

Review

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Review

Mapping Cold-Chain Waste in Immunization Programmes Across Waste Streams, Policy Coverage, and Operational Management

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Abstract

Background: Immunization programmes rely on cold-chain systems to protect vaccine quality, but these systems also generate waste streams that are not consistently addressed within conventional health-care waste frameworks. These include electronic temperature monitoring devices, data loggers, batteries, packaging materials, cooling accessories, damaged vaccine carriers, sensors, voltage stabilizers, obsolete parts, and decommissioned refrigerators and freezers. **Methods:** This review was conducted as a secondary evidence review with structured policy and guidance mapping. Peer-reviewed literature and guidance documents from global, technical, and national sources were reviewed to map cold-chain waste streams, assess policy and operational coverage, and identify relevant management pathways. **Findings:** Cold-chain waste is generated across vaccine shipment, storage, transport, outreach, maintenance, repair, replacement, and decommissioning. Existing guidance addresses some components, particularly obsolete refrigerators and freezers, but smaller items such as Q-tags, data loggers, batteries, sensors, packaging materials, ice packs, and broken accessories are covered indirectly, partially, or not as a unified programme-management issue. Relevant guidance is distributed across health-care waste management, e-waste regulation, procurement, asset management, vaccine logistics, and cold-chain equipment decommissioning documents. **Interpretation:** Cold-chain waste should not be treated as uniformly hazardous, but it should be recognized as a distinct operational category within immunization systems. A practical response requires risk-based classification, segregation, inventory, reuse or repair where appropriate, linkage with approved e-waste and disposal systems, stronger procurement clauses, and integration into EVM assessments, continuous improvement plans, vaccine-store SOPs, and national logistics working group processes. A concise global reference framework could help countries manage cold-chain waste through existing health, environmental, procurement, and asset-management systems.

Keywords: immunization; vaccine cold chain; vaccine supply chain; health-care waste; electronic waste; cold-chain equipment; temperature monitoring devices; sustainable health systems

1. Introduction

Immunization programmes depend on reliable cold-chain systems to maintain vaccine quality from manufacture to point of administration. Global guidance on vaccine management emphasizes temperature monitoring, appropriate storage, functional cold-chain equipment, and documented handling of temperature-sensitive biologicals across all supply-chain levels [1,2]. Electronic temperature monitoring devices, vaccine vial monitors, freeze indicators, data loggers, and remote temperature monitoring devices have become central tools for documenting temperature exposure during international shipment, national storage, subnational distribution, and service delivery [1,2]. The increasing digitization of cold-chain systems, including the adoption of electronic vaccine intelligence networks and sensor-based monitoring, has further expanded the range and volume of electronic components in use across immunization supply chains [3].

Cold-chain systems are most often discussed in relation to vaccine potency, equipment functionality, and supply-chain performance [4]. However, these same systems generate a distinct set of waste materials across their operational lifecycle. Such waste may include used or expired electronic shipping indicators, data loggers, batteries, damaged sensors, packaging material, coolant packs, vaccine carriers, cold boxes, voltage stabilizers, cables, obsolete spare parts, and decommissioned refrigerators and freezers. Some of these materials arise during routine vaccine receipt and distribution; others accumulate through equipment maintenance, replacement cycles, or end-of-life disposal. The processes, risks, and practical challenges associated with decommissioning and safe disposal of cold-chain equipment in low- and middle-income countries (LMICs) are only beginning to be documented in the literature [5]. Unlike sharps and infectious waste, these materials do not always feature prominently in conventional health-care waste management frameworks, yet they form a tangible part of the environmental footprint of immunization systems.

This waste profile sits at the intersection of several regulatory and programmatic domains, including immunization supply-chain management, health-care waste management, electronic waste regulation, procurement, and cold-chain equipment lifecycle management. WHO classifies most health-care waste as non-hazardous, while an estimated 15% is hazardous due to infectious, chemical, toxic, or radioactive properties [6]. Evidence from LMIC settings, including Malawi, demonstrates that existing health-care waste management frameworks often have notable gaps in legal coverage, practical implementation, and waste segregation, even for well-recognized waste streams, suggesting that less-visible cold-chain-related waste may face even greater management challenges [7]. Cold-chain-related waste does not fall neatly within existing classification schemes. Depending on composition, individual components may require general waste disposal, e-waste handling, battery-specific channels, or specialized treatment due to refrigerants, insulation foam, or embedded electronic circuits. The Global E-waste Monitor has documented the accelerating generation of discarded electrical and electronic equipment worldwide, with formal recycling infrastructure lagging significantly behind [8]. This context is increasingly relevant to immunization programmes as cold-chain systems become more digital, sensor-dependent, and equipment-intensive.

Some elements of this issue are already addressed in existing guidance. WHO and UNICEF have published guidance on decommissioning and safe disposal of cold-chain equipment, covering refrigerant recovery, insulation material, spare parts, and environmental safeguards [9]. WHO Performance, Quality and Safety documentation categorizes temperature monitoring devices used across vaccine supply chains [2]. Assessments of immunization supply chains through the Effective Vaccine Management initiative have highlighted the importance of adequate waste management provisions within supply-chain systems across multiple country settings [4]. However, whether the full range of cold-chain-related waste streams is systematically addressed across health-care waste policies, e-waste regulations, vaccine management guidance, procurement specifications, and immunization supply-chain standard operating procedures has not been comprehensively examined.

This review aims to map waste streams generated within immunization cold-chain systems, assess how these streams are addressed in existing literature, policy, and operational guidance, and identify management pathways relevant to immunization programmes, medical stores, procurement agencies, and health-care waste and environmental authorities.

