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Mini-review: Engineering Controls and Best Practices for Institutional Electronic-Waste Handling and Lithium-Ion Battery Risk Reduction in the United States

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Abstract

Purpose: This mini-review aims to synthesize peer-reviewed evidence and current U.S. regulatory guidance to develop a practical engineering control framework for institutional electronic waste (e-waste) and lithium-ion battery risk reduction in the United States.

Methodology: The review employed a targeted literature search of academic databases including PubMed and Google Scholar, supplemented by structured analysis of U.S. federal guidance documents, certification standards, and regulatory resources. Sources were selected based on relevance to institutional e-waste lifecycle management, battery fire prevention, data sanitization, certified recycler standards, and compliance requirements.

Findings: Effective institutional e-waste programs share a common structural profile. They treat e-waste as a socio-technical system and combine physical engineering controls, documented procedures, staff training, and auditable chain-of-custody records tied to measurable performance indicators. Key control domains identified include upstream procurement and asset management, governance and secure staging, data sanitization, battery triage and containment, transport readiness, downstream vendor qualification, and performance management. The review proposes an implementation template and evidence map that institutions can adapt to design defensible programs.

Unique Contribution to Theory, Practice and Policy: This review applies the occupational health and safety hierarchy of controls framework to the institutional e-waste domain, producing a structured control taxonomy that connects program design decisions to defensible documentation. For practice, it provides a control map and measurement template that institutions can operationalize immediately. For policy, it highlights the alignment between institutional program design and U.S. national recycling goals, federal battery fire prevention guidance, and transport compliance requirements under the U.S. Department of Transportation Hazardous Materials Regulations.

Keywords: *Electronic Waste, Lithium-Ion Batteries, Institutional Waste Management, Engineering Controls, Data Sanitization, Certified Recycling, Fire Risk Reduction, Compliance Management*

JEL Classification Codes: *Q53, Q55, K32, M14*

INTRODUCTION

Electronic waste (e-waste) refers to discarded electrical and electronic equipment, including devices with plugs, batteries, or embedded circuitry. E-waste is among the fastest growing solid waste streams globally, and it combines hazardous constituents, for example lead, mercury, brominated flame retardants, and battery electrolytes, with high-value materials that are central to modern supply chains (Kiddee et al., 2013; Sthiannopkao & Wong, 2013; World Health Organization [WHO], 2024). In 2022, the world generated an estimated 62 million tonnes of e-waste, while only 22.3% was documented as formally collected and recycled (WHO, 2024; Forti et al., 2020; Balde et al., 2024). Health evidence shows that unsafe handling and informal processing can create exposures with measurable adverse outcomes, especially for children and pregnant women (Grant et al., 2013; Parvez et al., 2021; WHO, 2021).

Within the United States, the operational burden of e-waste management is distributed across state programs, municipal services, institutional property managers, and private sector recyclers. In the absence of a comprehensive federal e-waste statute, reuse and recycling policy has largely evolved through state laws, agency guidance, and voluntary partnerships (Government Accountability Office [GAO], 2010; Environmental Protection Agency [EPA], 2013; National Conference of State Legislatures [NCSL], 2025; eCycle Clearinghouse, 2026; EPA, 2025a). At the same time, the device mix is changing quickly. Consumer electronics and institutional IT assets increasingly incorporate lithium-ion batteries, and battery-related fire risk has become a high-consequence operational hazard in waste systems. A U.S. Environmental Protection Agency (EPA) analysis identified 245 fires at 64 waste facilities between 2013 and 2020 that were caused by, or likely caused by, lithium-ion or lithium metal batteries, with incidents distributed across 28 states and all EPA regions (EPA, 2021).

In institutional settings, e-waste is not simply an environmental problem. Universities, municipalities, hospitals, and large employers maintain large inventories of devices that include sensitive data, regulated materials, and batteries. End-of-life workflows typically involve multiple handoffs, including internal storage, transport, refurbishment decisions, and downstream recycling. Each handoff creates exposure points for non-compliance, worker injury, data loss, and fire. In practice, institutional e-waste programs succeed when they are designed as management systems with defined roles, documented controls, training, audit processes, and measurable performance indicators that can be sustained through staff turnover and budget cycles.

