, collapsed further under the March 2020 total vehicle import ban, and then surged after the ban's lifting on 1 February 2025 [1], [2]. Electric Motor Cycles followed a different, far larger-volume trajectory, growing through the ban years and reaching 34,056 registrations in 2025 alone. The early fleet consisted of reconditioned, air-cooled Nissan Leafs with lithium manganese oxide (LMO) packs blended with nickel-rich cathodes, whereas the post-2025 market is led by BYD's lithium iron phosphate (LFP) vehicles and LFP e-scooters [3]. Despite this growth, Sri Lanka currently lacks a dedicated regulatory framework, formal collection infrastructure, or domestic recycling capacity for EOL batteries of either vehicle class.

This paper addresses that gap by developing a predictive model of EOL battery volumes for both Motor Cars and Motor Cycles in Sri Lanka and assessing the associated environmental impact under three end-of-life management scenarios. Because these two vehicle classes differ enormously in battery mass, chemistry and registration volume, the study runs parallel Weibull–Material Flow Analysis (MFA) pipelines for each class, rather than treating "electric vehicles" as a single undifferentiated category. Within each class, registrations are allocated to representative battery pack models, each with its own lifetime distribution and cathode chemistry, and the outputs are combined only at the hazardous-mass and scenario-release stage.

The objectives of this study are to:

- project annual and cumulative EOL battery volumes for Motor Cars and Motor Cycles separately, over a 2012–2040 forecast horizon;
- estimate accumulated EOL battery mass by cathode chemistry and quantify the hazardous material load (lithium, cobalt, nickel, manganese, electrolyte) for each vehicle class;
- assess the environmental impact of current disposal practices under a Business-as-Usual scenario, compared against Moderate and

Aggressive recycling/reuse intervention scenarios; and

- recommend policy and infrastructure interventions appropriate to the Sri Lankan context, sequenced by urgency.

The remainder of this paper is organized as follows. Section II reviews the international and Sri Lankan literature on EOL battery management and forecasting. Section III presents the Weibull–MFA methodology. Section IV reports projected volumes and hazardous material loads. Section V sets out policy recommendations, and Section VI discusses the findings and concludes.

II. Literature Review

Regulatory responses to the EOL battery challenge vary considerably by region. The European Union has taken the most structured approach, with a comprehensive Battery Regulation covering carbon footprint disclosure, minimum recovered-material content for cobalt, lead, lithium and nickel, and waste-management traceability obligations. By contrast, the United States has no binding national policy governing battery recycling at end-of-life, despite being a major EV market. China has developed extensive recycling infrastructure, though retired LFP batteries are often repurposed for second-life use rather than recycled, owing to their comparatively low precious-metal content. This divergence illustrates that EOL battery governance frameworks remain immature even in large EV markets, let alone in developing economies and that electric two-wheeler EOL policy, specifically, remains almost entirely undocumented internationally.

A growing body of life-cycle assessment (LCA) research quantifies the environmental consequences of different EOL battery pathways. Studies of improper disposal note that a significant share of EOL lithium-ion battery waste is incinerated, landfilled, or processed through informal channels, releasing toxic elements into air, soil and water [4]. Comparative studies show that formal recycling generates substantial net environmental benefit despite its own footprint, and that second-life use in stationary energy storage can meet a substantial share of projected demand while recycling covers a complementary share of material demand [5] a consideration reflected in this paper's multi-scenario approach.

A distinct strand of literature forecasts, rather than measures, future EOL battery volumes by combining MFA with a Weibull lifetime distribution. Richa et al. [6] used MFA to estimate EOL EV battery quantities in the United States under multiple lifespan and sales-volume scenarios. Ai et al. [7] tested uniform, Weibull and truncated normal distributions for battery discard probability, while Qiao et al. [8] applied a Weibull-based lifetime distribution paired with the Stanford estimation model to project retirement volumes in China, and Ziemann et al. [9] used dynamic MFA to assess lithium recycling. Shafique et al. [10] extended this to global NMC battery material flows, and Lygizos et al. [11] designed a reverse logistics network for Greece using dynamic Weibull scenarios in the absence of local waste-stream data — the closest methodological precedent to Sri Lanka. These studies typically use a shape parameter of 3.5 and cohort mean lives of about 8–16 years, assuming retirement at 70–80% state of health (SOH) [7], [10], [11]. None of them disaggregates by vehicle class; the Weibull–MFA literature has been developed almost exclusively around passenger EVs, leaving electric two-wheelers despite their large and rapidly growing global volume largely unmodeled.