2. Methods

2.1. Study Design

This review was conducted as a secondary evidence review with structured policy and guidance mapping. This design was selected because the objective was to map the range of waste streams generated within immunization cold-chain systems, examine how these waste streams are described in existing literature and guidance documents, and identify relevant management pathways. The review was not designed to estimate pooled effects or assess intervention effectiveness.

2.2. Data Sources

Two categories of sources were reviewed.

First, peer-reviewed and indexed literature was searched through PubMed/MEDLINE, Scopus, Web of Science, and Google Scholar. The search focused on immunization cold chains, vaccine supply chains, cold-chain equipment, health-care waste, electronic waste, batteries, packaging waste, temperature monitoring devices, and cold-chain equipment decommissioning.

Second, policy and guidance documents were retrieved from official institutional sources, including WHO, UNICEF, Gavi, PATH, TechNet-21, the Basel Convention, UNEP, UNITAR, and selected national health and environment ministry websites. These sources were used to identify direct or indirect guidance on cold-chain waste, health-care waste management, e-waste, vaccine logistics, procurement, asset management, and cold-chain equipment lifecycle management.

2.3. Search Strategy

Search terms combined immunization, cold-chain, waste-management, and policy concepts. Core terms included: immunization cold chain, vaccine cold chain, vaccine supply chain, cold-chain equipment, temperature monitoring device, electronic temperature indicator, data logger, remote temperature monitoring device, vaccine carrier, cold box, ice pack, gel pack, battery waste, packaging waste, electronic waste, health-care waste, e-waste, cold-chain equipment decommissioning, vaccine logistics, waste management policy, and standard operating procedure.

Boolean combinations were adapted for each database and institutional website. Both broad combinations, such as “vaccine cold chain AND waste”, and more specific combinations, such as “temperature monitoring device AND disposal”, “data logger AND vaccine cold chain”, “cold-chain equipment AND decommissioning”, and “vaccine supply chain AND e-waste”, were applied.

2.4. Eligibility Criteria

Sources were included if they met one or more of the following criteria: described waste generated from vaccine or immunization cold-chain operations; discussed temperature monitoring devices, data loggers, batteries, packaging, coolant packs, vaccine carriers, cold boxes, sensors, voltage stabilizers, or obsolete cold-chain equipment in relation to storage, transport, disposal, reuse, recycling, maintenance, or decommissioning; provided policy, regulatory, procurement, or operational guidance relevant to health-care waste, e-waste, vaccine supply chains, or cold-chain equipment management; or presented management pathways directly or indirectly applicable to cold-chain waste.

Sources were excluded if they addressed only routine clinical waste, sharps, infectious waste, or vaccine wastage without any link to cold-chain operations, equipment, packaging, or electronic devices. Sources were also excluded if they were not from a peer-reviewed journal, official institutional body, technical agency, or identifiable national authority.

2.5. Screening and Selection

Search results were screened for relevance using titles, abstracts, executive summaries, tables of contents, or full text, depending on the source type. Peer-reviewed articles were reviewed for relevance to cold-chain waste streams, e-waste, equipment decommissioning, health-care waste management, or vaccine supply-chain operations. Policy and guidance documents were screened by issuing institution, scope, content, and relevance to waste classification, handling, reuse, return, recycling, disposal, procurement, maintenance, or decommissioning.

The review prioritized sources that directly addressed immunization cold-chain operations or provided transferable guidance for the management of electronic, battery-related, packaging, cooling accessory, or equipment-related waste.

2.6. Data Extraction

A structured extraction matrix was applied to included sources. The following information was extracted: source type; issuing body, country or region, and year of publication; type of cold-chain waste addressed; supply-chain level addressed; whether the document provided direct, indirect, partial, or no guidance on management; management pathway described; responsible actors identified; and any operational gaps, ambiguities, or implementation considerations noted.

2.7. Data Synthesis

Findings were synthesized narratively and organized into three analytical domains: waste-stream mapping, policy and guidance coverage, and management pathways. Waste-stream mapping classified the main types of waste generated across immunization cold-chain operations. Policy and guidance coverage assessed how existing documents addressed these waste streams directly, indirectly, partially, or not at all. Management pathways summarized practical options for segregation, inventory, safe temporary storage, reuse, repair assessment, return, recycling, treatment, disposal, procurement, and decommissioning.

No meta-analysis was conducted because the review drew on heterogeneous sources, including peer-reviewed literature, policy documents, technical guidance, operational manuals, regulatory documents, and descriptive evidence.

2.8. Policy and Guidance Mapping Approach

Policy and guidance coverage was categorized as follows:

Direct coverage: the document explicitly addresses the cold-chain waste stream and provides a management instruction.

Indirect coverage: the document does not mention immunization cold-chain waste specifically but includes relevant provisions through health-care waste, e-waste, battery waste, packaging, procurement, asset management, or equipment disposal guidance.

Partial coverage: the document recognizes the material, device, or equipment type but does not provide a complete management pathway.

No identifiable coverage: no relevant instruction is found for the waste stream under review.

This approach allowed the review to assess existing coverage without assuming in advance that a policy gap existed.

2.9. Methodological Limitations

The review depended on publicly available literature, guidance, and policy documents. Internal SOPs, procurement clauses, supplier agreements, country-level implementation records, and informal operational practices may not be publicly accessible. As a result, the review may under-represent practices that exist within immunization programmes but have not been formally published.