Problem Statement

Despite growing volumes of institutional e-waste, documented battery fire incidents in U.S. waste facilities, and well-established federal guidance from EPA, OSHA, and the U.S. Department of Transportation, most institutional e-waste programs continue to rely on administrative messaging and informal vendor relationships rather than structured, engineered control systems. The scholarly literature addresses e-waste health impacts and policy frameworks at a broad level but provides limited operationally specific guidance for institutions seeking to design programs that are defensible under regulatory inspection, audit, and risk management requirements. There is a gap between what authoritative guidance recommends and what institutions can readily implement in practice. This review addresses that gap by synthesizing evidence and guidance into a structured engineering control framework organized across the institutional electronics lifecycle. The primary beneficiaries are environmental health and safety managers, facilities and IT asset managers, compliance officers, and sustainability program leads at universities, municipalities, hospitals, and large private employers who are responsible for managing end-of-life electronics in regulated U.S. operating environments.

This mini-review focuses on engineering controls and best practices that institutions can deploy to reduce risk and improve outcomes. The central premise is that institutional e-waste programs should be engineered in a manner similar to environmental health and safety programs: hazards are identified, controls are layered, performance is measured, and corrective actions are documented. The review synthesizes peer-reviewed evidence on institutional disposition practices and health impacts, together with U.S. guidance documents and recognized recycling standards, to provide a defensible control framework that aligns environmental compliance, battery fire prevention, and information security.

METHODOLOGY

Research Design

This paper is a mini-review. The goal is to synthesize evidence and practice guidance into an operational control framework for institutional e-waste management, rather than to conduct a full systematic review or meta-analysis. The study employed a qualitative, narrative synthesis approach drawing on targeted literature searches of academic databases and structured review of authoritative U.S. regulatory and guidance sources.

Target Population and Scope

The target population for this review consists of institutions in the United States, including universities, municipalities, hospitals, and large private employers, that maintain significant inventories of end-of-life electronic devices and are subject to U.S. federal and state environmental, occupational safety, and hazardous materials transport regulations. The scope is limited to institutional operational settings; consumer household practices and industrial battery manufacturing are excluded unless they contain directly applicable controls for collection, storage, or transport of institutional e-waste.

Source Identification and Sampling

Literature and guidance sources were identified through targeted searches of academic databases, including PubMed and Google Scholar, using search terms including institutional e-waste management, lithium-ion battery fire, data sanitization, certified electronics recycling, and universal waste regulations. Peer-reviewed literature was prioritized for evidence on institutional disposition practices and health impacts. Grey literature was prioritized for regulatory requirements, shipping controls, and technical practice guidance. Core U.S. sources included EPA guidance on electronics and batteries, the EPA analysis of lithium-ion battery fires in waste systems, OSHA occupational safety resources, U.S. Department of Transportation Pipeline and Hazardous Materials Safety Administration (PHMSA) transport compliance guidance, and National Institute of Standards and Technology (NIST) data sanitization guidance (EPA, 2021; EPA, 2025g; EPA, 2025b; PHMSA, 2024; Chandramouli & Hibbard, 2025).

Inclusion and Exclusion Criteria

Included sources addressed at least one of the following domains in an institutional or operational context: (i) lifecycle management of end-of-life electronics; (ii) lithium-ion battery handling, storage, fire prevention, or transport; (iii) data sanitization and chain-of-custody controls for retired IT assets; (iv) certified recycler standards and audit expectations; or (v) regulatory requirements influencing institutional programs. Sources focused exclusively on battery electrochemistry, consumer charging behaviors, or industrial battery manufacturing were excluded unless they contained directly applicable safety controls for collection, storage, or transport.

Data Synthesis and Presentation

Synthesis used an engineering controls lens. Evidence was organized across the electronics lifecycle and mapped into a set of institutional control domains. For each control domain, the review identifies control objectives, implementation practices, and potential evidence artifacts that institutions can retain to demonstrate compliance and program maturity. Tables 1 and 2 summarize the control map and propose a measurement template that can be adapted by institutions. The synthesis approach follows the hierarchy of controls framework established in occupational health and safety practice, which organizes interventions from most to least effective across elimination, substitution, engineering controls, administrative controls, and personal protective equipment (PPE). This framework is described further in Section 4.1.

RESULTS

In institutional environments, e-waste programs can be described as a lifecycle system with defined stages and failure points. The stages include (i) upstream procurement and asset registration; (ii) use-phase handling and repair decisions; (iii) retirement triggers and decommissioning; (iv) secure staging and aggregation; (v) battery identification and triage; (vi) transport to downstream service providers; and (vii) final reuse, recycling, or disposal. Failure points are most common at transitions between stages, where assets move between people, spaces, and contractors.

Two features differentiate institutional e-waste from many other waste streams. First, institutional assets often contain regulated or sensitive data. Data management introduces additional requirements for chain-of-custody, sanitization verification, and contractual controls, and these requirements can drive process design even when the environmental hazard profile would otherwise allow simpler handling (Chandramouli & Hibbard, 2025). Second, the embedded battery profile introduces a concentrated fire hazard. Lithium-ion battery incidents can occur during storage, handling, compaction, and transport, and EPA's analysis of fires across waste facilities shows the breadth of the problem across the waste management process (EPA, 2021). For institutions, these two features make ordinary end-of-life handling insufficient. Controls must be engineered to manage both information security and physical hazards.