Research specific to Sri Lanka's EOL battery challenge is minimal. Industry stakeholders warned as early as 2017 that battery disposal could become a national issue without proper policy [12]. Recent analysis confirms that Sri Lanka's e-waste management system suffers from insufficient integration between formal and informal sectors, with no separate regulatory category for traction batteries [13], [14]. This informal-sector dimension is particularly consequential given this study's finding that electric Motor Cycles dominate EOL unit counts: informal, small-scale disposal of a very large number of small batteries presents a more diffuse risk profile than the same hazardous mass concentrated in fewer large car batteries. No published study, to the authors' knowledge, combines Weibull–MFA forecasting with Sri Lankan registration data, nor disaggregates passenger EV and electric two-wheeler EOL streams a gap this paper addresses.

III. Methodology

A. Data Sources

Historical annual registrations for electric Motor Cars and Motor Cycles (2012–2025) were obtained from a DMT extract [1] and cross-checked against DMT fuel-type tables for 2022 and January–September 2023 and a corrected DMT table for 2012–2014 (Table I, Fig. 1). Car registrations for 2013 and 2024 are estimates, as no official figure was located.

TABLE I. Electric Vehicle Registrations Used in the Model, 2012–2025

Year	Electric Motor Cars	Electric Motor Cycles
2012	17	2,054
2013	13	9
2014	90	188
2015	3,238	167
2016	983	348
2017	197	565
2018	223	737
2019	102	643
2020	77	261
2021	41	229
2022	17	728
2023	76	1,237
2024	101[a]	12,003[b]
2025	7,239	34,056

a. Estimate (2023 January–September value of 76 annualised; 2024 proxy). b. Unverified. Other EVs (tricycles, dual-purpose; 14, 30 and 1 in 2012–2014) are excluded.

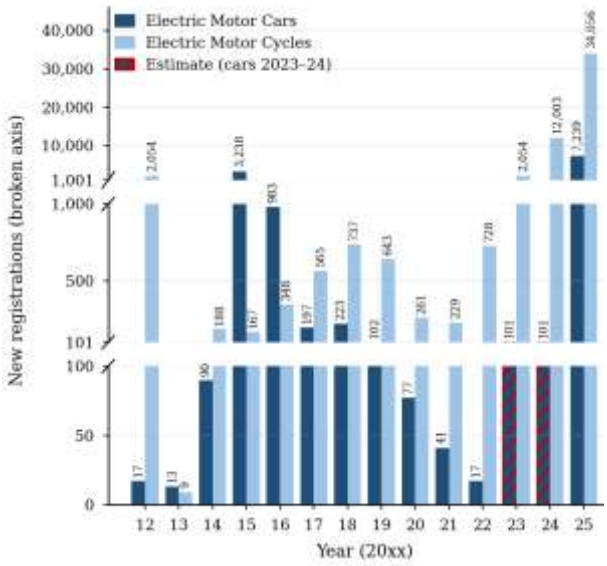


Figure 1. Electric vehicle registrations used in the model, Sri Lanka, 2012–2025 (broken axis).