The review may also have been affected by variation in terminology. Similar materials may be described across documents as cold-chain equipment, vaccine logistics material, biomedical waste, e-waste, packaging waste, asset scrap, maintenance waste, or general waste. This may have limited retrieval completeness despite the use of broad and specific search terms.

3. Results

3.1. Waste-Stream Mapping

Cold-chain waste represents a distinct waste stream generated through vaccine shipment, storage, transport, temperature monitoring, outreach preparation, equipment maintenance, repair, replacement, and decommissioning. Unlike routine immunization service-delivery waste, such as used syringes, safety boxes, droppers, broken vials, and expired vaccines, which are already addressed through sharps, pharmaceutical, and health-care waste management guidance, cold-chain-related materials are predominantly generated at vaccine stores, warehouses, maintenance points, logistics nodes, and equipment end-of-life stages [6,9].

Cold-chain waste does not represent a single risk category. Some materials, such as cardboard cartons, pallets, and selected packaging materials, may be low-risk and suitable for reuse, recycling, or routine waste management. Others, including batteries, electronic temperature monitoring devices, sensors, refrigerants, insulation foam, and obsolete electrical components, require more specific handling pathways [8]. For this review, cold-chain waste was grouped into six categories: electronic and digital monitoring waste; battery and power-related waste; packaging and logistics material waste; cooling accessories and transport-container waste; cold-chain equipment and component waste; and peripheral logistics asset waste.

Table 1. Indicative typology of waste generated in immunization cold-chain systems.

Waste category	Examples	Common point of generation	Management relevance
Electronic and digital monitoring waste	Electronic temperature indicators, Q-tags, data loggers, freeze indicators, damaged RTMD sensors, probes, event loggers	International shipment, national stores, regional stores, district health facilities	May require segregation, reuse assessment, return, recycling, or e-waste handling
Battery and power-related waste	Button cells, lithium batteries, rechargeable batteries, solar batteries, backup power components, voltage stabilizers, cables, wires	Stores, health facilities, maintenance points, equipment replacement	Requires battery-specific collection, safe storage, and approved disposal or recycling
Packaging and logistics material waste	Cardboard cartons, thermocol/expanded polystyrene, plastic casings, insulation material, packaging inserts, pallets	Vaccine receipt, national or primary stores, warehouses, distribution points	Often low-risk; may require reuse, recycling, volume reduction, or controlled disposal
Cooling accessories and transport-container waste	Broken vaccine carriers, damaged cold boxes, unusable ice packs, gel packs, coolant packs	Stores, health facilities, outreach sessions, campaigns, transport preparation	Reuse possible if functional; broken items require segregation, repair assessment, or disposal

Cold-chain equipment and component waste	Obsolete refrigerators, freezers, compressors, refrigerants, insulation foam, circuit boards, metal and plastic parts, spare parts	Maintenance workshops, equipment replacement, decommissioning sites	Requires planned decommissioning, safe dismantling, component recovery, and environmentally sound disposal
	Scrapped vaccine transport vans, damaged storage racks, trolleys, heavy handling equipment	Central stores, warehouses, fleet units, asset disposal systems	Relevant only when directly linked to cold-chain operations; primarily an asset management issue

Electronic temperature monitoring devices and data loggers are among the most operationally visible examples of cold-chain-related waste. WHO Performance, Quality and Safety guidance recognizes multiple temperature monitoring device categories used in vaccine cold chains, including thermometers, freeze indicators, temperature recorders, data loggers, equipment monitoring devices, and event loggers [2]. Electronic shipping indicators are described as single-use devices used to monitor vaccine temperature during international shipment from manufacturer to primary store [2]. After shipment verification, such devices may accumulate at national or primary stores where reuse, return, or disposal pathways are not defined. This accumulation pattern, along with broader challenges of decommissioning and safe disposal of cold-chain equipment in low- and middle-income country settings, has been documented in the published literature [5].

Cold-chain waste is generated across multiple levels of the immunization supply chain. At international shipment and national store levels, waste includes shipping indicators, data loggers, cartons, thermocol (expanded polystyrene), pallets, and insulation material. At regional and district stores, waste may include damaged cold boxes, broken ice packs, voltage stabilizers, cables, probes, and sensors. At health facilities and outreach points, waste typically includes damaged vaccine carriers, unusable coolant packs, small batteries, and temperature monitoring accessories. At maintenance and decommissioning points, waste includes refrigerator parts, compressors, refrigerants, insulation foam, circuit boards, metal and plastic parts, solar components, and obsolete electrical accessories [5,9].

Dry ice warrants separate consideration. Where used in vaccine shipment, dry ice is primarily an occupational safety and handling concern rather than a persistent solid waste stream, as it sublimates under ambient conditions. Its relevance to this review is therefore limited to safe handling and ventilation during shipment procedures, rather than end-of-life disposal [10].

3.2. Policy and Guidance Coverage

Cold-chain waste is not addressed as a single integrated waste stream in any identified document. Relevant guidance is instead distributed across health-care waste management, e-waste regulation, vaccine management, procurement, asset management, and cold-chain equipment decommissioning documents.

Health-care waste guidance provides a broad classification framework for waste generated by health services. WHO states that approximately 85% of health-care waste is general non-hazardous waste, while the remaining 15% is hazardous, encompassing infectious, toxic, carcinogenic, flammable, corrosive, reactive, explosive, or radioactive properties [6]. Cold-chain waste does not fit uniformly within this framework: cardboard and pallets are general waste; batteries and electronic devices fall under e-waste or chemical waste pathways; and refrigerants and insulation foam require specialized decommissioning processes. Evidence from LMIC settings indicates that even conventional HCWM frameworks often face implementation challenges with segregation, treatment,

and disposal of recognized waste streams, which implies that less-visible cold-chain waste may face additional management barriers [7].