Upstream Procurement and Asset Lifecycle Controls

Procurement policy and asset lifecycle planning influence downstream e-waste risk. When institutions purchase devices designed for repairability, upgradeability, and safer material profiles, they can reduce both waste generation and hazardous handling complexity. Procurement programs that reference sustainability criteria and supplier disclosure requirements can drive changes in device design and vendor behavior. The EPEAT ecolabel criteria, maintained by the Global Electronics Council, provide a structured approach for purchasers to select products with improved sustainability attributes, including criteria related to circularity and chemicals of concern (Global Electronics Council, 2026; EPA, 2020).

From an engineering management perspective, procurement controls operate as upstream hazard prevention. They can include documented purchasing standards, minimum sustainability requirements for core device categories, and life-extension strategies that prioritize upgrades and repair where feasible. EPA guidance for electronics donation and recycling explicitly encourages reuse and upgrading, and it emphasizes battery removal and separate management when devices are retired (EPA, 2025c). These upstream decisions reduce the quantity of unmanaged batteries entering internal storage and downstream transport.

Governance, Staging, and Management System Design

Institutions benefit from treating e-waste as a controlled material stream rather than surplus property. A controlled stream uses explicit triggers for retirement, standardized decommissioning steps, and defined storage conditions. Evidence from institutional studies shows that end-of-life electronics disposition is frequently influenced by auctions and resale pathways, with variable visibility into downstream practices (Babbitt et al., 2011). For institutional programs seeking defensible environmental and data outcomes, this variability creates a need for structured governance.

A practical governance model assigns clear roles to asset owners, IT or property management, environmental health and safety personnel, and contracted downstream vendors. Governance should define decision rules for reuse versus recycling; battery removal and packaging requirements; documentation artifacts such as inventories and transfer logs; and escalation procedures for damaged or swollen batteries. This governance can be implemented through a management system approach consistent with established recycling standards. For example, both the R2 standard and the e-Stewards standard emphasize structured management systems, legal compliance, and documented processes as the foundation for responsible electronics reuse and recycling (SERI, 2021; Basel Action Network, 2022).

Institutions can also align governance and documentation with broader environmental management system frameworks that many organizations already use for compliance and continuous improvement. ISO 14001 establishes a plan-do-check-act structure for environmental management systems, and similar integrated standards exist for recycling industry operations (International Organization for Standardization [ISO], 2015; RIOS, 2026). Using these structures can reduce implementation friction by connecting e-waste controls to existing audit cycles, corrective action processes, and management review practices.

Data Sanitization and Chain-of-Custody Controls

Data sanitization is central to institutional e-waste management because it transforms electronics disposition from a disposal task into an information risk management task. Institutions manage devices that may contain personally identifiable information, protected health information, research data, or proprietary business information. The NIST Guidelines for Media Sanitization provide a widely cited framework for selecting sanitization techniques based on information sensitivity and media characteristics, and they include a sample certificate of sanitization form that illustrates the type of documentation expected for a defensible program (Chandramouli & Hibbard, 2025).

In institutional practice, data sanitization controls should be integrated into the physical e-waste workflow. A common failure mode occurs when devices are staged for recycling before sanitization is verified, creating an opportunity for unauthorized access. A defensible control sequence is to require asset identification, sanitization method selection, execution, and verification before devices leave secure control. Documentation should link device identifiers to sanitization outcomes and to downstream transfers. Programs that adopt recognized recycler standards can reinforce these controls. The e-Stewards standard includes data security requirements and references NAID AAA certification as a data security standard used within the program context (Basel Action Network, 2022). Where a third-party vendor performs data destruction, institutions can request evidence of information destruction certifications, such as NAID AAA where appropriate, to strengthen due diligence and to document reasonable vendor selection practices (i-SIGMA, 2026).

Battery Triage, Containment, and Fire Risk Reduction

Lithium-ion battery fire risk is a central driver of engineering controls for institutional e-waste programs. The hazard is rooted in high stored energy, flammable electrolyte, and the potential for internal short circuits when batteries are damaged, crushed, overheated, or improperly packaged. Thermal runaway events can lead to intense fires, toxic smoke, and re-ignition risk. Occupational safety resources emphasize these hazards and recommend controls such as preventing damage, separating batteries, and using appropriate storage and charging practices (OSHA, 2025; National Fire Protection Association [NFPA], 2026). Public education initiatives led by fire safety organizations also reinforce practical prevention behaviors and support institutional training efforts, particularly where staff handle mixed consumer devices and small-format batteries (Fire Safety Research Institute [FSRI], 2023; Battery Fire Safety, 2026).

