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E-Waste and Emerging Waste Streams (E-Cigarettes, Gas Cylinders): A Systematic Review of Global Management Strategies and Implications for U.S. Stewardship Programs

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ABSTRACT

Background: Waste electrical and electronic equipment (WEEE/e-waste) is among the fastest-growing global waste streams, with complex environmental and health externalities and unexploited resource recovery potential. In parallel, emerging streams such as electronic nicotine delivery systems (ENDS/e-cigarettes) and pressurized gas cylinders present new hazards (chemical toxicity; battery fire risk; pressure vessel failure) that challenge current governance.

Objectives: To synthesize peer-reviewed evidence (2015–2025) on global management strategies across conventional e-waste and emerging streams, quantify environmental and technical performance, and derive implications for U.S. stewardship (EPR, HHW, retail take-back, deposit-refund).

Methods: PRISMA-guided systematic review (PCC/PICOS). Databases: Web of Science, Scopus, PubMed, Embase, IEEE Xplore, TRID. Eligible designs: empirical studies, LCA, MFA, policy evaluation, economic analyses; English, 2015–2025. Risk of bias: ROBINS-I/AXIS/CASP; LCA appraised for ISO 14040/44 elements.

Results: 132 studies met criteria (WEEE: 83; ENDS: 21; cylinders: 28). Formal EPR systems in high-income regions consistently outperform voluntary/fragmented regimes on collection efficiency and recovery yields. LCAs show hydrometallurgy often delivers lower global warming potential (GWP) relative to pyrometallurgy for batteries/WEEE, albeit with effluent management constraints; evolving pyrometallurgy can become competitive under optimized pre-treatment and lithium volatilization. Informal recycling in LMICs is associated with elevated toxic metal exposure and adverse health outcomes. Evidence for ENDS waste management is nascent; peer-reviewed work highlights battery fire hazards and nicotine toxicity, advocating hazardous-waste compatible pathways.

Conclusion: U.S. stewardship should integrate ENDS and cylinders into national frameworks via mandatory EPR, fee eco-modulation, retail take-back expansion, and cylinder requalification/return incentives, alongside investment in domestic battery/WEEE recovery capacity, standardized indicators, and transparent producer reporting.

KEYWORDS: e-waste, e-cigarettes, hydrometallurgy, pyrometallurgy,

INTRODUCTION

Discarded electrical and electronic equipment (WEEE/e-waste) contains valuable metals, including copper, gold, silver, nickel, cobalt, lithium, and rare earth elements, as well as hazardous constituents such as lead, cadmium, mercury, and brominated flame retardants (Marra et al, 2018). This dual nature generates intertwined environmental risks and resource recovery opportunities. Electronic waste, commonly referred to as e-waste or WEEE, encompasses discarded electrical or electronic devices or components containing circuitry or batteries, including broken equipment, obsolete devices, and non-functional components (Ahirwar et al, 2021). These waste streams frequently harbor both hazardous substances and valuable materials, thus posing environmental risks while simultaneously offering resource recovery opportunities. Systematic syntheses demonstrate rapid growth in global e-waste generation and persistent collection and recycling gaps, with consequences for emissions, toxicity, and circular material flows of metals and polymers (Ahirwar et al, 2021).

Beyond conventional e-waste, this review expands focus to two emerging waste streams that have only recently drawn regulatory and management attention. First, e-cigarettes and ENDS (electronic nicotine delivery systems), in both disposable and rechargeable forms, incorporate electronic and battery components, nicotine salts, and plastics. Second, pressurized gas cylinders, including liquefied petroleum gas (LPG) domestic cylinders and industrial compressed gas cylinders, may contain residual pressurized contents, valves, and heavy metals in their construction materials (Ward et al, 2020). The inclusion of these emerging streams recognizes that modern waste portfolios are diversifying and that stewardship systems must evolve accordingly.

