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Lead-Acid Battery Recycling in Selected African Settings

Status Quo and Considerations for Sector Policies

ANDREAS MANHART · FRED ADJEI

Abstract

Lead exposure presents a major public health challenge in many low- and middle-income countries, and unsafe recycling of used lead-acid batteries (ULABs) is increasingly recognized as an important driver. This paper synthesizes over a decade of applied research and cooperation projects on ULAB recycling, particularly in sub-Sahara Africa. The paper specifically draws from recent assessments in Ghana, Nigeria, and Tanzania and describes collection and recycling patterns, including interlinks between informal and formal operators, plant set-ups and operational practices.

The researchers assert that collection is largely organized through informal networks that supply collected batteries to registered industrial recycling plants that commonly apply sub-standard processes. Key lead exposure pathways include manual or semi-automated battery breaking, uncontrolled electrolyte draining, insufficient capture of furnace and refining fumes, poor housekeeping and dust control, unsafe handling of filter dust, and inadequate management of lead-bearing slags. Regulatory frameworks exist and inspections occur, yet limited resources, gaps in technical specificity and capacity, and weak enforcement allow persistent non-compliance by formal plants.

Economic analysis and recent experience indicate that relatively high standard plants face higher investment and operating costs and may lose access to ULABs because low-standard operators can offer higher purchase prices. The paper concludes with policy implications focused on effective and consistent sanctions, market consolidation through stricter licensing, polluter pays principles, regional exchange, supply chain due diligence, improved monitoring, and international support that strengthens local ownership and capacities.

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Lead-Acid Battery Recycling in Selected African Settings: Status Quo and Considerations for Sector Policies

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Abbreviations

AGENDA	AGENDA for Environment and Responsible Development (Tanzania)
AMCEN	African Ministerial Conference on the Environment
BLL	Blood lead level
BMZ	Federal Ministry for Economic Cooperation and Development (Germany)
EIA	Environmental Impact Assessment
EPA	Environmental Protection Authority (Ghana)
ETP	Effluent treatment plant
GIZ	Gesellschaft fuer Internationale Zusammenarbeit (Germany)
GNCPC	Ghana National Cleaner Production Centre
LAB	Lead-acid battery
LME	London Metal Exchange
MRI	Mountain Research Institute (Ghana)
mt	Metric ton
NEMC	National Environment Management Council (Tanzania)
NESREA	National Environmental Standards and Regulations Enforcement Agency (Nigeria)
OGEPA	Ogun State Environmental Protection Agency (Nigeria)
OSHA	Occupational Safety and Health Authority (Tanzania)
PP	Polypropylene
PPE	Personal protective equipment
ProBaMet	Partnership for Responsible Battery and Metal Recycling
SRADev	Sustainable Research and Action for Environmental Development (Nigeria)
SRI	Sustainable Recycling Industries
ULAB	Used lead-acid battery

Foreword

Over the past decade, researchers have documented a global crisis of lead poisoning. Worldwide, an estimated 800 million children—one in three—have blood lead levels exceeding five micrograms per deciliter,[1] which is the level at which the World Health Organization recommends clinical intervention.[2] Lead is highly toxic to humans even in very small quantities;[3] it impedes normal childhood cognitive development, impairs neurological function, and greatly increases risk of cardiovascular disease, among other multisystem effects.[4] The cumulative health and development impacts from such widespread exposure, overwhelmingly concentrated in low- and middle-income countries, is therefore staggering: lead is estimated to account for a fifth of the learning gap between rich and poor countries[5] and up to 5.5 million cardiovascular disease deaths each year.[6]

Humans encounter lead exposure through many channels, including but not limited to environmental exposure through air, soil, and water; ingestion of contaminated food, spices, and medicines; leaching from lead-glazed pottery and aluminum cookware; and lead-containing consumer products like paint, cosmetics, and jewelry.[7] Yet 86 percent of all lead is used for a single purpose: construction of lead-acid batteries,[8] commonly used to power automobiles, motorcycles, and some electric vehicles and to provide energy storage for off-grid solar and uninterrupted power supply systems.[9] Lead-acid batteries are widely used across world regions and can be fully recycled at the conclusion of their six-month-to-three-year lifespan.[10] Under stringent regulatory regimes,

1 Nicholas Rees and Richard Fuller, *The Toxic Truth: Children's Exposure to Lead Pollution Undermines a Generation of Future Potential* (UNICEF and Pure Earth, n.d.).

2 *Guideline for Clinical Management of Exposure to Lead: Executive Summary* (World Health Organization, 2021), 1–16, https://www.who.int/publications/i/item/9789240036888.

3 *Guideline for Clinical Management of Exposure to Lead: Executive Summary.*

4 "What Are Possible Health Effects from Lead Exposure?," Centers for Disease Control, https://archive.cdc.gov/www_atsdr_cdc_gov/csem/leadtoxicity/physiological_effects.html#:~:text=In%20severe%20cases%20of%20lead,an%20acute%20abdomen%20or%20appendicitis.

5 Lee Crawfurd et al., *How Much Would Reducing Lead Exposure Improve Children's Learning in the Developing World?* (Center for Global Development, 2023), https://www.cgdev.org/publication/how-much-would-reducing-lead-exposure-improve-childrens-learning-developing-world.

6 Bjorn Larsen and Ernesto Sánchez Triana, "Global Health Burden and Cost of Lead Exposure in Children and Adults: A Health Impact and Economic Modelling Analysis," *The Lancet Planetary Health* 7, no. 10 (2023): 831–40.

7 "Sources of Lead Exposure in LMICs," Lead Elimination Exposure Project, June 2, 2022, https://leadelimination.org/sources-of-lead-exposure-in-lmics-other-than-paint/; "Common Sources of Lead Poisoning," Washington State Department of Health, https://doh.wa.gov/community-and-environment/contaminants/lead/common-sources-lead-poisoning.

8 *The World Lead Factbook 2023* (International lead and Zinc Study Group, 2023), 1–56, https://www.ilzsg.org/wp-content/uploads/SitePDFs/1_ILZSG%20World%20Lead%20Factbook%202023.pdf.

9 "Essential Applications Powered by Batteries," Battery Council International, https://batterycouncil.org/battery-facts-and-applications/essential-applications/.

10 Christopher Kinally et al., "Solar Home Systems in Malawi: Commercialisation, Use and Informal Waste Management," *Sustainable Production and Consumption* 42 (November 2023): 367–79, https://doi.org/10.1016/j.spc.2023.10.008; Andreas Manhart et al., *End-of-Life Management of Batteries in the Off-Grid Solar Sector* (Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH, 2018), 1–44, https://www.giz.de/en/downloads/giz2018-en-waste-solar-guide.pdf.

like those in place in the United States and Europe, it is possible to operate safe and profitable battery recycling operations with minimal risk of occupational exposure or environmental contamination.

Unfortunately, in most low- and middle-income countries, the reality of used lead-acid battery (ULAB) recycling looks quite different. Few high-quality recycling operations exist in these contexts; instead, informal and low-quality formal recycling operations predominate, without the necessary safety equipment and protocols to protect workers and surrounding communities.[11] Even low-quality formal facilities recapture only about 90 percent of lead volume; the remainder is released as airborne emissions or into the soil.[12]

Until relatively recently, most experts believed that this pollution remained highly localized within about 300 meters of a polluting plant—causing severe local lead pollution for a relatively small number of people (8–22 million).[13] However, new evidence increasingly challenges this assumption. A recent paper from my colleagues Lee Crawfurd, James Hu, and Theo Mitchell finds evidence of further dispersion of lead emissions (albeit at lower levels) up to five kilometers away from recycling plants—in turn affecting *over 600 million people*. The implication, then, is that lead-acid battery recycling may be one of the largest contributors to widespread global lead exposure. The findings of Crawfurd et al. point to very high uncertainty, but suggest, as a central estimate, that about a third of global lead poisoning can be attributed to unsafe ULAB recycling. Further impacts might be found even further afield via contaminated food and water supplies; this question is the subject of current study within the lead community, but preliminary evidence points to the potential for even greater and more widespread harms than those captured by Crawfurd and colleagues.[14]

In this context, it is urgent to better understand practices of ULAB recycling in low- and middle-income countries—both to clearly document the sources and underlying causes of lead pollution and exposure and to identify potential policy remedies to address this challenge in the short, medium, and long term. The authors of the following paper—Andreas Manhart and Fred Adjei of the Oeko-Institut—are already experts in these issues in West Africa, benefiting from more than a decade researching ULAB recycling conditions at the country level, and working directly with regulators and facilities to address challenges of toxic waste. In the paper, they document

11 UN Environment Assembly, *UNEA/EA.3/Res.9: Eliminating Exposure to Lead and Promoting Environmentally Sound Management of Waste Lead-Acid Batteries* (UN Environment Assembly, 2017), https://wedocs.unep.org/bitstream/handle/20.500.11822/31024/k1800228.english.pdf?sequence=3&isAllowed=y; Brian Wilson et al., *Consequences of a Mobile Future: Creating an Environmentally Conscious Life Cycle for Lead-Acid Batteries* (Global Battery Alliance/World Economic Forum, 2020), 1–29, https://www.globalbattery.org/media/action-partnerships/energy-access/downloads/wef-lab-recycling-guidelines-2020.pdf#page=20.