E-waste guidance provides a second relevant entry point. The Global E-waste Monitor 2024 reported that 62 million tonnes of e-waste were generated globally in 2022, with only 22.3% formally collected and recycled [8]. Temperature monitoring devices, sensors, data loggers, circuit boards, batteries, cables, solar components, and obsolete equipment parts from cold chains may enter e-waste streams at end of life. However, general e-waste guidance does not specify how these materials should be identified, stored, returned, or disposed of within immunization supply-chain contexts.

Vaccine management and cold-chain guidance provide strong coverage for equipment use, temperature monitoring, and vaccine quality assurance, but less consistent coverage for the end-of-life management of smaller devices and accessories. WHO PQS guidance defines refrigerators, freezers, cold boxes, vaccine carriers, coolant packs, temperature monitoring devices, and cold-chain accessories [2], but operational pathways for used, expired, damaged, or single-use monitoring devices are less explicit than guidance on their use.

Cold-chain equipment decommissioning guidance offers more direct coverage for obsolete refrigerators and freezers. UNICEF and WHO guidance on decommissioning and safe disposal of cold-chain equipment supports governments in managing end-of-life equipment, including health and environmental considerations, regulatory requirements, decommissioning planning, and technical safety provisions [9]. Processes, risks, and practical challenges of this decommissioning pathway in LMIC settings have also been reviewed in the literature [5]. This makes decommissioned refrigerators and freezers better covered than smaller waste streams, including Q-tags, data loggers, broken ice packs, packaging material, voltage stabilizers, probes, and sensors.

Cold-chain waste is therefore partially covered through different policy and operational channels, but is not consistently framed as a unified programme-management issue. Larger equipment is more directly addressed through decommissioning guidance, while smaller electronic devices, batteries, packaging materials, cooling accessories, and broken cold-chain components are addressed indirectly through e-waste, procurement, general waste, asset disposal, or maintenance systems.

Table 2. Indicative policy and guidance coverage of cold-chain waste streams.

Waste stream	Main policy/guidance entry point	Level of coverage	Key observation
Obsolete refrigerators and freezers	Cold-chain equipment decommissioning guidance	Direct	Better covered than smaller cold-chain waste streams [9]
Refrigerants and insulation foam	Decommissioning and environmental guidance	Direct or partial	Requires specialized recovery and environmentally sound disposal
Electronic temperature indicators, Q-tags, data loggers	Temperature monitoring guidance and e-waste systems	Partial	Use is well described; end-of-life handling is less clearly operationalized [2]
Batteries	Battery, chemical waste, and e-waste regulation	Indirect	Requires safe collection and approved disposal or recycling pathways

Cardboard, cartons, thermocol, pallets, packaging material	Procurement, recycling, municipal or general waste systems	Indirect	Usually low-risk but may create volume and disposal challenges
Broken vaccine carriers, cold boxes, ice packs, gel packs	Cold-chain operational guidance and plastic waste systems	Partial	Reuse and repair may be possible; disposal pathways are often not explicit
Voltage stabilizers, wires, sensors, probes, cables, spare parts	Maintenance, asset management, and e-waste systems	Indirect	Often managed as repair scrap or asset disposal rather than immunization programme waste
Scrapped transport vans, racks, trolleys, large logistics assets	Asset management and fleet disposal systems	Peripheral	Relevant only when directly linked to cold-chain logistics
Expired syringes, droppers, broken vials, expired vaccines	Sharps, pharmaceutical, vaccine wastage, and HCWM guidance	Outside main scope	Acknowledged; established guidance exists and detailed analysis is outside this review's scope

3.3. Management Pathways

The review identified several management pathways applicable to cold-chain waste, depending on material type, condition, risk profile, and national regulatory context. These include segregation, inventory, safe temporary storage, reuse, repair assessment, return, recycling, treatment, disposal, and decommissioning [5,9].

Segregation at source is the primary operational requirement. Electronic devices, batteries, sensors, cables, broken accessories, and damaged monitoring devices should be separated from infectious waste, sharps, and general waste at vaccine stores, warehouses, maintenance points, and health facilities, and held in clearly labelled storage areas until an appropriate management pathway is identified [6].

Reuse and repair should be considered where technically appropriate. Vaccine carriers, cold boxes, ice packs, coolant packs, pallets, selected packaging materials, and reusable data loggers may continue in service if functional, safe, and fit for purpose. Criteria for functionality, cleaning, recalibration where relevant, and accountability should be defined before reuse is authorized [2].

Return and take-back mechanisms are particularly relevant for electronic temperature indicators, data loggers, batteries, and supplier-owned devices that enter the health system through international vaccine shipments and accumulate at national stores after shipment verification. Such provisions could be incorporated into procurement contracts, supplier agreements, or vaccine-shipment arrangements [11].

Recycling and e-waste channels are appropriate for batteries, sensors, circuit boards, voltage stabilizers, cables, electronic shipping indicators, RTMD components, and obsolete electrical accessories. Where available, these materials should be directed to approved national e-waste systems or licensed recyclers. Informal burning, dumping, or dismantling should be avoided, as

electronic waste may contain hazardous substances and can expose workers and communities to harm [8].