The scale of the e-waste challenge is vast and accelerating. According to the Global E-Waste Monitor 2024, global e-waste generation reached 62 million tonnes in 2022, approximately 7.8 kg per capita, and is projected to increase to approximately 82 million tonnes by 2030 under a business-as-usual trajectory (Castellani, 2025). However, only 22.3 percent of that mass was formally collected and recycled in an environmentally sound manner in 2022, and projections suggest the documented collection rate could decline to 20 percent by 2030. Regionally, Europe achieves the highest per-capita generation at 17.6 kg and also leads in formal recycling with 42.8 percent of e-waste collected in 2022, whereas Africa lags with less than 1 percent formally collected (Vishwakarma et al, 2023). This discrepancy between rapidly rising generation and lagging recycling underscores an urgent gap in waste management systems globally. The imbalance is compounded by shortening device lifespans, growing digitization, miniaturization, and planned obsolescence - trends that accelerate the inflow of discarded electronics faster than infrastructure can adapt.

E-cigarettes and ENDS typically comprise small lithium-ion or lithium polymer batteries, control electronics, plastic casings, heating coils, and e-liquid reservoirs containing nicotine or nicotine salts (Eaton et al, 2018). The combination of battery fire risk and the toxicity of residual nicotine positions discarded e-cigarettes as hazardous waste. The U.S. Environmental Protection Agency explicitly warns against disposing of e-cigarettes in regular trash or recycling bins, citing risks of battery damage and fires, and recommends delivery to household hazardous waste collection sites. Under U.S. regulation, nicotine is classified as an acute hazardous waste (code P075) under the Resource Conservation and Recovery Act (RCRA) when discarded, and e-cigarettes, e-liquids, and cartridges must be managed under hazardous waste pharmaceutical regulations (40 C.F.R. Part 266, Subpart P) when discarded (Eaton et al, 2018). This regulatory framing underscores how e-cigarette waste straddles the boundary between consumer electronics and chemical or hazardous waste.

Pressurized gas cylinders represent a different class of emerging waste. These are mechanical-structural devices engineered to safely contain gases under pressure, often built from steel or aluminum alloys with welded or threaded valves and seals (Palluzi, 2009). At the end-of-life, residual gas—whether flammable, toxic, or inert - along with valve components and internal corrosion or coatings, pose potential hazards. These cylinders must be depressurized, purged, and either recycled or requalified through processes such as retubing or recertification. The pressure hazard and residue content differentiate cylinder waste from standard scrap metal and require specialized management protocols under transport and hazardous material regulations administered by the U.S. Department of Transportation and Pipeline and Hazardous Materials Safety Administration (Quackenbush, 2025).

Together, e-cigarettes and gas cylinders are considered emerging because they combine multiple hazard vectors—chemical, thermal, and pressure—that are more complex than standard e-waste or scrap. Their volumes are rapidly growing, yet management frameworks remain nascent. Furthermore, their inclusion in producer stewardship or EPR schemes is often incomplete or absent in existing laws.

At the international level, the Basel Convention's technical guidelines on e-waste and transboundary movement set standards for distinguishing hazardous versus non-hazardous e-waste and require prior informed consent for cross-border shipments. Many countries have incorporated those principles into national legislation. In the European Union, the WEEE Directive (2012/19/EU) mandates that producers finance and operate take-back systems for electrical and electronic equipment, sets collection and recycling targets, and encourages eco-design (Ylä-Mella et al, 2014). The EU has progressively revised WEEE to include batteries, with recent proposals to capture small-format devices, including potentially small electronics like ENDS.

In the United States, stewardship for electronics has historically been fragmented. The EPA encourages voluntary electronics stewardship programs, and some states have enacted electronics EPR laws, including Washington and California. However, e-cigarettes and pressurized cylinders typically fall outside traditional electronic stewardship frameworks, requiring integration into hazardous waste or consumer product regulation. The lack of a cohesive federal-level EPR scheme in the United States provides both challenges and opportunities for extending stewardship to these emerging streams (Hicke, 2013).

Key policy instruments under consideration include extended producer responsibility, which requires producers to finance or manage end-of-life disposal; deposit-refund schemes; retail take-back mandates; household hazardous waste programs; and linkages to circular economy goals such as recovery of critical raw materials. The concept of eco-modulation—adjusting producer fees by product recyclability or hazards - is also emerging in advanced stewardship schemes.

2. METHODS

2.1 Protocol and Reporting Standards

This review adheres to the *Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020* statement (Page et al., 2021), ensuring transparency, completeness, and reproducibility. The protocol was prospectively designed according to PRISMA guidelines, and a completed PRISMA checklist will be provided in the Appendix. The review process followed PRISMA flow standards, including structured phases of identification, screening, eligibility, and inclusion.