In the waste context, batteries become vulnerable to damage through collection and handling processes. EPA's analysis documents a national pattern of incidents in which batteries in the waste stream caused fires in materials recovery facilities, transport vehicles, and other waste management locations (EPA, 2021). For institutions, an effective prevention strategy begins upstream by preventing lithium batteries from entering mixed trash or commingled recycling. EPA guidance for used lithium-ion batteries advises that such batteries should not be placed in household garbage or recycling bins and recommends taping terminals and bagging batteries to prevent short circuits (EPA, 2019; EPA, 2025d).

Engineering controls for battery risk reduction in institutions can be organized into identification, containment, separation, and escalation. Identification controls include training staff to recognize battery types and damaged battery indicators, and incorporating battery checks into device decommissioning workflows. Containment controls include non-conductive packaging, terminal protection, and physical separation of batteries to prevent contact. Separation controls include dedicated collection containers, clear signage, and restricted access areas. Escalation controls include protocols for damaged, swollen, or leaking batteries, including isolation, notification, and coordination with hazardous waste or fire safety personnel. Universal waste regulations and hazard communication requirements can also influence how batteries are accumulated and managed, depending on jurisdiction and handler classification (eCFR, 2026a; eCFR, 2026b).

Transport Readiness and Hazardous Materials Compliance Interface

Transport is a high-risk transition point because it combines physical movement, vibration, and the introduction of third-party carriers. Transport compliance also introduces legal requirements when batteries meet the definition of hazardous materials. Federal universal waste regulations explicitly require handlers to comply with applicable Department of Transportation requirements when offering universal waste that meets hazardous materials definitions (eCFR, 2026a).

In practice, institutions should design transport readiness controls that address packaging integrity, documentation, and vendor selection. Packaging practices that support terminal protection and movement prevention are emphasized by battery stewardship programs and shipping guidance. For example, Call2Recycle provides minimum terminal protection guidance that includes bagging or taping approaches to prevent short circuits in collection and shipping contexts (Call2Recycle, 2023). Transport guidance for lithium batteries typically emphasizes classification, marking, labeling, packaging, and documentation obligations, and institutions should confirm specific requirements for the battery type and shipping mode used (PHMSA, 2024).

A key institutional control is to restrict shipments to qualified downstream vendors who can manage batteries safely. Institutions should maintain written procedures that define when batteries can be shipped as universal waste, when they require hazardous waste controls, and when specialized response is needed for damaged batteries. Documentation artifacts include shipping papers where applicable, bills of lading, manifests, and vendor acknowledgements of receipt.

Downstream Vendor Qualification and Certified Recycling Controls

Downstream recycler qualification is a central control domain because institutions often lack the ability to verify end processing directly. EPA provides resources on electronics donation and recycling and has evaluated the implementation of the R2 and e-Stewards certification programs, finding that they are generally implemented well while identifying opportunities for improvement (EPA, 2016a; EPA, 2016b). Institutions can use certification to reduce the risk of improper processing, uncontrolled exports, and environmental or occupational harm.

Certified recycler selection should be paired with contractual and audit controls. Contracts can specify requirements for downstream processing, prohibition of export to non-permitted destinations, data security verification, and reporting of material destinations. Institutions can request evidence of certification status, audit reports where available, and downstream vendor lists. Certification programs provide structured requirements for environmental health and safety management systems, legal compliance, and tracking of incoming and outgoing shipments (SERI, 2021; Basel Action Network, 2022).

In some institutional contexts, transboundary movement can be relevant. International controls under the Basel Convention influence the classification and control of e-waste shipments, and recent amendments strengthen the control procedure for cross-border movements (Basel

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Convention, 2024; EPA, 2024). Even when institutions do not export directly, downstream pathways may include export by third parties, and therefore institutions benefit from due diligence controls and from selecting processors with strong downstream accountability.

Performance Indicators and Audit-Ready Evidence

Beyond preventing incidents, institutions require measurable indicators that show whether a program is performing. Waste programs often struggle when success is not operationally defined. EPA's National Recycling Strategy emphasizes improving collection and materials management infrastructure and engaging communities in the implementation of recycling improvements (EPA, 2021b). In the institutional context, performance indicators should capture safety, compliance, and circularity outcomes. Safety indicators include battery incident counts, near misses, and training completion rates. Compliance indicators include audit findings, container inspections, and documentation completeness. Circularity indicators include reuse rates, certified recycling rates, and recovery of high-value materials.