B. Battery Retirement (Weibull Survival) Model

The probability that a pack of model m retires in its a-th year after registration follows from the two-parameter Weibull cumulative distribution function:

$$P_m(a) = F_m(a+1) - F_m(a) \quad (1)$$

$$F_m(x) = 1 - exp[-(x/\lambda_m)^k] \quad (2)$$

where λ_m is the scale parameter (characteristic lifetime, years) and k the shape parameter ($k > 1$ implies wear-out-dominated failure). Following the literature, $k = 3.5$ for all pack models; $\lambda_m = \mu_m / \Gamma(1 + 1/k)$, where μ_m is the mean life. Published mean lives assume retirement at 70–80% SOH. Three Sri Lankan conditions modify them: heat (fleet data show about 0.4%/yr faster fade in hot climates [15]), reconditioned imports arriving about 1.5 years old, and owners driving to about 30% SOH, as observed for first-generation Leafs swapped at about 35%. The mean life from registration is therefore

$$\mu_m = min(0.45/r_m - a_m, c_m) \quad (3)$$

where r_m is the annual fade rate in Sri Lanka, a_m the import age and c_m a service-life cap; $0.45/r_m$ is the time to 30% SOH when fade is linear to 80% and twice as fast thereafter, consistent with accelerated late-life fade [16]. Fade rates were set from fleet data [15], [17], owner data and, for two-wheelers, manufacturer claims (Table II). The cap (15 years for cars, 13 for small LFP cars, 7 for two-wheelers) binds for durable LFP and liquid-cooled NMC packs, which leave service with 45–78% of capacity remaining (Fig. 2). Short- and long-life cases combine the fade-rate ranges with caps of 12/10/6 and 18/15/9 years.

TABLE II. WEIBULL RETIREMENT PARAMETERS BY PACK MODEL (K = 3.5)

ID	Representative pack	Fade %/yr	μ (range), yrs	λ
C1	Nissan Leaf 24 kWh	4.5	8.5 (7.5–9.2)	9.45
C2	Nissan Leaf 30 kWh	4.0	9.8 (7.5–11.4)	10.84
C8	Replacement 30 kWh	4.0	10.5 (8.2–12.1)	11.67
C3	Nissan Leaf 40 kWh	3.5	11.4 (9.8–13.5)	12.62
C4	BMW i3 22 kWh	3.25	12.3 (11.4–13.5)	13.72
C5	BYD Blade (55 kWh)	2.0	15 (12–18)	16.67
C6	Other NMC (60 kWh)	2.4	15 (12–18)	16.67
C7	Small LFP car (32 kWh)	2.2	13 (10–15)	14.45
B1	NMC e-scooter	8.0	5.6 (4.5–7.5)	6.25
B2	LFP e-scooter	3.0	7 (6–9)	7.78
B3	Perf. e-motorcycle	4.0	7 (6–9)	7.78

μ = mean life from registration (central; short–long range). Two-wheeler fade rates rest mainly on manufacturer claims.

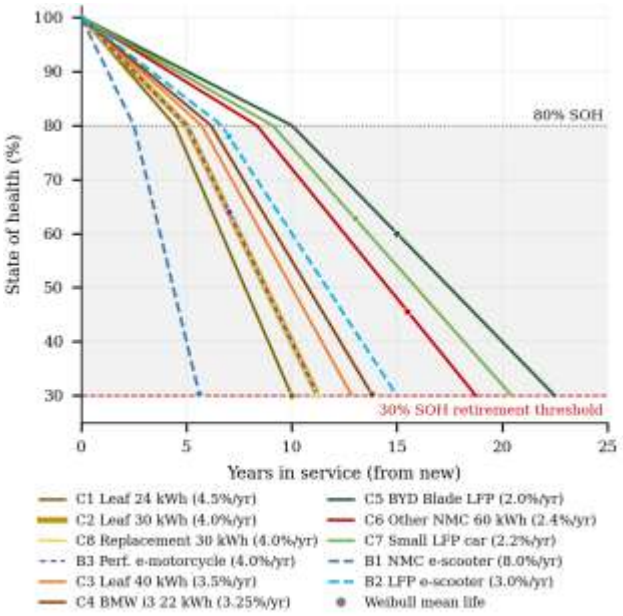


Figure 2. Illustrative capacity fade of all pack models in Sri Lankan conditions (central rates); dots mark Weibull mean life from new.