Planned decommissioning is required for cold-chain equipment at end of life. Refrigerators, freezers, compressors, refrigerants, insulation foam, solar components, and spare parts should be managed through asset verification, technical assessment, withdrawal from service, safe dismantling, parts recovery where appropriate, and environmentally sound disposal [9]. Responsibility should be clearly assigned across immunization programmes, cold-chain technicians, biomedical engineering units, asset management teams, environmental authorities, and approved waste handlers [5].

Procurement represents an important upstream intervention point. Specifications and supplier agreements can reduce downstream waste through requirements for product durability, repairability, battery type, packaging minimization, spare-parts availability, take-back options, end-of-life responsibility, and decommissioning support [11].

Integration into existing programme systems is the most practical and sustainable approach. Relevant entry points include national logistics working groups, EVM-based improvement planning, cold-chain equipment inventories, maintenance systems, national HCWM plans, e-waste regulations, vaccine-store SOPs, and procurement review processes [4]. This approach avoids creating a separate vertical management system.

3.4. Summary of Findings

Cold-chain waste is generated throughout immunization supply chains but is not consistently visible within conventional immunization or health-care waste management frameworks. Larger obsolete equipment has clearer decommissioning guidance [9], while smaller waste streams, including electronic temperature indicators, Q-tags, data loggers, batteries, broken sensors, ice packs, packaging materials, and voltage stabilizers, are addressed mainly through indirect channels such as e-waste, procurement, maintenance, or asset management systems [8]. The findings support a more integrated operational approach that links immunization supply-chain management with health-care waste management, e-waste systems, procurement, asset management, and cold-chain equipment lifecycle planning [4,7].

4. Discussion

This review maps cold-chain waste as a distinct but fragmented waste-management issue within immunization programmes. The principal finding is not that cold-chain waste is entirely absent from existing guidance, but that its components are distributed across multiple policy domains, none of which addresses the full waste stream as a unified programme-management concern [1,2,6,9]. Large obsolete equipment is relatively better covered through cold-chain equipment decommissioning guidance, while smaller items such as electronic shipping indicators, Q-tags, data loggers, batteries, probes, sensors, damaged ice packs, packaging materials, voltage stabilizers, and broken accessories are addressed, where at all, indirectly through e-waste, procurement, asset management, maintenance, or general waste systems [2,8,9].

To the authors' knowledge, published literature has not yet comprehensively mapped cold-chain waste across immunization supply chains as an integrated waste-management issue. Previous work has addressed cold-chain equipment decommissioning and safe disposal in low- and middle-income country settings, documenting the processes, risks, and practical challenges involved in managing end-of-life refrigerators and freezers [5,9]. Health-care waste management studies from LMIC settings have also documented that even well-recognized waste streams, such as sharps, infectious waste, and pharmaceutical waste, face significant implementation gaps in segregation, treatment, and disposal at facility and subnational levels [7,12]. Cold-chain-related waste, being less visible within conventional HCWM frameworks, is therefore likely to face even greater operational barriers [5,7].

This fragmentation matters because immunization cold chains are increasingly equipment-intensive and digitally monitored [3,4]. Temperature monitoring devices are essential for vaccine

quality assurance, particularly during international shipment and subnational distribution [1,2]. WHO PQS guidance describes electronic shipping indicators as single-use devices used to monitor vaccine temperature during international shipment from manufacturer to primary store [2]. After completing their quality-assurance function, these devices become small electronic waste items. Across repeated shipments, national stores, campaigns, and multiple supply-chain levels, cumulative volumes become operationally relevant, yet no standard pathway currently exists for their collection, return, recycling, or disposal [5,8,11].

Cold-chain waste also challenges conventional health-care waste classification systems. WHO describes most health-care waste as non-hazardous, with a smaller hazardous fraction encompassing infectious, toxic, chemical, radioactive, flammable, corrosive, reactive, or explosive materials [6]. Routine immunization waste, including used syringes, safety boxes, broken vials, and expired vaccines, fits more clearly within established guidance [6,13]. Cold-chain waste is different. It comprises a heterogeneous set of materials: some are low-risk and recyclable, some are reusable, some are electronic, some are battery-related, and some require specialized decommissioning due to refrigerants, insulation foam, or electrical components [5,9]. This heterogeneity means that a single-category waste policy cannot adequately address the full cold-chain waste profile [6,14].

The global e-waste literature provides an important contextual parallel. The Global E-waste Monitor 2024 reported 62 million tonnes of e-waste generated globally in 2022, with only 22.3% formally collected and recycled [8]. WHO has also documented that unsafe e-waste handling, including burning, dumping, and informal dismantling, can release hazardous substances and create environmental and occupational health risks [15]. Although immunization cold-chain devices represent a small fraction of global e-waste, they are part of the same broader transition toward electronic, digital, and sensor-based systems in health [3,8]. This is especially relevant in low- and middle-income countries, where formal e-waste collection and recycling pathways may be limited, unevenly regulated, or structurally disconnected from public health supply chains [8,15,16].

Cold-chain equipment decommissioning is comparatively better defined than the management of smaller cold-chain items. UNICEF and WHO guidance provides a structured approach for withdrawing obsolete refrigerators and freezers, managing environmental and safety risks, and planning safe disposal [9]. However, this equipment-focused guidance does not resolve how programmes should manage the wider set of smaller waste streams generated through daily cold-chain operations, including packaging, coolant packs, monitoring devices, sensors, wires, and broken accessories [5,9]. The result is an operational gap between what decommissioning guidance covers and what programmes encounter in practice [5,11].