12 *Closing the Loop on Energy Access in Africa*, White Paper (World Economic Forum, 2021), 1–44, https://www3.weforum.org/docs/WEF_Closing_Loop_Energy_Access_2021.pdf.

13 Bret Ericson et al., "The Global Burden of Lead Toxicity Attributable to Informal Used Lead-Acid Battery Sites," *Annals of Global Health* 82, no. 5 (2016): 686–99.

14 Lee Crawfurd et al., *Beyond Hot Spots: Estimating Population Lead Exposure from Battery Recycling*, Working Paper no. 739 (Center for Global Development, 2026), 1–49, https://www.cgdev.org/sites/default/files/estimating-population-lead-exposure-battery-recycling.pdf.

and integrate the cumulative learnings from their work in this sector over the past decade, with a particular focus on recent fieldwork in Ghana, Nigeria, and Tanzania. Through their firsthand experience, observation, and data analysis, supplemented by findings from the relevant literature, they paint a clear picture of real-world processes and conditions of ULAB recycling in the West African context; describe the economic forces and incentives that favor low-quality formal recycling; and offer incisive policy recommendations to improve the recycling ecosystem.

I am delighted to publish their findings as a CGD policy paper and look forward to integrating this important evidence into ongoing and emerging ULAB policy discussions.

—Rachel Bonnifeld,
Director of Global Health Policy and Senior Fellow, Center for Global Development

1 Introduction

1.1 Background

Lead exposure and its detrimental effects on human health, particularly that of children, is rapidly gaining public attention. While lead exposure from products, fuels, and industrial sources have been systematically monitored and addressed in many developed economies such as the US and Germany since the late 1970s and early 1980s (Dignam et al. 2019; Lermen et al. 2021), population exposure trends in low- and middle-income countries have long remained unmonitored. While cases of lead exposure from sources such as ore processing, smelting, battery production, and recycling have been documented and reported, they have long been regarded as isolated cases with limited geographical relevance.

In sub-Saharan Africa, this view started to shift approximately 15 years ago when researchers and environmentalists recognized systematic and very similar patterns of lead emissions and exposure across various countries. These patterns were first identified in relation to the use of lead in paints (World Health Organization 2015) and, shortly thereafter, in connection with the management and recycling of used lead-acid batteries (ULABs). Identification and mapping of contaminated sites (Pure Earth & Green Cross Switzerland 2016; Ericson et al. 2016), soil sampling, and testing around industrial battery recycling plants (Gottesfeld et al. 2018) and NGO-led country assessments (Manhart et al. 2016) have been milestones in this development.

Recent studies also give strong indications that exposure to lead is a major health risk factor globally (Brauer et al. 2024) and that around one-third of all children are subject to elevated blood lead levels (BLLs) (UNICEF & PureEarth 2020). Although systematic epidemiologic studies are still scarce for many African countries, there is growing evidence that average population BLLs are severely elevated in significant parts of the region (Bede-Ojimadu et al. 2018; Ericson et al. 2021). Furthermore, there are various findings that lead exposure is remarkably high in and around known ULAB recycling sites (Haefliger et al. 2009; Kenyan Ministry of Health 2015; Atiemo et al. 2016; Anyaogu 2018; Will Fitzgibbon 2023).

Although the exact contribution of lead-acid battery (LAB) recycling activities to lead exposure of the overall population has not yet been precisely quantified, it is evident that substandard ULAB management plays a major role in emissions of lead to the environment. Many ULAB recycling activities are carried out in urban or semi-urban areas where the release of lead particles is closely associated with direct exposure for large segments of the population. Moreover, LABs are by far the most relevant application of lead, representing 86 percent of world lead demand (ILZSG 2023). Thus, leakages of lead from battery production, use, and recycling can easily develop into some of the most important local exposure factors and biggest long-term legacies.

1.2 Scope, methods, & objectives

This paper documents findings on the technical, economic, and regulatory conditions of ULAB recycling in sub-Saharan Africa. It primarily draws on recent fieldwork conducted by the authors and their colleagues in collaboration with national regulatory authorities and environmental analysts in Ghana, Nigeria, and Tanzania, supplemented and corroborated by findings from previous fieldwork in Ghana, Nigeria, Ethiopia, and Uganda and the broader academic and gray literature. Findings and statements of facts in this paper are based on the authors' direct observations, original data collection/analysis, and accumulated expertise from over 10 years in the field, unless otherwise noted and cited.

Specifically, recent fieldwork that informs the findings of this paper includes the following activities:

- Nigeria: Two facility assessment campaigns in Ogun State, conducted jointly with NESREA, the Ogun State Environmental Protection Agency (OGEPA), SRADev, and Platform Lead in April and September 2024 within the framework of the Partnership for Responsible Battery and Metal Recycling (ProBaMet) project. The project was funded by the German Federal Ministry for Economic Cooperation and Development (BMZ), with support from the Deutsche Gesellschaft fuer Internationale Zusammenarbeit (GIZ).
- Ghana: A facility assessment campaign and training event with EPA, Department of Factory Inspectorate, MRI, and the Ghana National Cleaner Production Centre (GNCPC) in February 2024 within the framework of the Swiss-funded project Sustainable Recycling Industries (SRI).
- Tanzania: A facility assessment campaign and training event with NEMC and AGENDA in October 2024 within the GIZ program Go Circular.

The outcomes of these facility assessments have been thoroughly documented but cannot—for data protection reasons—be provided to the public. This paper presents the generalized findings from these assessments in a way that cannot be traced back to individual plants or companies unless there is explicit consent by the plant management.

This paper aims to summarize and present findings from ULAB-related project work with a view to inform project planners and policymakers in that field. To do so, chapter 2 gives an overview of currently practiced ULAB recycling in sub-Saharan Africa, by describing framework conditions and technical, economic, and regulatory patterns observed during recent projects and fieldwork in Ghana, Nigeria, and Tanzania. Chapter 3 elaborates on the economics of ULAB recycling and compares the cost structures of the currently dominating substandard processes with optimized and higher-standard operations. Based on this, chapter 4 derives relevant aspects for strategies and policies aiming at systematic sector upgrades and lead-exposure reduction.

2 Current end-of-life management of lead-acid batteries

2.1 Collection

Due to their high content of lead, as well as some alloying elements such as antimony and tin, ULABs have considerable economic value in all the geographies that were studied. Batteries are usually not dumped but given to collectors who offer cash in return. Collection is almost exclusively in the hands of informal networks, with mobile collectors contacting motor vehicle repair clusters, businesses, and sometimes even households to pick up metal containing scrap. In urban areas, collectors often use pushcarts, which limits collection volumes and transport radius, but can also defer to motorized vehicles for picking up larger battery volumes (e.g., from corporate sources). Collected batteries go through a sequence of aggregation hubs until volumes are sufficiently large for shipment to recyclers. At all stages of the collection chain, some batteries—particularly flooded (wet-cell) LABs with a good visual appearance—are occasionally sorted out to be given to battery repair businesses (see section 2.2). In addition, there is some limited local artisanal demand for lead, e.g., to be used as a solder paste in repairs. Thus, some smaller volumes are sold to informal recyclers and industries applying artisanal methods. But by far the largest volumes are sold to industrial recyclers (see section 2.3). This stream is in most cases shipped to recyclers after draining the electrolyte (acid). The dilute sulfuric acid is either drained into the environment or collected to be used for other purposes such as in the form of a cleaning agent (Smith 2025a). Both are linked to emission of lead, as the drainage process washes out some lead oxide sludge. Batteries are drained to reduce transport weight and because most ULAB recyclers either require suppliers to drain batteries before delivery or reduce their price offer for undrained batteries.[15]

2.2 Repair & reuse

Repair and reuse of ULABs has been observed in many low- and middle-income countries and has been documented in Ethiopia (Manhart et al. 2016), Nigeria (Smith 2025b), and Malawi (Kinally et al. 2024). Operations are usually small and informal and range from simple ones such as refilling electrolyte to more complex battery repairs that involve dismantlement, the extraction and replacement of damaged grids, reassembly, charging, and testing. Various process steps involve the handling and melting of lead materials, which is commonly done without adequate precautions and within populated environments, sometimes even in residential homes.