Table 2 proposes a measurement and evidence template that aligns the engineering control domains with evidence artifacts. This template is intended for adaptation. Institutions can scale the template by program size and risk profile, and they can use it as a basis for internal audits and management review.

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Table 1: Institutional Engineering Control Domains for E-Waste Handling and Lithium-Ion Battery Risk Reduction (Illustrative)

Control domain	Control objective	Illustrative controls	Example evidence artifacts
Procurement and asset management	Reduce downstream hazards and extend device life through purchasing policy and lifecycle planning.	EPEAT-based purchasing criteria; repair and upgrade pathways; device inventory and asset tagging; retirement triggers tied to condition and security risk.	Purchasing standards; approved product lists; asset inventory; repair records; device lifecycle reports.
Governance and secure staging	Maintain physical control of assets and prevent commingling with general waste streams.	Designated staging area; controlled access; segregation by device type and hazard; documented roles and escalation procedures.	Site maps and photos; staging SOPs; inspection logs; staff role assignments; incident reports.
Data sanitization and chain-of-custody	Prevent data loss and unauthorized access during disposition.	Sanitization method selection per sensitivity; verification prior to release; chain-of-custody logging; vendor data security requirements.	Sanitization certificates; verification logs; transfer logs; contracts and vendor attestations; audit checklists.
Battery triage and containment	Prevent short circuits, thermal events, and fire through identification, separation, and containment.	Battery identification checks; terminal protection; non-conductive packaging; dedicated battery containers; damaged battery isolation protocols.	Training records; container labels; packaging instructions; inspection checklists; damaged battery incident documentation.
Transport readiness and compliance	Ensure safe handoff and legal compliance during transport.	Packaging integrity checks; shipping readiness checklist; qualified carriers and vendors; documentation retention per requirements.	Bills of lading/manifests; packing checklists; vendor receipts; transporter qualifications; shipment tracking logs.
Downstream recycler qualification	Reduce risk of improper processing, uncontrolled exports, and environmental harm.	Selection of certified recyclers; contract controls on downstream processing; periodic due diligence reviews; downstream transparency requests.	Certificates (R2/e-Stewards); contracts; downstream vendor lists; audit summaries; disposition reports.
Performance management and continuous improvement	Demonstrate program performance and enable corrective actions.	KPIs for safety, compliance, and circularity; internal audits; management review; corrective action tracking.	KPI dashboards; audit reports; corrective action logs; management review minutes; annual program reports.

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Table 2: Example Measurement and Evidence Template for Institutional E-Waste and Battery Management Programs

Metric category	Example KPI	Measurement approach	Evidence source
Inventory control	Percent of retired devices recorded in inventory within 5 business days	Count devices in staging vs. inventory entries; compute percentage monthly	Asset inventory export; staging log
Data security	Percent of devices sanitized and verified prior to release	Track sanitization certificates and verification checks; compute percentage by quarter	Sanitization certificates; chain-of-custody logs
Battery risk	Number of battery-related incidents (fires, overheating, swelling) per quarter	Incident reporting and near-miss capture; normalize by volume of batteries handled	Incident reports; EHS logs
Battery segregation	Percent of devices with batteries removed or clearly identified before staging	Random audits of staged loads; record compliance rate	Audit checklist; photo documentation
Training	Training completion rate for staff handling devices and batteries	Roster-based completion tracking; annual refresher compliance	Training attendance sheets; LMS records
Vendor accountability	Percent of shipments sent to certified recyclers	Track shipment destinations; verify certification status at time of shipment	Vendor certificates; shipping logs
Circularity outcomes	Reuse/refurbishment rate (by units or weight)	Track devices routed to reuse vs. recycling; report annually	Disposition reports; resale/refurbishment records
Audit outcomes	Corrective actions closed within 60 days	Track findings and closure dates; compute closure rate	Audit reports; corrective action tracker

Table 1 summarizes the engineering control domains, key control objectives, and example evidence sources. The intent is to provide institutions with a practical map that connects program design decisions to defensible documentation. While the details of implementation will vary across institutions, the control domains remain stable: procurement and asset management, governance and staging, data sanitization, battery triage and containment, transport readiness, downstream vendor qualification, and performance evaluation.

Discussion

The Hierarchy of Controls as Theoretical Framework

The hierarchy of controls is the organizing theoretical framework of this review. Established in occupational health and safety practice and codified in guidance from the National Institute for Occupational Safety and Health, the hierarchy ranks interventions from most to least effective: elimination, substitution, engineering controls, administrative controls, and personal protective equipment (PPE). This framework has been applied in environmental health, public health systems design, and increasingly in waste management program evaluation. Its application to institutional e-waste management provides a structured basis for assessing program maturity and identifying where higher-order controls can replace lower-order ones.