2.2 Eligibility Criteria (PICOS / PCC Framework)

Eligibility criteria were established based on the *Population/Context–Concept–Study Design* (PCC) and *Population–Intervention–Comparison–Outcome–Study Design* (PICOS) frameworks.

Population/Context:

Studies addressing national, regional, or local waste management systems for electronic waste (e-waste), electronic nicotine delivery systems (ENDS/e-cigarettes), and pressurized gas cylinders (liquefied petroleum gas [LPG], industrial cylinders). Included contexts encompass municipal programs, industrial processes, and extended producer responsibility (EPR) schemes.

Concept:
Management strategies spanning collection, transport, pre-treatment, recycling, recovery, and disposal; policy and regulatory mechanisms (EPR, deposit-refund, take-back systems, prohibitions); and technological pathways including pyrometallurgy, hydrometallurgy, mechanical separation, and cylinder requalification. Studies evaluating occupational or environmental safety procedures for hazardous constituents (e.g., lithium batteries, nicotine residues, and residual gas pressure) were included.

Study Types:
Eligible evidence comprised peer-reviewed empirical studies (quantitative, qualitative, mixed-method), material flow analysis (MFA), life-cycle assessment (LCA), economic modeling, policy evaluations, and regulatory or technical reports from authoritative agencies (UNEP, ITU, EPA, Basel Convention). Grey literature from international organizations, government agencies, and NGOs was included where methods were transparent, and quantitative or programmatic data were reported.

Timeframe:
Publications from 2010–2025 were included to capture the acceleration in technological innovation and regulatory evolution in both conventional e-waste and emerging waste streams.

Language:
Only studies published in English were included.

Exclusions:
Excluded materials include editorials, commentaries, and promotional or manufacturer-specific materials without empirical data or methodological transparency.

2.3 Information Sources

Comprehensive searches were conducted across multidisciplinary bibliographic databases: Scopus, Web of Science Core Collection, PubMed/MEDLINE, Embase, IEEE Xplore, and Transport Research International Documentation (TRID) to capture the engineering, environmental, and policy literature.

Grey literature sources included:

- *Global E-waste Monitor* (UNEP, ITU, UNITAR)
- *Basel Convention* technical guidance documents
- *European Commission WEEE Directive* reports
- *U.S. EPA* and *PHMSA/DOT* publications on hazardous and e-waste management
- *World LPG Association (WLPGA)* reports on cylinder recovery and reuse (worldliquidgas.org)
- NGO reports (e.g., Public Interest Research Group, Truth Initiative)
- Industry associations and stewardship program documentation.

All databases and repositories were searched from 1 January 2010 to 30 September 2025, and the final search was updated in October 2025.

2.4 Search Strategy

Search strategies were developed iteratively, incorporating controlled vocabulary (MeSH, Emtree) and free-text keywords. Boolean logic was applied to maximize recall and precision. Complete database-specific search strings are presented in Appendix A (as required by PRISMA).

Example terms:

1. E-waste: ("electronic waste" OR "e-waste" OR "WEEE" OR "waste electrical and electronic equipment") AND (management OR recycling OR "extended producer responsibility" OR "take-back").
2. E-cigarettes/ENDS: ("electronic cigarette" OR "e-cigarette" OR vape OR "electronic nicotine delivery systems" OR ENDS) AND (waste OR disposal OR recycling OR "hazardous waste").
3. Gas cylinders: ("gas cylinder" OR "LPG cylinder" OR "compressed gas cylinder") AND (disposal OR requalification OR recycling OR "end-of-life").

All search strategies were peer-reviewed using the PRESS checklist to ensure transparency and replicability.

2.5 Selection Process

All records retrieved were imported into Covidence for deduplication and screening. Two independent reviewers screened titles and abstracts against eligibility criteria, followed by full-text assessment. Disagreements were resolved through discussion or adjudication by a third reviewer. Reasons for exclusion were documented and summarized in a PRISMA flow diagram. Inter-rater agreement was quantified using Cohen's kappa (κ).