15 There are different views on the reduction of prices for undrained ULABs. Many recyclers stress that they have no economic use for the electrolyte and therefore deduct its weight share (typically between 10 and 12 percent) before applying their price formula (usually a fixed rate per ton of delivered batteries). Suppliers perceive this system in a way that supplying undrained (wet) batteries is a real economic disadvantage leading to a lower net price for their batteries.

2.3 Recycling

The bulk of collected ULABs are sold to industrial recyclers in all studied countries. While there are various studies suggesting that the ULAB recycling landscapes in low- and middle-income countries are mostly dominated by informal operators (UNEA 2017; World Economic Forum & Global Battery Alliance 2020), there is clear evidence from fieldwork and market observations that the recycling process itself is dominated by industrial enterprises that are registered and licensed, fulfilling all indicators of formal industries.[16] The reasons for the strong position of formal industries can be found in the recycling process itself, which involves lead melting and smelting. In sub-Saharan Africa, informal operations in waste management and recycling are characterized by the use of simple tools and mobile or semipermanent structures and installations. While such informal operations can engage in battery breaking, extraction of lead, and melting of the elementary lead components (e.g., in pans over open fires), they usually do not have the means to recycle the lead oxide and lead sulfate, which make up roughly half of the lead material contained in batteries. Recycling these nonelementary lead components require smelting operations in metallurgical furnaces, which can only occur in permanent structures. Businesses that can set up and operate one or more metallurgical furnaces are typically formally registered industries and can significantly increase the lead recovery rate from the around 50–60 percent found in informal recycling to 90 percent and above (Wilson and Manhart 2021).[17] This allows higher income per recycling volume and a situation in which formal recyclers can offer attractive prices to (informal) operators. The prices offered by formal recyclers to informal networks for collected ULABs therefore exceed the revenues that are possible from inefficient backyard melting.[18]

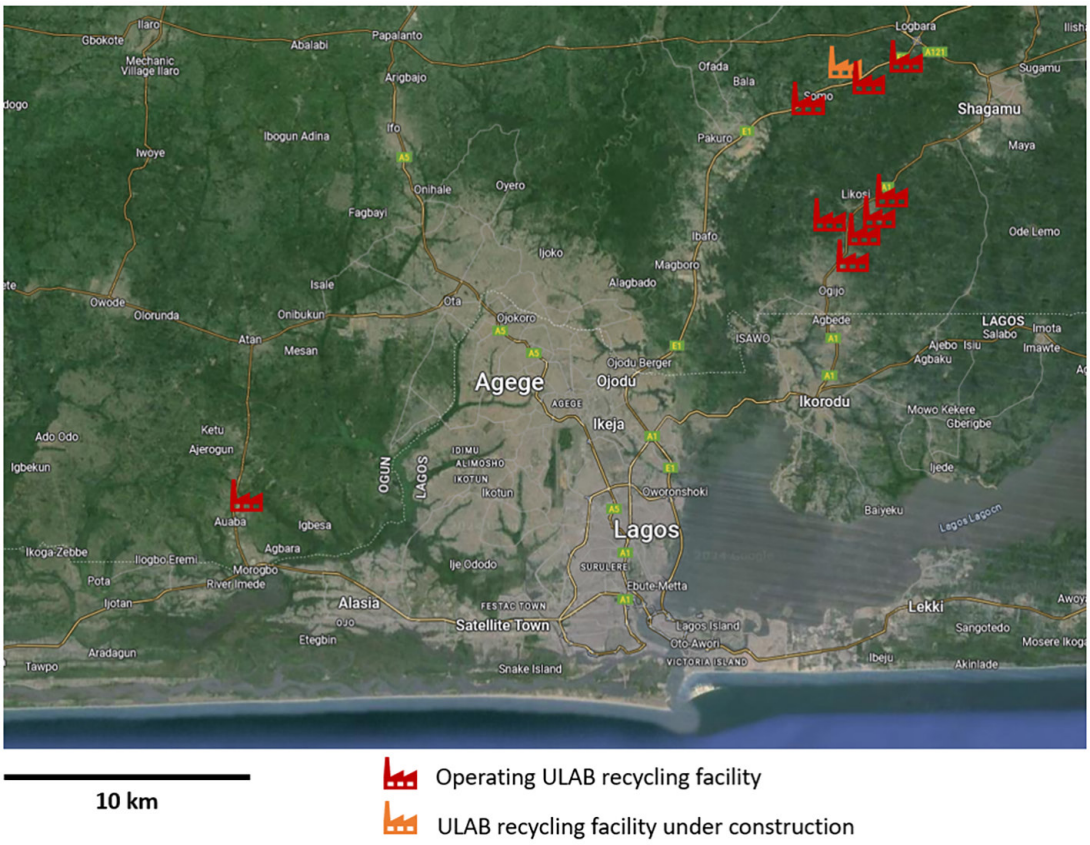
Figure 1 gives an impression on numbers and spatial distributions of industrial ULAB recycling plants in Lagos and Ogun State in Nigeria.

16 The discrepancies can partly be explained by recycling market trends over time and the fact that many publications focusing on the informal nature of ULAB recycling are several years old. Other reasons likely involve common difficulties researchers have in getting data from and obtaining access to formally registered industrial recycling plants. While informal sectors can often be accessed with local guides, managers of industrial plants have a close eye on who is granted access to their plant. Thus, there is structural bias towards more reporting on informal sector activities compared to formal sector recycling.

17 It is noteworthy that the situation and possibilities of informal operators in Asia seem to be different from those in the studied African countries. Many small-scale recyclers are reported to use simple self-made blast furnaces, particularly in countries in South Asia, such as Bangladesh and Myanmar (Manhart et al. 2018; Jarrell and Forsyth 2025), a pattern that has not been observed in any of the studied African countries. Nevertheless, the status of these plants may not be fully informal. At least in Myanmar, operators of small blast furnaces were found to be registered with local authorities.

18 Using the data of section 3.2, industrial recyclers can typically pay between 1,000 and 1,160 US$ per metric ton (mt) of ULABs. By contrast, informal backyard recyclers can at best recover 60 percent of the lead contained in batteries, which corresponds to a recoverable lead value of approximately 780 US$ per mt of batteries. In practice, revenues of informal backyard recyclers are even lower as they produce unrefined lead (bullion) with a market value below the LME price used as a reference price in international lead purchases.

FIGURE 1. Geographic overview of industrial ULAB recycling plants in Ogun State, Nigeria



Source: Map: Google, ©2025 TerraMetrics. Icons added by authors.

The total installed capacities of the recycling plants indicated in Figure 1 (plus one additional plant located in another region of Nigeria) match or even exceed the ULAB volumes generated annually in the country (Manhart et al. 2025). The situation is very similar in Ghana and Tanzania, where a total of five registered plants (Ghana) and seven registered plants (Tanzania) compete for ULABs collected by informal networks. In these countries, the spatial distribution of industrial recycling plants also follows similar patterns, with most plants being located in geographic proximity to major urban areas. Similarly, informal networks in Ghana and Tanzania mostly focus on battery collection, drainage of electrolyte, and supply to formal plants.

Industrial recyclers in Nigeria, Ghana, and Tanzania mostly use manual or semimanual battery breaking, rotary furnaces, and lead refining lines. Plastic cases are also recycled. The steps are briefly described in the following sections.

2.3.1 Battery breaking

Out of 17 assessed ULAB recycling plants in Nigeria, Ghana, and Tanzania, 8 solely referred to manual methods whereby workers were tasked with cutting and breaking battery with machetes or axes. Six plants used battery saws where rotating sawblades remove the battery covers so that workers can manually tip out the contained lead scrap. Only one of the six plants used a battery saw model that effectively protects workers from acid mist and injury hazards from the rotating sawblades. The five other plants used open saws and workers had to feed in the batteries; their hands were exposed to injury risks as well as acid mist. Two of the assessed plants used machines that shear off the batteries' top cover by mechanical force. This is followed by further manual dismantling operations. Only 2 of the 17 plants had a fully automated hammer mill breaker. In one of the two plants, this breaker has not been in use and the plant deployed open battery saws instead.

FIGURE 2. Battery breaking as commonly conducted in industrial ULAB recycling plants in sub-Saharan Africa

Notes: 1. Manual battery breaking with axes. 2. Semiautomated battery breaking with an open battery saw. 3. Semiautomated battery breaking with a machine shearing off the battery covers.
Source: Oeko-Institut.