Cold-chain waste is best managed through integration with existing systems rather than through a separate vertical programme. The immunization supply chain already provides practical entry points: vaccine-store SOPs, cold-chain equipment inventories, maintenance plans, EVM-based improvement planning, national logistics working groups, and procurement specifications [4,17]. Linking these mechanisms with national e-waste systems and licensed recyclers would be more feasible and sustainable than building a parallel cold-chain waste management structure [8,16]. Strengthening sustainable health-system architecture, including integration of environmental, procurement, and supply-chain dimensions, remains a broader imperative for health systems in LMICs [18].

Procurement deserves particular attention as an upstream control point. Many cold-chain waste streams enter the health system through procurement or international shipment processes: temperature monitoring devices, packaging materials, cold boxes, vaccine carriers, ice packs, electronic accessories, and spare parts [2,11]. Procurement specifications can therefore directly influence downstream waste burdens through requirements for durability, reparability, battery type, packaging minimization, spare-parts availability, labelling, supplier take-back, and end-of-life responsibility [11,19]. These provisions are particularly relevant for devices supplied with international vaccine shipments or introduced through cold-chain digitalization initiatives such as electronic vaccine intelligence networks [3].

A risk-based classification is more operationally useful than treating all cold-chain-related discards uniformly [6,14]. Cardboard, pallets, and selected packaging materials are generally low-risk and can be managed through routine logistics, reuse, or municipal systems. Batteries, electronic devices, refrigerants, insulation foam, obsolete compressors, circuit boards, and damaged electrical accessories, by contrast, require specific handling pathways [8,9,15]. Distinguishing between these material types allows immunization programmes to prioritize action proportionately and avoid either under-managing hazardous components or over-classifying low-risk materials as hazardous waste [6,14].

Evidence Gaps and Future Research

Several evidence gaps limit current understanding. First, there is no published evidence quantifying the volume of cold-chain waste generated by national immunization programmes [5,20]. Second, documentation on how stores and subnational facilities currently manage used electronic shipping indicators, Q-tags, data loggers, batteries, and damaged accessories is limited [5,11]. Third, few published studies describe supplier take-back models, procurement-linked end-of-life clauses, or costed operational pathways for cold-chain waste [19,20]. Fourth, there is limited evidence on how immunization programmes connect with national e-waste systems, environmental authorities, or licensed recyclers [8,16]. Addressing these gaps would strengthen the evidence base for practical guidance and programme-level action.

Limitations

This review relied on publicly available literature, global guidance, and policy documents [20]. Internal SOPs, procurement clauses, supplier agreements, and country-level waste-management practices may not be publicly accessible, potentially under-representing operational practices that exist within programmes but are not formally published. Terminology variation across documents, where the same materials may be described as cold-chain equipment, vaccine logistics material, biomedical waste, e-waste, packaging waste, asset scrap, or general waste, may also have limited retrieval completeness despite the adapted search strategy [5,14]. Despite these limitations, this review provides a structured framework for recognizing cold-chain waste as a programme-relevant issue at the intersection of immunization supply chains, health-care waste management, e-waste regulation, procurement, and equipment lifecycle management [4,7,18].

5. Recommendations and Operational Implications

The findings indicate that cold-chain waste should be managed through existing immunization, health-care waste, e-waste, procurement, and asset-management systems rather than through a separate parallel structure. The priority is not to classify all cold-chain-related materials as hazardous, but to identify which items require reuse, return, recycling, controlled disposal, or formal decommissioning.

First, national immunization programmes should define cold-chain waste as a distinct operational category within vaccine-store and cold-chain standard operating procedures. This definition should include electronic temperature indicators, Q-tags, data loggers, batteries, sensors, probes, voltage stabilizers, wires, damaged ice packs, broken vaccine carriers and cold boxes, packaging materials, obsolete cold-chain equipment parts, refrigerants, and decommissioned refrigerators and freezers. Routine immunization waste such as syringes, droppers, broken vials, and expired vaccines should remain under established sharps, pharmaceutical, vaccine wastage, and health-care waste guidance.

Second, vaccine stores should introduce basic segregation and inventory procedures for cold-chain waste. Small electronic devices, batteries, damaged sensors, cables, and broken accessories should not be mixed with sharps, infectious waste, or unmanaged general waste. National and primary stores should maintain simple records of accumulated temperature monitoring devices,

batteries, packaging materials, unusable ice packs, broken vaccine carriers, and equipment parts. This would help programmes understand the scale of accumulation and identify suitable reuse, return, recycling, or disposal pathways.

Third, immunization programmes should apply a risk-based approach. Low-risk materials such as cardboard cartons, pallets, and some packaging materials can usually be managed through reuse, recycling, or routine waste systems. In contrast, batteries, electronic devices, circuit boards, refrigerants, insulation foam, compressors, and obsolete electrical components should be linked to approved e-waste, chemical waste, or equipment-decommissioning pathways. Dry ice, where used, should be managed mainly as an occupational safety and ventilation issue rather than as a persistent solid waste stream.

Fourth, procurement and shipment arrangements should include end-of-life considerations. Procurement specifications for temperature monitoring devices, cold boxes, vaccine carriers, ice packs, RTMD components, voltage stabilizers, and cold-chain accessories should include provisions for durability, repairability, battery type, packaging minimization, spare-part availability, labelling, and safe disposal. Where feasible, supplier take-back or return mechanisms should be explored for single-use electronic shipping indicators, used data loggers, batteries, and selected packaging materials.