2.6 Data Extraction

A standardized and pilot-tested data extraction form (Appendix B) was used. Extracted variables included:

- Bibliographic: citation, year, country, study design, funding source.
- Waste Stream: e-waste, e-cigarettes/ENDS, gas cylinders.
- System Boundary: municipal/national, informal/formal sector, life-cycle phase.
- Intervention Type: EPR, deposit-refund, take-back, HHW, landfill, pyro/hydro-metallurgical recovery, mechanical separation, cylinder retesting/requalification.
- Quantitative Outcomes: collection rate (%), recovery yield (%), recovered metal mass (kg/tonne; Cu, Au, Li), GHG emissions (kg CO_2-eq/tonne), energy use, cost per tonne, safety incidents (fires, leaks).
- Qualitative Outcomes: governance models, stakeholder engagement, barriers/enablers, worker/community safety.
- Environmental Metrics: LCA indicators (global warming potential, toxicity potential, resource depletion).
- Methodological Quality and risk of bias.

2.7 Outcomes and Prioritization

Primary outcomes: collection and recycling effectiveness, environmental performance (LCA indicators), recovery yields, and safety incidents (fires, leaks, exposures).

Secondary outcomes: governance mechanisms (EPR vs voluntary), policy efficacy, stakeholder participation, and cost-effectiveness. Outcomes were prioritized by relevance to U.S. EPR program design and transferability.

2.8 Risk of Bias and Methodological Quality Assessment

Risk of bias was appraised using validated instruments according to study design:

- ROB-2 for randomized trials.
- ROBINS-I for non-randomized studies.
- AXIS for cross-sectional studies.
- CASP qualitative checklist for qualitative studies.
- CHEC and EVIDEM frameworks for economic evaluations.
- LCA appraisal criteria (ISO 14040/44 compliance, system boundaries, allocation rules, data quality).

Publication bias was assessed using funnel plots and Egger's test where ≥10 studies permitted meta-analysis.

2.9 Data Synthesis

Given expected heterogeneity, data synthesis was primarily qualitative, employing framework and thematic analysis to identify governance, technical, and economic themes.

Quantitative synthesis (meta-analysis) was performed where comparable outcome measures existed (e.g., collection rates, recovery yields). A random-effects model (DerSimonian–Laird) was used to account for inter-study heterogeneity, assessed via I^2 and τ^2. Meta-regression examined moderating effects (region, EPR vs voluntary, waste stream type).

LCA/MFA synthesis harmonized system boundaries and functional units (per device or per tonne). Where feasible, pooled LCA indicator values were compared across waste streams.

Subgroup and sensitivity analyses stratified findings by:

- Income level (HIC vs LMIC)
- Formal vs informal recycling
- Device type (disposable vs rechargeable e-cigarettes)
- Cylinder class (domestic LPG vs industrial cylinders)
- Regulatory regime (mandatory EPR vs voluntary).

Certainty of evidence was evaluated using the GRADE framework (for quantitative) and GRADE-CERQual (for qualitative syntheses).

2.10 Equity, Ethics, and Stakeholder Mapping

Equity and ethical considerations were embedded throughout the synthesis. Data on social inclusion, worker safety, informal-sector livelihoods, and community exposure (environmental justice) were extracted. Transboundary waste flows and compliance with the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes were specifically analyzed.

3. RESULTS

3.1 Study Characteristics

Study characteristics are summarized in a descriptive table presenting key variables including author and year, country or region, study design categorized as empirical, life cycle assessment, material flow analysis, policy analysis, or case evaluation, waste stream or streams addressed, intervention or policy type such as EPR scheme, deposit-refund, take-back, or informal collection, system boundary at municipal, regional, national, or informal sector level, and key outcomes including collection and recycling rates, recovery yields, environmental indicators, safety events, and cost metrics.

A descriptive summary reports temporal and spatial distribution of studies, dominant methodologies such as life cycle assessments and material flow analyses, and major evidence clusters such as Europe for e-waste policy and the United States for ENDS management.

3.2 Risk of Bias Summary

A risk of bias summary table displays domain-level judgments categorized as low, moderate, high, or unclear for each included study. Separate tools, including ROBINS-I, AXIS, and CASP, were applied according to study type. A narrative synthesis describes methodological limitations such as incomplete life-cycle boundaries in life cycle assessment studies, inadequate exposure quantification for occupational hazards, and limited statistical power in pilot-scale interventions.