C. Convolution and Material Flow Analysis

Each cohort is allocated to pack models by an assumed fleet mix: 2012–2015 cars 90% Leaf 24 kWh (C1) and 10% BMW i3 (C4); 2016–2017 40% C1, 45% Leaf 30 kWh (C2), 15% C4; 2018–2024 70% Leaf 40 kWh (C3), 10% C2, 20% other NMC (C6); 2025 onwards 55% BYD Blade LFP (C5), 25% C6, 15% small LFP cars (C7), 5% C3. Motor Cycles are split between NMC e-scooters (B1), LFP e-scooters (B2) and performance NMC e-motorcycles (B3), with the LFP share rising from 20% to 55%. About 90% of retired C1 packs are replaced in service by a 30 kWh pack (C8). The number of packs of model m retiring in year T is obtained by convolving its cohort entries E_m with P_m:

$$R(m,T) = \Sigma_{t \le T} E(m,t) \cdot P_m(T - t) \quad (4)$$

This is the Stanford estimation model in convolution form, implemented as cohort-year × forecast-year matrices, one per pack model. Pack mass and cathode active material (CAM) mass follow from pack energy and the cathode's practical specific energy, and element masses from stoichiometry (e.g., NMC532: 7.2% Li, 30.4% Ni, 12.2% Co, 17.1% Mn; LFP: 4.4% Li);

electrolyte is 9% of car and 10% of motorcycle pack mass [18]. Table III lists per-pack contents. Released mass is the hazardous load (Li, Ni, Co, Mn, electrolyte) multiplied by (1 − recycle rate − reuse rate) under the scenarios in Table IV, applied uniformly to both classes.

TABLE III. BATTERY PACK MATERIAL CONTENT (KG PER PACK)

ID	Chem.	kWh	Pack	Li	Ni	Co	Mn	Elec.
C1	LMO-LNO	24	294	2.4	6.1	1.2	22.8	26.5
C2, C8	LMO-NMC	30	300	3.3	6.0	6.0	23.6	27.0
C3	NMC532	40	303	4.6	19.3	7.8	10.9	27.3
C4	NMC111	22	230	2.7	7.5	7.6	7.1	20.7
C5	LFP	55	393	5.0	–	–	–	35.4
C6	NMC622	60	375	6.5	32.7	11.0	10.2	33.8
C7	LFP	32	256	2.9	–	–	–	23.0
B1	NMC532	1.5	12.5	0.17	0.72	0.29	0.41	1.25
B2	LFP	2.3	24.2	0.21	–	–	–	2.42
B3	NMC622	3.5	26.9	0.38	1.91	0.64	0.60	2.69

Pack names as in Table II. Elec. = electrolyte.

TABLE IV. END-OF-LIFE MANAGEMENT SCENARIOS

Scenario	Recycle	Reuse
Business-as-Usual	0%	0%
Moderate Intervention	30%	15%
Aggressive Intervention	60%	25%

D. Registration Growth Projection

Two registration scenarios are modelled. Scenario A uses historical cohorts only (2012–2025). Scenario B adds future registrations projected with a two-stage compound growth model applied separately per class: a one-off 2026 normalization factor, reflecting an assumed partial cooling of the 2025 post-import-ban surge, followed by a steady-state annual growth rate from 2027 onward. Motor Cars are assigned −10% normalization and 15% growth, and Motor Cycles −5% and 20%, reflecting an assumption that two-wheeler adoption driven by affordability and urban commuting economics continues to outpace passenger EV adoption. Both sets of parameters are provisional pending 2026–2028 DMT data.

E. Model Validation and Limitations

For the first-generation Leaf (C1), the two-stage Sri Lankan fade curve reaches 30% SOH at 10.0 years from new, consistent with the observed swap at about 35% SOH after about 10 years; linear fade at published mild (3.1%/yr [17]) or fleet-average (4.2%/yr [15]) rates would take 16.7–22.6 years (Fig. 3a). The C1 Weibull median (10.0 years from new) coincides with the fade-model time to 30% SOH. Weighted by corrected registrations, the Central case implies that 85% of 2012–2017 C1 packs had retired by mid-2026 (Short-life 94%, Long-life 76%), against about 90% observed, whereas a class-level distribution (λ = 11, k = 2.5) implies only 66% (Fig. 3b).