Fifth, cold-chain equipment decommissioning should be planned as part of the equipment lifecycle. Refrigerators, freezers, solar components, compressors, refrigerants, insulation foam, panels, wires, and spare parts should be withdrawn through documented asset-management procedures. Decommissioning should include technical assessment, recovery of reusable parts where appropriate, safe handling of refrigerants and insulation materials, and disposal through approved environmental or e-waste channels. This process should involve immunization programmes, cold-chain technicians, biomedical engineering units, asset-management teams, environmental authorities, and licensed waste handlers.

Sixth, cold-chain waste should be integrated into existing programme monitoring and improvement mechanisms. Entry points include Effective Vaccine Management assessments, continuous Improvement Plans, cold-chain equipment inventories, maintenance plans, national logistics working groups, health-care waste management plans, vaccine-store supervision tools, and environmental health reviews. Including cold-chain waste in these mechanisms would support practical follow-up without creating additional reporting burdens.

Seventh, countries should link immunization cold-chain waste with national e-waste and environmental management systems. This is particularly important for batteries, electronic monitoring devices, sensors, cables, RTMD components, voltage stabilizers, solar components, and obsolete electrical parts. Where formal e-waste systems are weak or unavailable, programmes should at minimum define safe temporary storage, prevent informal burning or dumping, and coordinate with national environmental authorities to identify approved disposal options.

Finally, global and regional partners should consider developing a concise reference framework or SOP template for immunization cold-chain waste management. Such guidance should not duplicate existing HCWM or e-waste documents. Instead, it should help immunization programmes classify cold-chain waste streams, assign responsibilities, identify management pathways, include end-of-life clauses in procurement, and connect cold-chain operations with existing national waste-management systems.

Table 3. Suggested operational actions for cold-chain waste management.

Programme area	Suggested action	Main responsible actors
Policy and SOPs	Define cold-chain waste in vaccine-store and cold-chain SOPs	EPI, national vaccine store, HCWM unit
Segregation and storage	Separate electronic devices, batteries, sensors, broken	Vaccine stores, health facilities, warehouse teams

	accessories, and packaging from sharps and infectious waste	
Inventory	Record accumulated devices, batteries, damaged accessories, and obsolete equipment parts	Store managers, cold-chain officers
Reuse and repair	Assess vaccine carriers, cold boxes, ice packs, data loggers, pallets, and accessories for safe reuse or repair	Cold-chain technicians, logistics teams
Procurement	Include durability, repairability, packaging reduction, take-back, and end-of-life requirements	Procurement teams, UNICEF/partners, suppliers
E-waste linkage	Channel batteries, sensors, electronic devices, circuit boards, and cables to approved systems	EPI, environmental authority, licensed recyclers
Decommissioning	Manage obsolete refrigerators, freezers, refrigerants, insulation foam, and compressors through planned asset withdrawal	EPI, asset management, technicians, environmental authority
Monitoring	Include cold-chain waste in EVM, cIP, supervision, and national logistics working group discussions	EPI, NLWG, partners

These recommendations are intended to support proportionate management. Cold-chain waste should not be exaggerated as a uniformly hazardous problem, but it should no longer remain invisible within immunization systems. A practical, risk-based approach can help countries protect vaccine quality while also improving environmental responsibility and equipment lifecycle management.

6. Conclusions

Immunization cold-chain systems are essential for protecting vaccine quality, but they also generate waste streams that are not consistently visible within conventional immunization or health-care waste management frameworks. These include electronic temperature monitoring devices, data loggers, batteries, packaging materials, cooling accessories, damaged vaccine carriers and cold boxes, sensors, voltage stabilizers, obsolete equipment parts, refrigerants, and decommissioned refrigerators and freezers.

Cold-chain waste is not a single category and should not be treated as uniformly hazardous. Some materials can be reused, recycled, or managed through routine waste systems, while others require e-waste handling, battery-specific disposal, controlled storage, or formal decommissioning. Unlike routine immunization service-delivery waste, which is more directly addressed through established sharps, pharmaceutical, and health-care waste guidance, cold-chain-related waste occupies a less clearly defined space across multiple policy and operational domains.

The central challenge is that cold-chain waste is addressed unevenly across immunization supply-chain guidance, health-care waste management, e-waste regulation, procurement, asset management, and cold-chain equipment decommissioning documents. Large obsolete equipment

has clearer decommissioning pathways, while smaller items such as Q-tags, data loggers, batteries, sensors, broken accessories, and packaging materials are more often covered indirectly or not at all.

A practical response does not require building a separate waste management structure. Countries can begin by defining cold-chain waste in vaccine-store and cold-chain SOPs, segregating and recording accumulated materials at vaccine stores, linking electronic and battery waste with approved e-waste systems, strengthening procurement clauses for end-of-life responsibility, and integrating cold-chain waste into EVM assessments, continuous improvement plans, maintenance systems, supervision tools, and national logistics working group processes.

As immunization systems become more equipment-intensive, digitally monitored, and environmentally accountable, cold-chain waste should be recognized as an integral part of vaccine supply-chain stewardship. A concise global reference framework or SOP template could help countries classify these waste streams, assign responsibilities, and manage them through existing health, environmental, procurement, and asset-management systems. This would support a more complete model of vaccine quality assurance, one in which protecting vaccines and protecting the environment are treated as complementary responsibilities.