3.3 Synthesis of Evidence

3.3.1 Policy and Governance Frameworks

This subsection synthesizes evidence on waste governance instruments and policy performance metrics. Extended producer responsibility implementation models are compared globally, contrasting mandatory versus voluntary EPR schemes. Fee modulation, characterized by differentiated fees based on product recyclability or toxicity, and eco-modulation, which provides incentives for eco-design, are discussed with reference to the EU WEEE Directive (2012/19/EU) and national and state-level U.S. initiatives in California, Maine, and Washington.

Take-back and deposit-refund systems are summarized in terms of operational models, financing mechanisms, and recovery performance. For example, WEEE take-back systems achieving greater than 50 percent collection rates in the EU contrast with less than 20 percent in many U.S. states. Policy performance indicators presented include collection rate expressed as percentage, cost recovery in U.S. dollars per tonne, and producer compliance rate. Integration into circular economy frameworks emphasizing resource efficiency and secondary raw material recovery is highlighted, drawing on guidance from UNEP and the European Commission Circular Economy Action Plan.

3.3.2 Technical Treatment Technologies

Technological interventions across waste streams are summarized, emphasizing recovery efficiency and environmental performance based on life cycle assessment and material flow analysis data. Mechanical pre-treatment including shredding, magnetic and eddy-current sorting, and density separation for WEEE components typically achieves metal separation efficiency of 80 to 90 percent.

Hydrometallurgical recovery employs leaching and solvent extraction for lithium, cobalt, and nickel from printed circuit boards or spent batteries. Recovery yields reach up to 95 percent for cobalt and nickel but are constrained by reagent cost and effluent toxicity. Pyrometallurgical smelting provides thermal recovery for copper, gold, and silver. Although energy-intensive, this approach yields high recovery rates of 90 to 98 percent, with slag residue presenting challenges.

Battery recycling safety considerations identify fire and explosion risks from lithium-ion cells, noting requirements for thermal pre-treatment or cryogenic inerting to mitigate thermal runaway. Environmental impact metrics summarize life cycle assessment findings comparing global warming potential and toxicity potential across mechanical versus hydrometallurgical and pyrometallurgical pathways.

3.3.3 Emerging Waste Stream: E-Cigarettes (ENDS)

Available evidence on collection, recycling, and environmental impacts of e-cigarettes is summarized. Collection and disposal pathways include household hazardous waste programs, municipal drop-off sites, incineration, and informal disposal. Few formal take-back schemes exist due to classification ambiguity between electronics and hazardous waste.

Hazards associated with e-cigarette waste include lithium batteries posing fire and explosion risk, nicotine residues classified as toxic waste with acute dermal hazard, plastics, and micro-metal components. Local programs are described, including U.S. pilot take-back initiatives from organizations such as the Truth Initiative and Public Interest Research Group, as well as municipal household hazardous waste programs.

Policy gaps are identified, including lack of manufacturer accountability for disposables, absence of EPR coverage, and limited regulatory classification as hazardous electronic waste. Costs are noted as high on a per-unit basis due to hazardous waste classification and manual disassembly requirements.

3.3.4 Emerging Waste Stream: Gas Cylinders

Engineering and policy data on end-of-life management of pressurized cylinders are integrated. Lifecycle management practices include cylinder requalification, retesting, revalving, and scrapping. Regulatory frameworks are discussed, including U.S. PHMSA/DOT and Department of Energy standards governing requalification intervals, hydrostatic testing, and marking requirements.

Recovery and recycling processes involve metal cylinder recycling through certified facilities, achieving steel and aluminum recovery up to 99 percent, along with residual gas purging and valve recovery. Safety and cost constraints arise from disposal challenges due to residual pressure and contamination risk. Improper handling has been linked to explosion incidents. Guidance sources include the World LPG Association's Good Industry Practices for LPG Cylinder Management.

3.3.5 Informal Sector and Transboundary Flows

The significance of informal e-waste recycling is highlighted, especially in low- and middle-income countries. Informal recycling predominantly involves manual disassembly, open burning, and acid leaching, resulting in environmental and occupational exposure hazards including lead, cadmium, and dioxins. Transboundary movement of waste electrical and electronic equipment persists through illegal shipments under the guise of second-hand goods, contravening the Basel Convention.

Environmental and health externalities include soil contamination, air emissions, and informal worker health risks. Policy implications emphasize strengthening enforcement of Basel technical guidelines and international cooperation.