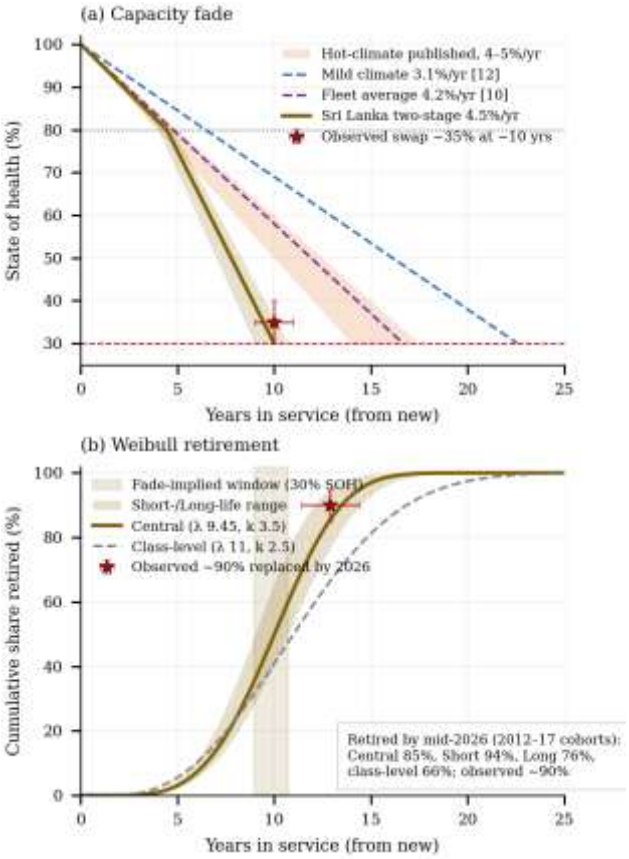


Figure 3. C1 (Leaf 24 kWh) validation: (a) capacity fade, theoretical vs. Sri Lankan; (b) Weibull retirement vs. fade model and field evidence.

The principal limitations are: (i) the assumed fleet mix, as no make-and-model registration data were available; (ii) Motor Cycle battery lifetime and pack parameters, which rest mainly on manufacturer claims; (iii) the service-life caps that govern post-2025 car packs and the unconfirmed field observations; (iv) estimated 2013 and 2024 car registrations and provisional growth projections; and (v) the study estimates hazardous mass released to the waste stream but not site-specific soil or groundwater contamination risk.

IV. RESULTS

A. EOL Battery Volumes

About 8,400 packs (1,073 t) had already reached end-of-life by 2025, the first wave beginning around 2018 as the 2015 car cohort started to retire. Motor Cycle retirements dominate unit counts: by 2040, annual EOL volume reaches about 6,900 Motor Car and 150,100 Motor Cycle packs, i.e., motorcycles account for about 96% of units (Fig. 4). Cumulative retirements over 2012–2040 are 66,700 packs under Scenario A and 830,200 under Scenario B.

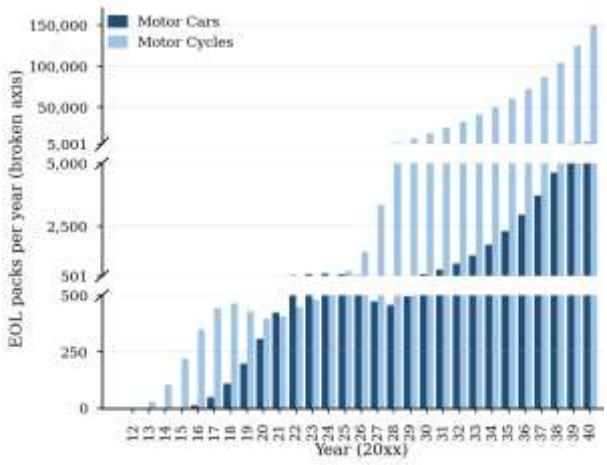


Figure 4. Projected annual EOL EV batteries by vehicle class, Sri Lanka, 2012–2040 (Scenario B, Central case; broken axis).