References

1. World Health Organization. How to monitor temperatures in the vaccine supply chain. WHO Vaccine Management Handbook. Geneva: World Health Organization; 2015. URL: <https://www.who.int/publications/i/item/WHO-IVB-15.04>
2. World Health Organization. E006: Temperature Monitoring Devices. WHO Prequalification of Medical Products, Immunization Devices. Geneva: World Health Organization; 2025. URL: <https://extranet.who.int/prequal/immunization-devices/e006-temperature-monitoring-devices>
3. Devgan S, Singh SK, Sharma L, Sinha S. eVIN: role of digitization in improving the efficiency of vaccine logistics system across India. *Healthline*. 2021;12(3):7–13. doi:10.51957/Healthline_245_2021. URL: https://doi.org/10.51957/Healthline_245_2021
4. Juneja S, Wadi F, Kannure M, Singh SK. Strengthening immunization systems through effective supply chains: insights from the global Effective Vaccine Management initiative. *Int J Pharm Sci Res*. 2025;16(2):387–394. doi:10.13040/IJPSR.0975-8232.16(2).387-94. URL: <https://ijpsr.com/bft-article/strengthening-immunization-systems-through-effective-supply-chains-insights-from-global-effective-vaccine-management-initiative/>
5. Singh SK, Haile DA, Syed S, Bhatt D, Sethy G, Hassan A, et al. Decommissioning and safe disposal of vaccine cold chain equipment in low- and middle-income countries: focusing on processes, risks, and practical challenges. *Cureus*. 2025;17(12):e100397. doi:10.7759/cureus.100397. URL: <https://www.cureus.com/articles/449197-decommissioning-and-safe-disposal-of-vaccine-cold-chain-equipment-in-low--and-middle-income-countries-focusing-on-processes-risks-and-practical-challenges>
6. World Health Organization. Health-care waste. WHO Fact Sheet. Geneva: World Health Organization; 2024. URL: <https://www.who.int/news-room/fact-sheets/detail/health-care-waste>
7. Sethy G, Singh SK, Chisema MN, Ganizani A, Kafanikhale HM, et al. Healthcare waste management in Malawi: overcoming challenges, seizing opportunities. *J Community Med Public Health*. 2024;8:442. doi:10.29011/2577-2228.100442. URL: <https://www.gavinpublishers.com/article/view/healthcare-waste-management-in-malawi-overcoming-challenges-seizing-opportunities>
8. Forti V, Baldé CP, Kuehr R, Bel G. The Global E-waste Monitor 2024. Bonn/Geneva: UNITAR/ITU; 2024. URL: <https://globalewaste.org/>
9. United Nations Children's Fund, World Health Organization. Decommissioning and safe disposal of cold chain equipment. New York/Geneva: UNICEF/WHO; 2018. URL: <https://www.technet-21.org/en/resources/guidance/decommissioning-and-safe-disposal-of-cold-chain-equipment>
10. Centers for Disease Control and Prevention. Dry ice safety for healthcare professionals. Atlanta: CDC; 2021. URL: <https://www.cdc.gov/vaccines/covid-19/info-by-product/pfizer/downloads/dry-ice-safety-hcp.pdf>

11. United Nations Children's Fund. UNICEF Supply Catalogue: cold chain equipment. Copenhagen: UNICEF Supply Division; 2023.URL: <https://supply.unicef.org/all-materials/cold-chain-equipment.html>
12. Chartier Y, Emmanuel J, Pieper U, Prüss A, Rushbrook P, Stringer R, et al., editors. Safe management of wastes from health-care activities. 2nd ed. Geneva: World Health Organization; 2014.URL: <https://www.who.int/publications/i/item/9789241548564>
13. World Health Organization. Immunization in practice: a practical guide for health staff, 2015 update. Geneva: World Health Organization; 2015.URL: <https://www.who.int/europe/publications/i/item/9789241549097>
14. United Nations Environment Programme. Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal. Geneva: UNEP; 1989, updated 2019.URL: <https://www.basel.int/TheConvention/Overview/tabid/1271/Default.aspx>
15. World Health Organization. Electronic waste (e-waste). WHO Fact Sheet. Geneva: World Health Organization; 2023.URL: [https://www.who.int/news-room/fact-sheets/detail/electronic-waste-\(e-waste\)](https://www.who.int/news-room/fact-sheets/detail/electronic-waste-(e-waste))
16. Baldé CP, Forti V, Gray V, Kuehr R, Stegmann P. The Global E-waste Monitor 2017: quantities, flows and resources. Bonn/Geneva/Vienna: United Nations University, International Telecommunication Union, and International Solid Waste Association; 2017.URL: <https://www.itu.int/en/ITU-D/Climate-Change/Documents/GEM%202017/Global-E-waste%20Monitor%202017%20-%20Executive%20Summary.pdf>
17. World Health Organization, United Nations Children's Fund. Effective Vaccine Management initiative: assessment tools and guidance. Geneva/New York: WHO/UNICEF; 2022.URL: <https://www.who.int/teams/immunization-vaccines-and-biologicals/essential-programme-on-immunization/supply-chain/guidanceandtools>
18. Singh SK, Syed S, Singh SK, Syed S, et al. Pathways to sustainable public health systems: integrating economic and social strategies. Preprints. 2026. doi:10.20944/preprints202601.2409.v1.URL: <https://www.preprints.org/manuscript/202601.2409>
19. United Nations Children's Fund. Procurement guidelines: compression system refrigerators and freezers. Copenhagen: UNICEF Supply Division; 2021.URL: <https://www.unicef.org/supply/media/6396/file/Mains-Power-Refrig-Freezer-proc-guideline-2021.pdf>
20. Arksey H, O'Malley L. Scoping studies: towards a methodological framework. *Int J Soc Res Methodol.* 2005;8(1):19–32. doi:10.1080/1364557032000119616.URL: <https://doi.org/10.1080/1364557032000119616>**Disclaimer/Publisher's Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.