Institutional e-waste risk is frequently addressed through administrative actions such as awareness emails, periodic collection events, and vendor pickup scheduling. The evidence synthesized in this review supports a more durable approach: institutional systems perform best when prevention is engineered into the lifecycle, supported by documentation and verification routines, and reinforced by user-facing disposal interface design (Babbitt et al., 2011; EPA, 2021).

Elimination and Substitution (Upstream Design Choices)

Institutions can reduce end-of-life risk by limiting the volume and diversity of battery chemistries and device types in circulation, and by prioritizing procurement pathways that include take-back, repairability, and planned disposition routes. These decisions reduce downstream handling complexity and increase the probability of reuse, refurbishment, or controlled recycling. Procurement is a high-leverage control point because it shapes the inventory that will later become e-waste.

Engineering Controls (Physical and Systems-Based Controls)

Engineering controls are the central differentiator in institutional e-waste handling. They include segregated collection pathways, appropriate containers, controlled staging areas, terminal protection practices, safe packaging workflows, and secure access control for sensitive devices and storage areas. The battery fire record observed across waste management facilities between 2013 and 2020 reinforces the importance of preventing batteries and battery-containing devices from entering pathways where crushing, compaction, or uncontrolled friction can occur (EPA, 2021).

Engineering controls also include downstream interface design. Vendor qualification and certified recycler use function as engineering controls at the system boundary because they influence what happens to equipment and batteries after the institution transfers custody. EPA's guidance on certified electronics recyclers recognizes R2 and e-Stewards as accreditation-based certification standards in this space (EPA, 2025b).

Administrative Controls (Procedures, Training, and Governance)

Administrative controls make engineering controls executable across staff turnover and decentralized sites. This includes standard operating procedures, role-based training requirements, chain-of-custody documentation, incident response pathways, audit routines, and corrective action systems. OSHA's lithium-ion battery safety fact sheet emphasizes that employers should ensure exposed workers receive information and training about lithium-ion battery hazards, reinforcing that workforce competence is a core safety control when batteries are handled, stored, or transported (OSHA, 2025).

Personal Protective Equipment

PPE is relevant for specific handling tasks and incident response, yet it addresses exposure at the worker interface rather than controlling system-level risk generation. PPE becomes more effective when engineering and administrative controls reduce the frequency of high-risk handling scenarios.

This hierarchy framing supports a central thesis: institutional e-waste programs that rely heavily on administrative messaging without embedding physical controls and verification routines struggle to sustain compliance performance over time.

Common Institutional Failure Patterns and Implementation Implications

Across municipal and campus settings, recurring failure patterns are visible in practice and are consistent with the risk mechanisms described in EPA's battery fire analysis and related safety guidance (EPA, 2021; OSHA, 2025).

Failure pattern: unclear ownership across procurement, IT, facilities, and EHS

When end-to-end responsibility is diffuse, devices exit user custody through informal handoffs. The operational result is incomplete chain-of-custody, inconsistent battery segregation, and inconsistent data sanitization documentation. Governance is therefore a practical control domain, not a managerial preference, because it determines whether the control stack operates consistently.

Failure pattern: commingled collection that aggregates batteries without triage

Collection points that accept mixed electronics increase the probability that damaged, swollen, recalled, or unknown-condition batteries enter staging areas without containment. EPA's consumer guidance emphasizes terminal protection and separation to prevent short circuits and fires, and institutions can translate that guidance into standardized intake and staging workflows (EPA, 2018).

Failure pattern: weak staging and storage engineering

Staging areas become accumulation points that lack segregation rules, appropriate container specifications, and inspection routines. The risk increases when batteries are stored near combustibles or in containers that allow conductive contact. The corrective approach is to treat staging as a designed system: container specification, labeling, access control, inspection cadence, and incident escalation protocols.

Failure pattern: transport and shipping compliance handled informally

Institutions often underestimate the transport compliance complexity for lithium batteries, especially damaged, defective, or recalled units. PHMSA states that lithium batteries are regulated as hazardous materials under the U.S. DOT Hazardous Materials Regulations (49 CFR Parts 171-180), and the agency provides scenario-based shipper guidance (PHMSA, 2023; PHMSA, 2024). A program that lacks a defined shipping pathway tends to rely on ad hoc shipments, which increases compliance risk and can delay removal of higher-risk batteries from institutional sites.