B. EOL Mass by Chemistry

Accumulated EOL mass is 5,054 t (Scenario A) and 28,159 t (Scenario B) (Table V). The chemistry of the stream shifts sharply (Fig. 5): LMO-based Leaf packs account for 80–92% of annual EOL mass in 2018–2025, LFP becomes the majority from 2031, and LFP makes up 59% of accumulated Scenario B mass and 65% of the 5,422 t retiring in 2040.

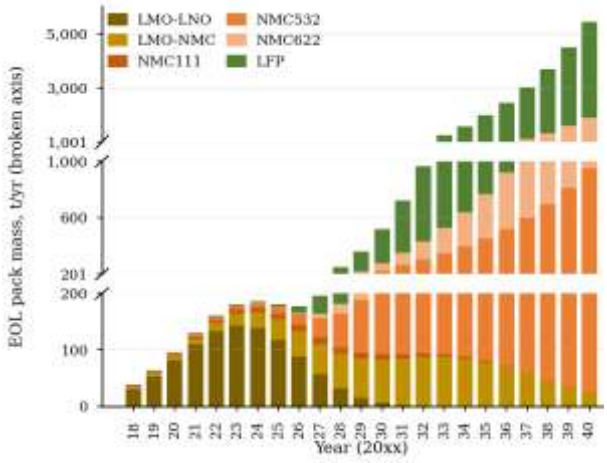


Figure 5. Annual EOL pack mass by cathode chemistry, 2018–2040 (Scenario B, Central case; broken axis).

TABLE V. ACCUMULATED EOL PACK MASS AND HAZARDOUS CONSTITUENTS, 2012–2040 (T, CENTRAL CASE)

	Cars A	Cycles A	Total A	Cars B	Cycles B	Total B
LMO-LNO	1,027	–	1,027	1,027	–	1,027
LMO-NMC	1,081	–	1,081	1,081	–	1,081
NMC	790	413	1,203	3,499	6,036	9,535
LFP	1,118	624	1,742	7,029	9,487	16,516
Pack mass	**4,016**	**1,038**	**5,054**	**12,636**	**15,523**	**28,159**
Lithium	46	11	57	164	165	329
Nickel	100	25	125	320	375	695
Cobalt	49	10	58	125	141	267
Manganese	189	12	201	269	177	445
Electrolyte	362	104	465	1,137	1,552	2,690
Hazardous	**745**	**162**	**907**	**2,016**	**2,410**	**4,425**

A = registered vehicles only; B = with 2026–2040 projection. NMC = NMC111, NMC532 and NMC622.

C. Hazardous Load and Scenario Releases

Hazardous constituents make up 16–18% of EOL pack mass, with electrolyte the largest component (61%), followed by nickel (16%), manganese (10%), lithium (7%) and cobalt (6%). Motor Cars carry 82% of the hazardous load of the existing fleet, but Motor Cycles carry 54% once projected registrations are included, because the projected fleet grows fastest in two-wheelers and about half of the 2025–2040 car packs are still in service in 2040. Because the release calculation is linear in (recycle rate − reuse rate), the reduction relative to Business-as-Usual is constant (45% for Moderate and 85% for Aggressive Intervention), but the tonnage at stake grows steeply after 2030. The difference between Business-as-Usual and Aggressive Intervention is about 3,762 t under Scenario B (Table VI). Scenario A is robust to the lifetime assumptions (801–1,015 t), whereas Scenario B ranges from 3,067 to 6,041 t.