2.3.2 Lead smelting

Rotary furnaces are currently the predominant furnace type in secondary lead smelting in sub-Saharan Africa. Out of the 17 plants assessed, 15 operated rotary furnaces for lead smelting. While a few smaller facilities relied on a single furnace, most plants were equipped with several units. The largest facility evaluated had five rotary furnaces installed in parallel, each with a processing capacity of approximately 10 metric ton (mt) per batch. While rotary furnaces are currently the predominant smelting technology, the landscape is not static, and many operations used blast furnaces until some years ago. In addition, 2 out of the 17 plants used reverberatory furnaces, a smelting technology often favored by plants with Chinese management. It is also noteworthy that two new investments that are not yet in operation (one in Tanzania, one in Ghana) are installing cupola furnaces (see Figure 3).

FIGURE 3. Furnace types used for secondary lead smelting in sub-Saharan Africa

Notes: 1. Rotary furnace: The feeding port is located at the right end and the tapping port in the middle over the lorry. The pipe at the left end connects the furnace with the off-gas treatment system. 2. Blast furnace: Sometimes also referred to as a "temple furnace." The one in the picture is not in use anymore. 3. Reverberatory furnace: The blue device blows fuel (coal dust) into the brick-made furnace. The iron cone covers the tapping port. Charging is done from the opposite side (not visible in the picture). 4. Cupola furnace: This model is still under construction. The visible opening is the feeding port. The diagonal yellow pipe connects the furnace with the off-gas treatment system.

Source: Oeko-Institut.

While rotary furnaces are widely considered appropriate for lead smelting due to their versatility in use and capability to also recycle lead oxide particles captured in the facilities' filter plants, sound operation requires a connection to a complete, fully functional, and well-maintained off-gas treatment system. Moreover, furnace charging, smelting operation, and tapping must be done in a

safe and hygienic manner not allowing lead emissions and exposure of workers. These aspects are often insufficiently implemented in the assessed plants:

- Furnaces are often not housed-in or equipped with fume hoods that effectively capture fumes and dust during charging, smelting, and tapping. This causes emissions of lead fumes and dust to the workplace and nearby environment. Here furnace tapping is the most critical step that—without adequate extraction ventilation—causes significant emissions in a short period of time.
- Where furnaces are housed-in or equipped with fume hoods, extraction ventilation was often found to be not strong enough or completely dysfunctional. It appears that some of these installations have been made to satisfy auditors rather than having tangible effects on emission control.
- In 5 of the 17 assessed plants, furnace charging was done purely manually with workers being tasked to shovel the charge material into the preheated furnace. This laborious step takes considerable time and unnecessarily exposes workers to lead fumes and dust. Most other plants used forklifts for furnace charging, but here also operators were exposed to hazards (in no case was the driver's cabin enclosed and supplied with filtered air).

The situation in the two plants using reverberatory furnaces was even more dire. These furnaces are operated nonstop for several months and the models witnessed required manual charging and tapping with only rudimentary extraction ventilation for the latter.

It must be noted that some few exceptions have been observed where furnaces were operated in a widely sound and hygienic manner. One of these cases was Green Recycling Ltd, which was publicly listed as a best-performing ULAB recycler in its region (Manhart and Adjei 2024).[19]

2.3.3 Lead refining

Out of the 17 secondary lead plants assessed, 16 were found to operate their own lead refinery units. Most of these facilities typically operated with two refining kettles, although in some plants the number of kettles reached five. The use of a greater number of kettles allows for more flexibility in producing a broader range of lead alloys.

19 This recycler was listed as the best performing recycler because it a) met the licensing conditions of local and national authorities; b) operated significantly above the commonly encountered industry practices in Nigeria; c) complied with a set of minimum criteria; and d) was committed to continuous improvements.

FIGURE 4. Substandard refining kettle as frequently observed in ULAB recycling plants in sub-Saharan Africa

Notes: This operating refining kettle is not equipped with a ventilated fume hood/extraction ventilation, resulting in emissions of lead fumes. Moreover, the kettle's rim is quite low, resulting in occupational risks for operators (e.g., during the necessary manual dedrossing steps). The visible surroundings of the kettle also show substantial weaknesses in housekeeping and dust control, a common weakness of many assessed plants.
Source: Oeko-Institut.

Several refinery units were observed to operate under substandard environmental and safety conditions. In some facilities, the refinery kettles were not equipped with fume hoods and extraction ventilation systems, resulting in emissions of lead fumes and exposure of workers. Certain refining sections also had unsafe layouts and inadequate safety measures, such as tipping and tripping hazards, lack of handrails, and upper rims of kettles that were sometimes low and unprotected (risking operators falling into them) (see Figure 4).

Automated casting machines were used in various plants and (when compared to previous plant visits in African countries) suggest a gradual modernization of casting operations. Nevertheless, these machines were still not universally adopted, and a significant number of facilities continued to rely on manual casting with higher labor requirements, as well as multiple occupational safety and lead-exposure risks.

Among the 17 assessed plants, 4 used the refined lead output for their own battery manufacturing lines. These plants tended to recycle ULABs primarily to secure a consistent supply of raw material for their own production needs. In contrast, the remaining 13 plants focused mainly on refining and exporting lead and lead alloys to external markets, reflecting a more trade-oriented operational model.

One of the assessed facilities engaged in additional value-adding activities by producing specialized materials such as battery-grade lead oxide and lead chromate pigments.

2.3.4 Management of battery electrolyte

As indicated in section 2.1, supply chains for LABs are organized in such a way that battery electrolyte is mostly already drained before the ULABs reach recycling plants. Subsequently, the assessed ULAB recycling processes do not yield any significant amount of sulfuric acid. Some residual electrolyte/acid is commonly observed in the battery reception and breaking area (muddy ground coverage mostly consisting of lead material and battery electrolyte) and most of the plant managers claimed that liquids are captured and channeled to an effluent treatment plant (ETP) where liquids are neutralized. While the existence of these ETPs can usually be verified, most of them have not been in operation during assessment visits. Moreover, the common designs of electrolyte capture and drainage systems, accumulation of mud and alien material in and around these systems, and exposure to rain- and stormwater raise severe doubts that the systems were ever designed to effectively capture and treat battery electrolyte. It appears that many ETPs are mainly constructed to fulfil the function of visually satisfying environmental auditors.

FIGURE 5. Battery breaking area with no functional system to capture electrolyte

Notes: Common floor cover of battery breaking areas. Leaking electrolyte forms a sludge containing some lead, plastic and other debris. It is unlikely to be captured and channeled to controlled treatment.
Source: Oeko-Institut.

2.3.5 Off-gas treatment

All of the assessed plants used off-gas treatment systems consisting of cooling towers, baghouse filters, and stacks.[20] Some plants additionally used wet scrubbers to remove sulfureous emissions. The use of cooling towers and baghouse filters is not only an environmental necessity but is also in the economic self-interest of recyclers, as these systems capture considerable amounts of lead material that can be fed back into smelting and would otherwise be lost.

Nevertheless, some off-gas treatment systems were clearly not fully functional and well maintained, with various plants showing visible particle emissions from stacks. Another very common weakness was the handling of captured filter dust. This dust is a fine white-gray powder, has a lead content between 50 and 70 percent, and is extremely hazardous, particularly when inhaled (Wilson and Manhart 2021). While all plants captured this dust, subsequent handling was in almost all cases substandard causing systematic leakages to the workplace and surrounding environment and exposing workers.

2.3.6 Recycling of plastic cases

All assessed facilities recycled the battery plastic cases. Recycling always involved the shredding of the cases into flakes. A few recyclers further processed them into pellets to be sold to local or foreign plastic producers. Four of the seventeen assessed plants had their own LAB manufacturing lines and hence in-house demand for the same polymer types and specifications. However, not all plants had in-house plastic injection-molding machines and therefore had no internal use for this output fraction.

Most, but not all, plants washed plastic cases or shredded plastic flakes. In many cases, washing was limited to one or two washing cycles. Visual observations indicate that lead oxide is often not fully removed from the plastic during these washing steps, which can be identified based on its brownish color. In one plant, no washing was done at all, and highly contaminated plastic chips were sold to local plastic manufacturing markets. Most of the plastic is polypropylene (PP)—a polymer type commonly used for producing day-to-day goods such as tables, chairs, bowls, and buckets—and cross contamination of lead oxide into such products is very likely.

2.3.7 Management of slags

Next to the intended metals, every smelting process generates slags that require sound management. Slags from the rotary furnaces as observed and operated in sub-Saharan Africa (see section 2.3.2) generate a soda-iron slag. This slag system is based on a two-stage reduction of the feed's lead sulfate and requires the addition of iron and sodium carbonate to the charge (Stevenson 2009). After furnace tapping, the slags are blackish, solid, and hydroscopic. After exposure to atmospheric moisture for

20 The cooling towers reduce the off-gas temperature to a level at which lead vapours condense into solid particles. These particles can then be captured by the baghouse filters before the gas stream is released through the stack. This basic off-gas treatment set up is intended to capture lead particles.

some days, they break down into a loose, reddish or grayish substrate. The slags have a residual lead content of 3 to 4 percent but may also feature higher values of up to 10 percent (Stevenson 2009; Wilson and Manhart 2021) and are therefore classified as hazardous waste and must be stored, handled, and treated accordingly.