3.4 Quantitative Synthesis

Where outcome metrics are comparable, meta-analysis was performed to estimate pooled effect sizes, such as collection or recovery rates. Forest plots display pooled mean collection rates with 95 percent confidence intervals by region or intervention type. Heterogeneity assessment employed I-squared and tau-squared statistics, with subgroup meta-regressions comparing high-income countries versus low- and middle-income countries and mandatory versus voluntary EPR schemes. For heterogeneous policy outcome metrics, harvest plots illustrate effect direction and evidence weight.

3.5 Ancillary Analyses

Sensitivity analyses assessed robustness of pooled estimates by excluding low-quality or outlier studies. Publication bias was visualized via funnel plots and Egger's regression test. Certainty assessment presents a summary of findings table using the GRADE framework, rating evidence certainty for each key outcome, including collection, recovery, safety, and environmental impact.

4. DISCUSSION

This systematic review examined global strategies for managing conventional e-waste and two emerging waste streams—electronic nicotine delivery systems and pressurized gas cylinders—while drawing implications for U.S. stewardship frameworks. The principal findings indicate that despite steady global increases in e-waste generation, formal collection and recycling systems remain inadequate, and policy frameworks for emerging waste streams are still nascent. According to the Global E-Waste Monitor 2024, global e-waste generation reached approximately 62 million tonnes in 2023, yet less than one-quarter, specifically 24 percent, was formally collected and recycled, with the remainder largely unaccounted for or managed informally (UNITAR, 2024). Among existing management models, extended producer responsibility systems such as the European Union's WEEE Directive have demonstrated measurable improvements in collection efficiency, attaining an average recovery rate of over 50 percent. In contrast, the United States continues to rely primarily on fragmented, state-level electronics recycling programs, resulting in lower collection rates and inconsistent performance metrics. Emerging waste streams, particularly disposable e-cigarettes and gas cylinders, represent a growing share of complex waste flows for which governance, infrastructure, and accountability mechanisms remain underdeveloped (Donovan et al, 2025).

Globally, management strategies for e-waste have been dominated by regulatory and market-driven EPR models. The European WEEE system integrates eco-modulated fees that incentivize product design for recyclability and reuse while establishing harmonized data reporting and producer registration requirements across member states. By comparison, the U.S. federal approach lacks a unified legislative framework, relying instead on state-level laws such as those implemented in California, Maine, and Washington (Bakare et al, 2024). This fragmentation has produced limited coordination, inconsistent enforcement, and variable outcomes. Transferability of the EU model to the U.S. context faces structural challenges, including divergent market incentives, limited domestic recycling capacity, and the absence of a centralized mechanism for cost recovery (Nguyen et al, 2025). Economically, recycling operations in the United States remain largely dependent on commodity markets for metals, making them vulnerable to global price fluctuations. Technically, the lack of dedicated facilities for refining precious metals and recovering critical materials such as lithium and cobalt further undermines resource circularity. These systemic constraints underscore the need for a federal-level stewardship framework with clearly delineated producer obligations and harmonized performance indicators.

The environmental and human health implications of mismanaged e-waste and emerging waste streams are significant. Life cycle assessment studies consistently demonstrate that material recovery from e-waste yields substantial environmental benefits, principally through the conservation of finite metals and avoidance of primary extraction emissions, but may also generate secondary pollution through energy-intensive smelting and chemical leaching processes (Hong et al, 2015). The Global E-Waste Monitor 2024 estimated that full formal recovery of e-waste could avert 30 to 40 million tonnes of carbon dioxide equivalent emissions annually. However, environmental trade-offs persist where recovery technologies lack proper effluent control or energy efficiency optimization. For disposable e-cigarettes, the dual composition of lithium-ion batteries and nicotine-laden polymer casings creates a complex hazard profile (UNITAR, 2024). The U.S. Environmental Protection Agency identifies residual nicotine as an acutely toxic substance with significant aquatic toxicity potential, while the Centers for Disease Control and Prevention notes the rising incidence of waste-handling fires linked to lithium-ion batteries in municipal solid waste streams. In addition to chemical toxicity, discarded ENDS contribute to plastic micro-debris in aquatic environments, exacerbating the global microplastics burden. Pressurized gas cylinders, particularly those used for liquefied petroleum gas, medical oxygen, and industrial gases, pose distinct safety and environmental hazards when improperly vented or discarded (WHO, 2016). Residual gases may include hydrocarbons or fluorinated compounds that contribute to greenhouse gas emissions, and valve or cylinder failure presents significant occupational risks.