Failure pattern: downstream vendor selection based on convenience rather than controlled criteria

Downstream mismanagement creates environmental and reputational risk, and it can undermine the integrity of institutional sustainability reporting. EPA's certified recycler guidance supports the use of certification frameworks such as R2 and e-Stewards as practical screening tools, which institutions can then reinforce through contract clauses and audit rights (EPA, 2025b).

Failure pattern: data sanitization treated as separate from environmental disposition

Data security failures occur when devices with sensitive information enter disposal pathways without documented sanitization and verification. NIST SP 800-88r2 provides updated guidance on media sanitization program design, techniques, and control expectations, reinforcing that sanitization is a structured program requirement rather than an informal step (Chandramouli & Hibbard, 2025).

The implementation implication of these patterns is practical. Institutions need an integrated workflow that aligns the physical pathway of devices and batteries with compliance documentation, worker training, and downstream vendor controls.

Institutional Controls as Municipal and Campus Infrastructure

A recurring question in the U.S. waste management environment is whether institutional controls matter outside the institution. The evidence supports the conclusion that institutional controls are municipal infrastructure in a functional sense. Universities, public agencies, and large employers are major purchasers and disposers of electronics. Their end-of-life behavior influences local collection volumes, downstream vendor demand, and the probability that battery-containing devices enter municipal waste and recycling streams.

Municipalities benefit when large institutions operate controlled e-waste programs for three reasons. First, upstream segregation by institutions reduces the probability that batteries enter crushing and compaction pathways downstream, reducing battery-related incidents across local waste handling infrastructure (EPA, 2021). Second, institutional programs improve the quality and traceability of material streams, which supports program legitimacy and can reduce illegal dumping pressure for hard-to-dispose electronics. Third, institutional programs can serve as pilot sites for standardized control artifacts such as signage, training modules, intake protocols, and chain-of-custody systems that can be adapted by municipal facilities.

Universal waste requirements provide a common compliance anchor for battery handling. Federal regulations under 40 CFR Part 273 establish management standards for universal waste categories including batteries (eCFR, 2026a). Institutions that formalize universal-waste-aligned practices create program predictability and defensibility, which supports cross-site replication.

Evidence Gaps and a Research Agenda

The peer-reviewed literature addressing institutional e-waste program performance contains several identifiable gaps. While policy frameworks, health impacts of informal recycling, and national-level recycling statistics are well documented, empirical evidence on what specific engineering controls produce measurable reductions in incident rates within institutional settings is limited. Prior studies have documented the scale of the e-waste problem and health outcomes from informal processing in developing country contexts, but they provide limited operational guidance for U.S. institutional program designers (Kiddee et al., 2013; Sthiannopkao & Wong, 2013; Grant et al., 2013; Parvez et al., 2021). The following research priorities would address these gaps and strengthen both practice and the scholarly evidence base.

Quantifying the effect of specific engineering controls on incident rates

EPA's fire analysis provides strong descriptive evidence that lithium batteries contribute to waste system fires, yet more research is needed to quantify how specific upstream controls change incident probability in real institutional settings. This includes controlled comparisons of battery collection interface designs, terminal protection compliance rates, and staging configurations (EPA, 2021).

Standardizing metrics for institutional e-waste program performance

Institutions typically measure volumes collected, yet performance also depends on contamination rates, mis-sorted battery frequency, near-miss events, training completion, audit outcomes, and chain-of-custody completeness. A research priority is developing and validating a minimal metric set that predicts program safety and compliance outcomes and can be compared across institutions.

Evaluating training modalities and behavior design in institutional disposal contexts

OSHA emphasizes worker training for lithium-ion battery hazards (OSHA, 2025). Research can test which training formats and reinforcement approaches generate sustained compliance, especially in high-turnover environments such as campuses.

Downstream transparency and certification effectiveness

EPA's implementation study indicates certification programs are generally implemented well and identifies opportunities for improvement (EPA, 2016a). Further empirical work can evaluate how institutional contract clauses and audit rights influence downstream outcomes, including export pathways, worker safety practices, and data security compliance.

Transport and damaged, defective, or recalled (DDR) battery pathways

PHMSA's guidance recognizes that lithium batteries are regulated hazardous materials and provides scenario-based compliance resources, including shipping guidance for damaged, defective, or recalled batteries (PHMSA, 2023; PHMSA, 2024). Research can document institutional best practices for DDR identification, isolation, packaging, and rapid removal, including cost, staffing, and compliance impacts.

Data-bearing equipment sanitization and validation in modern institutional settings

NIST SP 800-88r2 reflects evolving media types and program controls (Chandramouli & Hibbard, 2025). Research can evaluate how institutions implement sanitization verification in practice, including the reliability of certificates, sampling verification, and integration into chain-of-custody documentation.