The two plants using reverberatory furnaces produced iron-calcia-silicate slags, which typically have a high lead content of around 50 percent and require further processing in other furnace types (e.g., a rotary furnace). This process was not available in the two plants, and it was indicated that parts of the slag (the "matte" layer between the tapped lead and upper part of the slag) is fed back to a reverberatory furnace, while other parts are disposed or used in road construction.

Slag handling was observed to be inappropriate in most of the assessed plants. This includes storage in insufficiently sheltered or even fully exposed areas from which slag material is transported to the nearby environment by wind and rainwater runoff. When being asked of the final whereabouts of the slags, almost all plant managers referred to "licensed agents" who would care for sound disposal. Due to time limitations, these downstream management pathways could not be followed up on, but there are visual observations and field testing in industrial ULAB recycling clusters in Ogun State (Nigeria) suggesting that uncontrolled dumping may be a common pathway (see Figure 6 and Adie et al. 2025). As a response to this situation, NESREA conducted a slag evacuation program and announced standardized procedures for this waste stream in September 2025 (Adejoro 2025a).

FIGURE 6. Unsound management of slags as commonly observed in and around ULAB recycling plants in sub-Saharan Africa

Notes: 1. Interim storage of soda-iron slags from rotary furnaces. 2. Uncontrolled roadside dumping of metallurgical slags.
Source: Oeko-Institut.

The currently predominant ULAB recycling method (processing lead grids and paste together in rotary furnaces) generates around 4,500 mt of soda-iron slag per 15,000 mt of lead output, with a residual lead content likely between 3 and 4 percent.

It is noteworthy that the amount of slag can be reduced in facilities that separate elementary lead (mostly lead grids) from lead paste and apply a desulfurization step to the paste prior to charging it into the furnace. This method requires the use of an automated hammer mill breaker[21] and has only been applied in 1 out of the 17 assessed plants (see section 2.3.1).

TABLE 1. Indicative data on slag generation in different plant setups

Process Type	Assumed Lead Output	Slag Generation [%]	Slag Generation
Plant with no desulfurization prior to smelting	15,000 mt/a	~30% of lead output	4,500 mt/a
Plant with desulfurization prior to smelting	15,000 mt/a	~12% of lead output	1,800 mt/a

Source: Calculated with data from (Stevenson 2009) and further industry input.

Stevenson (2009) further indicates that desulfurization prior to smelting additionally reduces the lead content of generated slag, adding further environmental benefits to this process setup.

2.3.8 Housekeeping & dust control

In most of the ULAB recycling facilities visited, housekeeping practices and dust control exhibit broadly similar deficits, with few notable exceptions. The majority of plants lacked intact, impervious (concretized) floor surfaces that permit routine, thorough wet cleaning and dust suppression; floors were frequently fractured or extensively degraded. In the most severe cases, sections of the production area lacked concrete entirely, consisting of unconsolidated, dust-laden soil and debris. These conditions facilitated the retention of lead particulates and make effective dust control virtually impossible.

Material storage was commonly disorganized, with heterogeneous stockpiles occupying circulation and work zones. This created tripping and tipping hazards and, critically, obstructed the use of integrated housekeeping equipment such as ride-on wet sweepers. Consequently, resuspension of settled dust and fugitive emissions remained poorly controlled. Even in facilities that possessed partially improved floor substrates (for example, localized concretized areas), housekeeping and dust control systems were typically under-implemented or ineffective.

Predominantly manual practices in battery breaking and handling of lead materials, as well as common leakages of fugitive emissions from the off-gas treatment systems, caused persistent accumulation of dust in corners, floor depressions, architectural niches, and outdoor areas. There was also visual evidence in various plants that workers had used brooms to attempt to clean plant floors prior to plant assessments, leading to further agitation of particulates.

21 In an automated hammer mill breaker, the elementary lead is separated from the lead paste in enclosed and water-based processes. This yields two dedicated lead outputs that can be handled separately in subsequent melting and smelting processes. In contrast, manual and semiautomated operations cannot separate these different lead materials. While this is theoretically possible, it would require substantial labor input and almost certainly cause inappropriately high lead exposure.

The absence of engineered liquid capture, graded drainage, and containment systems[22] further limited the feasibility of wet cleaning, as wash water cannot be properly collected, treated, or disposed of in compliance with environmental requirements. Without sealed floors, wall and floor curbing, effluence and water collection sumps, and interceptors that prevent the spread of fluids, wet methods risk redistributing lead contamination and generating uncontrolled effluent.

While the regional pattern is largely uniform, there were isolated outliers demonstrating good practice. For instance, one assessed facility in Nigeria maintained continuous concrete flooring, effective drainage, and liquid capture infrastructure, and reported routinely implementing wet cleaning protocols. However, such examples were exceptional rather than representative of sectoral norms. Most plants in sub-Saharan Africa fell between pictures 1–3 as shown in Figure 7 below.

FIGURE 7. Characteristic situations linked to housekeeping and dust control in ULAB recycling plants in sub-Saharan Africa

Notes: 1. Dust-covered floor with signs of broom usage in a ULAB recycling plant. 2. Heterogenous storage of materials and accumulation of dust and debris renders housekeeping and dust control measures difficult and most likely impossible. 3. In a few instances, a ULAB plant that was assessed had significantly better conditions, with a smooth concretized floor, effective dust control measures, and drainage pathways to allow for wet cleaning measures. A well-designed drainage channel can be seen in the photo.

Source: Oeko-Institut.

22 These systems ensure that cleaning water or battery fluid effluent is automatically collected in an enclosure, such as a sump, to allow for further treatment. For example, covered drainage channels integrated into the factory floor can be used to direct runoff to subsequent treatment. Such systems must also be designed to avoid other material such as soil entering the system, which can lead to blockages and system overloading.

2.3.9 Safety

Across the majority of assessed ULAB recycling plants, safety culture was weak or absent, with limited institutionalization of occupational health and safety functions. Where health and safety professionals existed, they frequently held multiple concurrent responsibilities, often within human resources or general operations, which diminishes role independence and efficacy. Assessments indicated that health and safety officers are rarely integrated into strategic decision-making or senior management forums, resulting in minimal authority to enforce controls. While safety pictograms and signage were sometimes displayed at entrances and on plant walls, there was scant evidence of systematic enforcement, supervision, or consequence management aligned with these requirements.

Physical hazards arising from machinery and facility layout were prevalent. Several plants exhibited unsafe floor plans characterized by obstructed circulation routes due to stockpiled materials, the presence of exposed corroded metal components, and an absence of clearly indicated fire suppression systems, marked evacuation routes, or readily accessible first aid and emergency response stations. Open and unguarded machine drive belts and chains were observed, along with widespread tipping and tripping hazards stemming from uneven surfaces, disordered storage, and inadequate housekeeping. Noise levels in plastic crushing operations were frequently elevated, with additional risks from splinter projection during size reduction, indicating deficiencies in acoustic control and guarding.

Process-specific risks related to battery breaking were significant; manual battery breaking commonly results in skin and eye exposure to acid, while semiautomated sawing of batteries generates acid mist that increases inhalation exposure in addition to contact risks. These hazards are increased by poor particulate control and inadequate housekeeping, which allow accumulation and resuspension of lead-bearing dust.

Even where personal protective equipment was available in the appropriate quantity and specification for tasks and workstations, its protective efficacy was compromised by the absence of primary pollution controls, poor maintenance of equipment, and insufficient supervision of correct PPE selection, fit, and use.

Safety performance was heterogeneous, with a small number of facilities demonstrating noticeably higher safety standards and more mature safety culture, including clearer governance structures, better equipment guarding, and improved emergency preparedness. However, such cases were isolated and should not be interpreted as representative of the sector. Overall, the convergence of organizational weaknesses, hazardous layouts, insufficient pollution controls, and inconsistent PPE implementation indicates systemic risks that require comprehensive interventions spanning governance, monitoring and enforcement, facility engineering and layouting, maintenance, industrial hygiene, and consistent training.

FIGURE 8. Symptoms of underdeveloped safety culture as observed in many ULAB recycling plants in sub-Saharan Africa

Notes: 1. Obviously unsafe walkway in a ULAB recycling plant (additionally contaminated with hazardous filter dust).
2. A worker operates an automated battery saw with unprotected hands, half-open shoes, and inadequate protection from potential acid mist and without ear protection against noise.

Source: Oeko-Institut.