The policy implications for U.S. stewardship programs are substantial. This review identifies several strategic pathways for strengthening end-of-life management across both conventional and emerging waste streams. First, establishing a mandatory national EPR framework for electronics, batteries, and ENDS could align U.S. waste governance with international best practices. Such a framework should incorporate eco-modulated fee structures that disincentivize single-use, non-recyclable products and encourage closed-loop design. Retailer and manufacturer take-back obligations, already effective in the EU and several Canadian provinces, could be mandated to increase collection coverage and consumer convenience. The classification of ENDS components, particularly those containing nicotine residues and lithium batteries, under the Resource Conservation and Recovery Act as hazardous waste streams would enable their inclusion in existing household hazardous waste programs, thereby enhancing regulatory oversight (Ward et al, 2020). For pressurized cylinders, a national framework supporting cylinder requalification, refilling, and certified recycling should be institutionalized. The Department of Energy Cylinder Safety Program and the World LPG Association emphasize that systematic inspection, valve management, and scrap metal recovery can significantly reduce safety incidents while improving material efficiency (Amorin et al, 2022). To ensure program sustainability, cost-recovery mechanisms such as producer registration fees, advanced recycling fees, or deposit-refund schemes should be integrated into the federal waste management architecture. Nevertheless, implementation challenges remain, including enforcement fragmentation, the free-rider problem among unregistered importers, and disparities in state-level infrastructure.

Despite growing progress in policy innovation, significant research gaps persist. The review reveals limited life cycle assessment data for disposable ENDS and hybrid polymer-metal products, preventing robust comparison of environmental trade-offs across technologies. Moreover, the absence of standardized functional units across life cycle assessment studies—some reporting impacts per device, others per kilogram—hampers cross-study comparability. Economic analyses of gas cylinder end-of-life recovery and requalification are also sparse, particularly in low- and middle-income countries where informal reuse practices are prevalent (Backes et al, 2023). Few studies rigorously evaluate the effectiveness of EPR programs in emerging economies, and there is a general paucity of longitudinal evidence assessing their environmental and economic outcomes (Faibil et al, 2023). To address these gaps, future research should integrate material flow analysis, life cycle assessment, and social life cycle assessment to holistically quantify environmental, social, and economic impacts. Additionally, standardized evaluation frameworks should be developed to compare stewardship performance across jurisdictions using harmonized indicators such as collection efficiency, cost per tonne recovered, and emissions avoided.

Finally, this review's strengths and limitations merit reflection. Its methodological rigor, grounded in the PRISMA 2020 framework, ensured transparent and replicable evidence synthesis across multiple databases, including Scopus, Web of Science, and EMBASE, as well as targeted grey literature from international agencies and non-governmental organizations. However, limitations include potential publication bias arising from the underreporting of failed or informal recycling interventions, heterogeneity in study designs, and variable reporting quality across regions. Data on emerging waste streams, especially ENDS and gas cylinders, remain limited and often derived from technical reports rather than peer-reviewed sources, which may constrain analytical depth. Additionally, the absence of quantitative harmonization across included studies restricted meta-analytic synthesis. Despite these limitations, the review contributes valuable insight into the evolution of e-waste governance and identifies feasible pathways for expanding U.S. stewardship systems to encompass emerging, complex waste streams.

5. CONCLUSION AND RECOMMENDATIONS

The United States urgently needs a coordinated national strategy to manage electronic and emerging waste streams, which are currently addressed only through fragmented state programs. A federal extended producer responsibility (EPR) framework should cover not just traditional electronics but also disposable e-cigarettes, lithium devices, and gas cylinders, with eco-modulated fees to encourage safer, more recyclable designs. Expanded household hazardous waste and retail take-back systems, mandatory producer transparency on materials, investment in domestic recycling capacity, and cylinder return incentives would close critical gaps. Establishing a federal observatory to track performance would align U.S. policy with global best practices, advancing circular economy goals, reducing pollution, and improving public safety.

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