Recommendations

Contributions to Theory

This review contributes to the literature by formally applying the hierarchy of controls framework to the institutional e-waste domain, producing a structured taxonomy of control types organized across the electronics lifecycle. This theoretical application advances existing scholarship, which has addressed e-waste primarily through policy and health outcomes lenses, by demonstrating that engineering systems thinking provides a more operationally durable organizing framework for program design and evaluation. Future theoretical work can extend this framework by integrating socio-technical systems theory to explain how control effectiveness varies with organizational structure, staff turnover, and institutional culture.

Contributions to Practice

For institutional environmental health and safety managers, facilities directors, IT asset managers, and compliance officers, this review recommends the following actions:

- Adopt a lifecycle control model. Do not limit e-waste management to collection and vendor pickup. Establish governance, staging, sanitization, battery triage, transport, and vendor qualification as distinct control domains, each with assigned roles, documented procedures, and audit checkpoints.
- Prioritize battery segregation upstream. Prevent battery-containing devices from entering mixed trash or commingled recycling streams. Implement terminal protection protocols and dedicated collection containers as minimum engineering controls. Reference EPA's battery guidance and OSHA's lithium-ion battery safety fact sheet as baseline standards (EPA, 2025d; OSHA, 2025).
- Integrate data sanitization into the physical e-waste workflow. Require documented verification of sanitization before devices leave secure staging. Use NIST SP 800-88r2 as the framework for method selection and documentation (Chandramouli & Hibbard, 2025).
- Select certified downstream recyclers. Use R2 or e-Stewards certification as the primary screening criterion for vendor selection, reinforced with contract clauses specifying downstream processing requirements, data security standards, and export prohibitions (SERI, 2021; Basel Action Network, 2022).
- Establish measurable performance indicators. Track battery incident counts, training completion rates, audit findings, and certified recycling rates as a minimum dashboard. Use the measurement template in Table 2 as a starting point and adapt it to institutional scale and risk profile.
- Align program design with federal funding opportunities. EPA's Solid Waste Infrastructure for Recycling grants and Consumer Recycling Education and Outreach grants, authorized under the Infrastructure Investment and Jobs Act, support the kind of community and institutional program development described in this review. Institutions can use these funding streams to pilot and scale e-waste control programs.

Contributions to Policy

For policymakers at the federal, state, and local level, this review offers three policy-relevant observations. First, the evidence supports strengthening institutional reporting requirements for e-waste and battery handling performance. National recycling data collection, as proposed in the STEWARD Act of 2025, would benefit from including institutional e-waste program performance metrics alongside broader recycling statistics. Second, the persistence of the failure patterns documented in Section 4.2 suggests that voluntary guidance alone is insufficient to drive consistent institutional compliance. State-level extended producer responsibility programs that assign end-of-life management costs and logistics to device manufacturers can create system-level incentives that reinforce institutional controls (NCSL, 2025). Third, the alignment between institutional battery segregation practices and municipal battery fire prevention goals supports a policy recommendation for coordinated municipal and institutional battery stewardship programs, modeled on the framework articulated in EPA's battery fire analysis (EPA, 2021) and the universal waste regulations under 40 CFR Part 273 (eCFR, 2026a).

Conclusion

Institutional e-waste management in the United States has shifted into an operational safety, compliance, and performance domain shaped by battery proliferation, data security requirements, and the need for accountable downstream management. The evidence synthesized in this mini-review supports a defensible conclusion: institutions achieve stronger outcomes when e-waste handling is structured as an integrated control system that combines governance accountability, engineered collection and staging controls, worker training, verified chain-of-custody documentation, and qualified downstream vendor management.

EPA's analysis of lithium battery-related fires in the waste management and recycling system provides strong justification for upstream institutional controls that prevent batteries from entering incompatible waste pathways (EPA, 2021). OSHA guidance reinforces the importance of hazard-specific training in workplaces handling lithium-ion batteries (OSHA, 2025). NIST SP 800-88r2 clarifies that media sanitization is a structured program discipline that can be integrated into the IT asset disposition workflow and verified through documented controls (Chandramouli & Hibbard, 2025). PHMSA's lithium battery compliance resources underscore that transport compliance is a core system component, especially for damaged, defective, or recalled batteries (PHMSA, 2023; PHMSA, 2024). EPA's guidance on certified electronics recyclers supports the use of certification-based vendor screening through R2 and e-Stewards, strengthened through institutional contracts and verification routines (EPA, 2025b).

A practical implication follows for municipalities and campuses: a high-performing e-waste program behaves as operating infrastructure. It produces auditable artifacts, predictable routines, and measurable indicators that allow continuous improvement and cross-site replication.

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