2.3.10 Industrial hygiene

The adequacy of basic infrastructure and procedural controls that underpin industrial hygiene, worker safety, and decent working conditions was frequently insufficient in the ULAB plants that were assessed. A large share of facilities lacked canteens or designated eating areas. Where such areas existed, they were often substandard and not designed to provide effective barriers against lead contamination. Typical deficiencies include inadequate zoning from production areas, absence of negative-pressure ventilation, and insufficient handwashing and decontamination stations at entries.

Changing rooms and sanitary amenities exhibited similar shortcomings. Showers, lockers, and laundering provisions were either absent or configured in ways that did not prevent cross contamination between soiled work garments and clean personal clothing. Lack of segregation between dirty and clean zones and insufficient storage for separate clothing sets are common. In many contexts, including African cultural settings, the absence of private, secure, and gender-appropriate facilities discourages use by women due to concerns about privacy, safety, and dignity.

These deficits increased the probability of "take home" lead, a pathway by which lead contamination on clothing, footwear, skin, and personal items is transported into households, thereby exposing family members and amplifying the community burden of lead exposure.

Provision and consistent use of personal protective equipment were variable and often episodic. Assessments suggested that PPE issuance and visible compliance rise during announced visits by authorities and external stakeholders, indicating weak integration of PPE into routine controls. Given the frequent presence of particulates, acid mist, and settled debris in many ULAB recycling plants, reliance on PPE without robust pollution controls and housekeeping was insufficient to achieve adequate protection. Fit, selection relative to task and hazard, maintenance, and replacement cycles are inconsistently managed, further reducing protective efficacy.

Blood lead testing and monitoring was limited in scope and rigor. Many assessed facilities in Ghana and Nigeria did not conduct systematic BLL testing. Where testing occurred, it often involved small, non-representative samples initiated after external assessments or regulatory prompting. There are few documented protocols for medical management of elevated BLLs, including criteria for temporary removal, task reassignment, and follow-up testing. In Nigeria, since 2024, the National Environmental (Battery Control) Regulations include a requirement for at least biannual BLL testing under Article 48 paragraph j. Implementation guidance on standardized methodologies, quality assurance, reporting formats, and data governance has not yet been developed. In Tanzania, the Occupational Safety and Health Authority (OSHA) conducts annual BLL testing for employees of lead processing plants and maintains a database, but routine data sharing and integration with broader environmental compliance systems remain limited. NEMC did not have structured, routine access to these data, which constrains coordinated risk and mitigation management.

Workforce composition presented additional monitoring challenges. The sector frequently employed temporary and casual labor for unskilled tasks. Policies and practices for inclusion of short-term workers in occupational health surveillance, including enrolment in BLL monitoring, medical clearance, training, and record keeping, were often unclear or undocumented. This gap risked systematic under assessment of exposure in a group likely to face higher task related risks and lower access to protective measures.

FIGURE 9. Typical washroom amenities as observed in ULAB recycling plants in sub-Saharan Africa

Notes: 1. A severely substandard washroom amenity without gender segregation. 2. Washroom amenities observed at the premises of another ULAB recycler with significantly better standards, although falling short of what would be considered "best practice" in more developed countries.

Source: Oeko-Institut.

2.4 Policy framework, licensing, & monitoring

All countries studied have elaborated regulatory frameworks and monitoring procedures for industrial activities, including the following:

- Mandatory benchmarks for emissions to air, water, and soil, as well as mandatory requirements for management of waste.
- The requirement to apply for and obtain various licenses, including environmental permits or licenses issued by the national environmental authority, fire safety certification, and health and safety certification, as well as the standard business operation authorizations such as incorporation and commencement documents. Before a plant is built, the company must conduct an Environmental Impact Assessment (EIA), which is reviewed by the environmental authorities. The EIA document as well as potential further requirements form part of the initial licensing conditions. Licenses must be renewed periodically, and the renewal process may lead to additional requirements such as on emission controls and industrial hygiene.

- In all three countries, compliance audits are conducted more or less regularly by the responsible authorities. For environmental aspects, these audits are conducted by the EPA in Ghana, NESREA and the state environmental protection agencies in Nigeria, and NEMC in Tanzania. These institutions have robust mandates, can conduct inspections at any time, and, in the case of identified shortcomings, can order remedial actions. Repeated failure to implement remedy steps can lead to sanctions such as fines and temporary or permanent closure. It is noteworthy that these agencies have the mandate for environmental inspections and licenses, but not for conducting health-related monitoring, as this falls to the competence of institutions responsible for health and workplace safety.

The regulatory and monitoring framework above is applied to registered industries. Small operators commonly stay "under the radar" of authorities and are part of the informal economy. This is particularly the case for ULAB collectors (see section 2.1) and battery repair workshops (see section 2.2). The industrial ULAB recyclers described in section 2.3 are all subject to these licensing and monitoring systems.

Beyond the regulation and monitoring systems above, the following aspects are noteworthy:

- Nigeria enacted National Environmental (Battery Control) Regulations in 2024. The regulations contain extensive provisions for managing and recycling ULABs, including responsibilities along the product-waste chain and its governance. More details can be found in Manhart et al. 2025.
- In Ghana, Tanzania, and Nigeria, shortcomings in operations have already led to instances in which ULAB recycling plants were temporarily shut down by the authorities. In one case, a plant was relocated to another site. In many other cases, plants were allowed to restart operations after some upgrades had been made.
- In Tanzania, the national regulations require all lead processing industries to cooperate with OSHA to conduct annual BLL testing of employees. Out of the three surveyed countries, Tanzania is currently the only one with established systematic blood lead testing. Nevertheless, interagency cooperation is not yet fully developed, so unfavorable testing results do not necessarily lead to more stringent operating requirements (which are typically imposed by the environmental authorities). Nigeria's National Environmental (Battery Control) Regulations from 2024 also mandate occupational BLL testing. Procedures on scope, frequency, test methods, and data provision are still to be specified in technical guidelines.
- The procedures described above are a major factor for why all plants are equipped with a certain level of emission control systems (see section 2.3.5). Procedures such as the EIA and subsequent inspections make it impossible for plants to escape facing consequences for cruder plant setups that lack equipment required by the authorities.

- Nevertheless, government resources for monitoring are limited. Plant inspections are time and resource intensive and means of remote monitoring (e.g., fenceline air monitoring) are uncommon.[23]
- Inspectors are often well trained in regulations, licensing procedures, and general auditing methods, which makes them capable of identifying general misconduct. Nevertheless, to mandate improvements, inspectors must be able to describe identified shortcomings and clearly specify the required technical changes. These skills are significantly less developed, which sometimes leads to unspecific requirements or requirements that do not address a plant's main shortcomings.[24]
- Moreover, the managers of plants with identified shortcomings commonly try to influence administrative decision-making on their operation, e.g., by using arguments around foreign direct investment and generating jobs and suggesting that recycling activities would be per se environmentally friendly. Thus, even with well-proven shortcomings, many plants manage to stay in operation without taking effective (but also costly) improvement steps.

3 Economics of different lead-acid battery recycling patterns

3.1 Investment costs

Table 2 provides estimated investments costs for a mid-sized plant following a high environment, health and safety standard. While the size of the plant would represent a comparably large unit in the African context, there are various existing plants with similar processing capacities in the studied African markets (Manhart et al. 2025).

Investment costs for a low-standard plant with the characteristic patterns described in section 2.3 are estimated in Table 3.

23 Remote monitoring is common in many sectors and world regions and involves equipment that constantly measures the concentration of pollutants at critical points of a plant and transmits this data simultaneously to the plant's control room and to the regulatory authorities in charge. Common air pollutant measurement points are a) the stack, b) the boundary of a plant's property (fenceline), and c) within the recycling/production hall. Remote monitoring cannot replace physical inspections and BLL testing routines but can provide an additional monitoring level to track a plant's emissions over time.

24 For example, requirements asking for regular maintenance of equipment without further specification. Another common requirement is to build an effluent treatment plant (ETP). While ETPs are important elements of soundly operated plants, it is also important that plants collect batteries with acid so that this hazardous constituent is managed properly. Many of the assessed plants that built an ETP did not use it because their sourcing strategies and processes were focusing on dry batteries (see section 2.3.4).