TABLE VI. CUMULATIVE HAZARDOUS MATERIAL RELEASED, 2012–2040 (T)

Weibull case	Scen.	BAU	Moderate	Aggressive	Car share
Central	A	907	499	136	82%
Central	B	4,425	2,434	664	46%
Short-life	B	6,041	3,322	906	52%
Long-life	B	3,067	1,687	460	45%

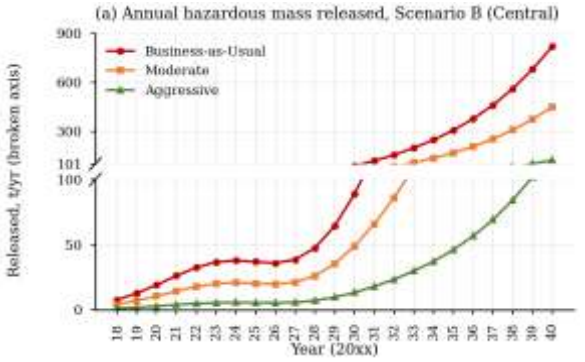


Figure 6. Hazardous material released to the uncontrolled waste stream:

V. RECOMMENDATIONS

Based on the findings above, and sequenced by urgency and the two distinct risk profiles identified in Section IV, this study recommends the following measures for Sri Lanka's Central Environmental Authority (CEA) and Department of Motor Traffic (DMT).

A. Immediate (2026–2028)

- Establish a dedicated EOL EV battery regulatory category, distinct from the general e-waste framework, with separate provisions for Motor Car and Motor Cycle battery streams;
- Set up interim collection and fire-safe storage for packs already retired, particularly first-generation Nissan Leaf packs held by repair shops and dealers;
- Design a dealer and retailer take-back scheme for Motor Cycle batteries now, so that it

operates before the 2025 cohort retires in large numbers around 2030;

- Commission a joint DMT/CEA registration-and-disposal tracking system that records battery chemistry and capacity at registration;
- Commission primary research on Sri Lankan electric vehicle batteries (mass, chemistry, real-world lifetime), and a site-specific soil and groundwater leaching risk assessment in areas with informal e-waste handling.

B. *Medium-Term (2028–2032)*

- Introduce an Extended Producer Responsibility (EPR) scheme for EV importers and assemblers covering both vehicle classes, with fees sized to cover collection and processing of low-value LFP packs;
- Evaluate a domestic or regional second-life battery hub, prioritising LFP and modern NMC car packs that retire with substantial remaining capacity.

VI. Discussion and Conclusion

The results imply that Sri Lanka faces two distinct EOL battery streams rather than one undifferentiated problem, and that they differ in timing as well as form. The Motor Car stream is concentrated, already present and dominated by first-generation Leaf packs; it is well suited to centralized collection through importers and service networks. The Motor Cycle stream is diffuse and high-unit-count, dispersed across many owners and informal repair shops, and arrives next: the 2025 cohort retires mainly in 2030–2032 (mean lives 5.6–7 years), while most 2025 car packs retire only from the late 2030s. Sri Lanka therefore has a planning window of about four years for motorcycle collection, and the car results for Scenario B are a lower bound on a wave that continues beyond 2040.

The shift to LFP changes the economics of EOL management. LFP contains no cobalt or nickel and has low recovery value, so recycling will not pay for itself; collection and safe processing must be financed through EPR fees. Many LFP and modern NMC car packs will leave service with 60–80% of their capacity, making second-life storage a realistic complement, while electrolyte (61% of the hazardous load) is the main handling risk regardless of chemistry. Methodologically, replacing one distribution per vehicle class with pack-specific parameters reduced the Scenario B hazardous load by about 40% and brought the car share below half, while improving agreement with local field evidence. The finding that unit-count and mass dominance can diverge between vehicle classes, and shift between them over time, may generalize to other markets with substantial two-wheeler EV adoption, such as much of South and Southeast Asia.

This study developed the first quantitative, vehicle-class and pack-disaggregated forecast of EOL EV battery volumes for Sri Lanka, combining a Weibull–MFA framework with Sri Lanka's corrected DMT registration history. Vehicles already registered will yield about 5,054 t of EOL batteries and 907 t of hazardous constituents by 2040; with continued growth, about 4,425 t of hazardous material would enter the uncontrolled waste stream under current practices — reducible by 85% under an aggressive recycling-and-reuse policy. Because the next retirement wave is closely tied to the 1 February 2025 import-ban lift, Sri Lanka has an identifiable window in which to act on the recommendations in Section V.

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