TABLE 2. Estimated investment costs for a high-standard medium-sized plant (10,000–20,000 mt/a lead output)

		Cost Estimate (Lower Range)*	Cost Estimate (Upper Range)*
Technology line			
Automated hammer mill breaker		~1	~4
Paste desulfurization & crystallization unit		~2	~3
Lead smelting unit (housed-in with automated charging)		~2	~3–4
Refining section (incl. automated casting)		~2	~4
Quality assurance lab (spectrometer)		~0.2	~0.5
Off-gas treatment system (with life monitoring)		~0.5	~1
Gypsum production unit		~0.2	~0.5
Total		**~7.9**	**~16.5**
Non-technology line			
Main production hall	With overhead crane, solid smooth floor, separate areas for storage of lead scrap, and charge preparation	Non-technology investment costs are estimated at around 40% of total investment costs	
Ancillary hall	For repairs, equipment storage		
Slag storage	Enclosed, for interim storage		
Amenity block	Change rooms, lockers, washroom, showers, in-house laundry, health section, canteen. In a separate building with filtered air supply, etc.		
Office block	Including furniture & IT equipment		
Supporting machinery	Lifting and transport equipment, equipment for maintenance & repairs, etc.		
Weigh bridge			
Ancillary installations	Design of outside areas (incl. smoothly paved with runoff-capturing systems), wet cleaning machines for inside and outside areas, firefighting equipment, etc.		
Others	Incl. costs for land & civil works		
Total		**~5–6**	**~11**
Technology line + non-technology line			
Grand total		**~13.5**	**~27.5**

Note: *All data in million US$.

Source: Estimates with data points from various sources.

TABLE 3. Estimated investment costs for a low-standard medium-sized plant (10,000–20,000 mt/a lead output)

		Cost Estimate (Lower Range)*	Cost Estimate (Upper Range)*
Technology line			
Battery breaking equipment (open battery saws, axes, etc.)		~0.01	~0.2
Lead smelting unit (not housed-in, no automated charging)		~0.5	~1.5
Refining section (no extraction ventilation)		~0.3	~0.5
Quality assurance lab (spectrometer)		~0.2	~0.5
Basic off-gas treatment system		~0.2	~0.5
Total		**~1.21**	**~3.2**
Non-technology line			
Main production hall	With overhead crane, basic floor, no separated areas	Non-technology investment costs are estimated at around 60% of total investment costs	
Ancillary hall	For repairs, equipment storage		
Slag storage	Not enclosed		
Amenity block	Basic change rooms & washroom		
Office block	Including furniture & IT equipment		
Supporting machinery	Basic lifting and transport equipment, equipment for maintenance & repairs, etc.		
Weigh bridge			
Others	Incl. costs for land & civil works		
Total		**~1.8**	**~4.8**
Technology line + non-technology line			
Grand total		**~3.01**	**~8**

Note: *All data in million US$.
Source: Estimates with data points from various sources.

The comparison of estimates from Tables 2 and 3 suggest that high-standard medium-sized plants require significantly higher investment costs compared to the plant types that currently dominate the African market. These differences are estimated to be at least 10 million US$.

3.2 Total cost structure

Indications on the cost structure of ULAB recyclers can be derived from the prices they can offer to collectors and maintain over extended periods. This method builds on the following framework conditions and calculations:

- All recyclers that sell refined lead on the (international) market get the same or similar price for their output, which strongly correlates with world market prices fixed at the London Metal Exchange (LME). The LME price for refined lead varies over time but has not shown major fluctuations since 2010. In recent years the price has stayed between 1,620 US$/mt

and 2,720 US$/mt, mostly fluctuating around 2,000 US$/mt (International Monetary Fund 2025). An average price of 2000 US$/mt for refined lead is used in the calculations that follow.

- Industrial recyclers require a consistent supply of sufficient amounts of ULABs. As indicated in section 2.1, collection is largely in the hands of informal operators who aim to get the best price for their collected volumes. In that effort they carefully compare price offers from buyers and usually sell to the highest bidder within a given geographic setting. Therefore, industrial recyclers have to offer attractive prices high enough to secure their required ULAB supply but low enough to enable profits.
- Transaction prices are typically determined with the following formula:

  Weight of delivered ULABs [mt] × LME price [US$/mt] × plant-specific factor [%]

  The plant-specific factor considers the ULABs' lead content, the plant's costs for processing/recycling, shipment of lead to buyers, and an expected profit margin.
- In September 2024, the only existing high-standard recycler in Nigeria (which widely uses a plant setup as described in section 3.2) reported it was able to use a maximum factor of 50 percent, meaning the plant was at best able to offer 1,000 US$/mt of ULABs assuming an LME price of 2,000 US$/mt of refined lead. At the same time, competing industrial low-standard recyclers were able to apply a factor of 58 percent, which translated into 1,160 US$/mt of ULABs.
- With an assumed lead recovery efficiency of 99 percent for a high-standard facility and an assumed average lead content of 65 percent,[25] 1 mt of ULABs yields 0.644 mt of lead with an international market value of 1,287 US$/mt. The same amount of ULABs yields 0.618 mt of lead with an international market value of 1,235 US$/mt, assuming a lead recovery efficiency of 95 percent for a low-standard industrial recycler.
- Table 4 compares the figures from the sections above, which indicates that processing costs in a soundly operating facility in Nigeria (including shipment of refined lead) is somewhere around 287 US$/mt of ULABs. In contrast, the currently dominating substandard recyclers have indicative processing costs of about 75 US$/mt of ULABs.

25 The lead content of unbroken batteries (with acid) is typically in the range of 55–60 percent. As many ULAB recyclers focus on purchasing drained ULABs, the relative lead content increases to around 65–70 percent.

TABLE 4. Comparison of cost structures of high- and low-standard industrial ULAB recycling plants

	ULAB Input	Maximum Possible Expenditure for Collection	Lead Content[26]	Lead Recovery Efficiency	Refined Lead Output	Value of Refined Lead Output[27]	Estimated Costs for Recycling[28]
High-standard industrial recycler	1 mt	1,000 US$/mt	65%	99%	0.644 mt	1,287 US$	287 US$/mt
Low-standard industrial recycler	1 mt	1,160 US$/mt	65%	95%	0.618 mt	1,235 US$	75 US$/mt

Source: Own calculation.

While the calculation in Table 4 is only indicative, it supports the assessment conducted in section 3.1 and suggests that high-standard industrial ULAB recycling facilities have, despite having somewhat higher lead recovery rates, higher costs compared to their low-standard competitors.[29] This disadvantage in cost structure plays out in the acquisition of ULABs for recycling, where high-standard plants cannot compete with the prices offered by their low-standard competitors. This leads to a situation in which potential investors interested in setting up high-standard operations are deterred from entering such markets, as their investment would not be able to compete with existing substandard plants. In the few studied cases where investors have—despite the competitive market situation—set up a high-standard facility, the operation struggled to secure a stable ULAB supply while staying profitable.

According to various plant managers in the three countries, this situation is worsening:

- The number of industrial ULAB recycling plants is increasing in all three countries. New investors are coming in and are granted operating licenses by the authorities. Thus, competition over securing sufficient and stable ULAB supply is increasing. At the same time, ULAB availability on the local markets remains comparably constant.[30]
- Some industrial recyclers do not sell the recovered lead on the world market but use it for their own LAB production (4 out of the 17 studied plants). In the case that their battery production and sales business do well, they have higher revenues due to more value addition. These plants, therefore, have higher chances to prevail in such

26 High-standard plants predominantly source complete batteries with electrolyte. Such batteries have a lead content in the range of 55 to 60 percent. For reasons of simplicity, this calculation is based on the batteries' weight without electrolyte—independent from whether ULABs are supplied with or without electrolyte.

27 At an LME price of 2,000 US$/mt of refined lead.

28 Including shipment costs of refined lead and profit margins.

29 The assessment does not consider potential differences in revenues from alloying and is solely based on returns from refined lead with 99.97–99.99 percent purity. Alloys such as antimonial lead can fetch higher prices and may allow higher revenues. Likewise, the assessment does not consider revenues from recycling the batteries' plastic cases. Recycling of plastic cases was observed in all studied plants, so differences in these revenues are likely to be negligible.

30 Some plants follow the strategy to source ULABs from neighboring countries. Nevertheless, the numbers of industrial ULAB recyclers are also increasing in many other African countries. Among others, there is evidence of new plant constructions in Côte d'Ivoire, Togo, and Ethiopia.

competitive settings.[31] Local market observers in Nigeria and Tanzania even report that new and expanding battery producers are a major factor for the increasing competition over ULABs.

4 Summary and policy implications

The current LAB recycling sectors in Ghana, Nigeria, and Tanzania are largely characterized by substandard industrial facilities that source (drained) ULABs from informal networks. Emissions of lead into the workplace and the environment occur at multiple stages of the recycling chain and in most plants and appear to be a widely accepted aspect of business practice. This situation can be primarily attributed to the prevailing economic drivers and framework conditions under which investments in high-standard plants and operations yield lower economic returns and endanger competitiveness.

Although quantitative data on emissions are limited, it appears very likely that substandard industrial ULAB recycling plants represent some of the most significant point sources of lead emissions in the countries examined. While this paper primarily focuses on Ghana, Nigeria, and Tanzania, project work and expert exchange in and with other African countries indicate that similar patterns exist across much of the continent.

Regulatory attention to this sector has increased considerably in recent years, and countries such as Ghana and Nigeria have initiated several measures aimed at comprehensive sector improvements. Although these activities have produced initial results, the structural challenges around this sector are far from being resolved.

The following section lays out the main recommendations for policymakers and intervention planners at national, regional, and international levels for this sector.

Thorough considerations on informal—formal sector interactions

There are various authors and papers suggesting that informal and formal operators compete against each other in ULAB recycling in low- and middle-income countries and that policymakers are advised to promote formal recycling over informal operations (World Economic Forum & Global Battery Alliance 2020). While authors such as (Ericson et al. 2016) rightly state that "a higher number of informal industrial sites are located within residential areas than their formal counterparts and pollute more per unit than their formal counterparts," it is sometimes overlooked that informal and formal sectors work closely together in the ULAB collection and recycling chain. Polluting informal

31 In that context it must be noted that the recycling sections of three of the four assessed battery producers have not been found to apply any higher standard. If there is a correlation, it tends to be the other way round, with three of the four battery producers being among the plants with the lowest environmental and hygiene standards in ULAB recycling.

sector practices such as battery breaking and draining are motivated by the purchasing conditions of formal recyclers. Sound policy responses must consider these interactions and stay away from simplified models attributing all problems to one stakeholder group.

Likewise, the strong focus on the hazards of informal operations sometimes lead to the assumption that pollution from formal industries would be comparably low and that formal operators should be given preferential treatment such as tax exemptions (World Economic Forum & Global Battery Alliance 2020; Jacobs 2025). Considering the findings from fieldwork in various African countries, we strongly reject this assumption. While informal operators are large in number and cause pollution and lead exposure in numerous, often densely populated areas, substandard industrial ULAB recycling is causing substantial lead emissions, likely reaching several hundred mt per year per plant. While this makes them likely to be some of the biggest lead-emitting entities in many low- and middle-income countries, they also have the ability to influence their supply chains and can adjust their purchasing practices to discourage informal operators and networks from damaging or breaking collected batteries. Thus, we strongly recommend focusing a large section of policy responses on registered industrial ULAB recyclers. While informal sectors also deserve attention, it must be noted that policy enforcement is much more challenging in informal settings, with limited overall impact on overall lead emissions if the industrial ULAB recyclers are ignored.

Effective sanctions against polluting entities

The competitive situation for acquiring enough ULABs for recycling is the key factor limiting the prospects of high-standard recyclers in countries such as Ghana, Nigeria, and Tanzania. While the three countries undertook efforts to upgrade their ULAB recycling sectors, it is still unclear if this will translate into a long-term situation in which polluting recyclers have the choice to either undertake significant upgrades or stop operations. While until recently many plants got away with some efforts around provisions of PPEs and limited but unsubstantial upgrades, concerted assessment and (temporary) facility closure campaigns in Ghana (Carlos Atsu Calony 2023) and Nigeria (Adejoro 2025b) sent clear signals that more substantial upgrades are expected. To have long-term effectiveness, such regulatory pressure on low performers must be upheld and be consistent over time. The coming months and years will show whether the promising regulatory approaches in Ghana and Nigeria will be sustained, including under future political and administrative leaderships. It will also be interesting to observe if these efforts will have a replication effect in others African jurisdiction. A recent decision at the African Ministerial Conference on the Environment (AMCEN) points toward more regional exchange on this topic, which may catalyze the replication and adoption of successful sector upgrade strategies on the continent (see the section on regional exchange below).

Need for market consolidation

The competitive situation described above is aggravated by government policies routinely granting operating licenses for new ULAB recycling plants without considering the limited market sizes

and the need for consolidation in favor of a few high-standard facilities.[32] This results in a growing number of plants and makes many operators struggle to stay in business, which in turn prevents investments in higher standards and will also cause a situation in which some of the plants will fail and stop operations. Each abandoned ULAB recycling plant and its surroundings are likely highly contaminated and require remediation. Therefore, an unplanned sector development causes multiple detrimental effects, namely:

- High competition that stimulates a race toward low operating standards.
- A fragmented market, with most recyclers receiving comparably small volumes of batteries. This prevents economies of scale and further limits the feasibility of substantial upgrades.
- A growing number of contaminated sites from failed ULAB recycling ventures requiring remediation.

It is advised that government authorities reassess their criteria for granting operating licenses. While liberal economies can usually not prescribe an upper limit for the number of licensed plants, they can shape licensing conditions in a way that only credible high-standard investors can qualify. This should entail: a) mandatory compliance with ambitious technical and operational requirements/standards; b) mandatory and regular occupational BLL testing; c) digital live monitoring of air and stack emissions (with full data access for regulatory agencies); d) financial guarantees that can cover the costs for facility closure and site remediation; e) the polluters-pays-principle, including taking over of decontamination, health treatment, and compensation payments in pollution and exposure cases; and f) adequate insurance cover.

Thorough implementation of the polluter-pays-principle

There are various documented pollution cases from industrial ULAB recycling in sub-Saharan Africa, namely Kenya (Kenyan Ministry of Health 2015), the Democratic Republic of Congo (Will Fitzgibbon 2024), Ghana (Carlos Atsu Calony 2023), and Nigeria (Manhart et al. 2025; Adejoro 2025b). In all these cases, pollution and exposure of workers and neighboring communities have led to temporary or permanent closure of one or more substandard facilities; however, none of them has led to compensation payments from the polluting companies to victims.[33] Additionally, no company was required to conduct and finance site remediation in any of the cases. Although some remediation efforts have been undertaken in Ghana and Nigeria, they have been fully financed by other sources.

While—as noted above—regulatory action against polluting recyclers is a central part of any sector upgrade strategy, the current situation is still unsatisfactory, as the burden of pollution continues

32 To date, Ghana has five, Nigeria ten, and Tanzania seven industrial ULAB recycling plants. In contrast, Germany has only four ULAB recyclers, while at the same time being the world's fifth largest user of lead (ILZSG 2023). Economies of scale are a relevant precondition for sound ULAB recycling.

33 In Kenya, a court ordered the compensation and remediation of the affected Owino Uhuru community with substantial contributions of the ULAB recycling company (Supreme Court of Kenya 2024). However, so far no compensation payment or structured remediation has been made.

to be carried by workers, neighboring communities, and wider society as a whole. Substandard recycling facilities can still count on being able to operate while having the required licenses and can withdraw from their operations without being held responsible for covering the costs for remediation, health treatment, and adequate compensation. Although Ghana, Nigeria, and Tanzania have the polluter-pays-principle embedded in their legal systems, it has not yet been applied to any ULAB related pollution case. The difficulties in this respect are mostly linked to the following:

- No systematic and regular blood lead testing, and no other form of health surveillance that could be used as a scientific indicator for lead exposure and health impacts.
- Unspecific symptoms of lead poisoning such as chronic fatigue that cause workers to drop out of their jobs without having clarity on the medical and occupational root causes.
- The low education status of most victims (workers, neighboring communities) and limited resources for lawsuits.
- A lack of lawyers working in the field of occupational health and environmental justice.
- Limited trust in legal systems.

It must be stressed that a thorough application of the polluter-pays-principle is not only important for justice reasons but also offers great potential to change the economic framework conditions in this sector: Once ULAB recycling companies have to factor in potential compensation claims from workers and neighboring communities, measures to mitigate emissions and exposure will gain higher importance. Usually, mitigating measures are much cheaper than the potential financial consequences of lawsuits, remediations, and compensation.

Such dynamics play a large role in more developed economies such as the US and Germany. There, companies often apply standards that are significantly more ambitious than the legally required minimum, and a main motivation is to avoid future compensation claims.

Regional exchange

In various African countries, steps have been taken to reform and upgrade the sector. While some countries such as Ghana, Nigeria, and Ethiopia initiated systematic reform and upgrade strategies, other countries such as Kenya and the Democratic Republic of Congo have been primarily focusing on resolving individual pollution cases. Approaches vary from country to country and range from situations in which civil society groups confronted industries and government agencies with pollution cases (Kenya) to situations in which governments, academia, and civil society groups joined forces for sector reform (Ghana, Nigeria). While these countries have already gained valuable experience on how to upgrade this sector, others have not yet begun. In any case, a regular regional exchange between policymakers, academia, civil society groups, and industries from African countries could facilitate the exchange of lessons learned and catalyze sector reform within the region. A first (partial) regional exchange took place in March 2025 in Abuja at the Upgrading the Lead-Acid Battery Recycling Sector in the African Region conference and led to the Call for

Action on Africa's Lead-acid Battery Recycling Industry, which, among other things, calls for more regional exchange and coordination in a multistakeholder initiative (PAN Ethiopia & SRADev 2025; Manhart et al. 2025).

This initiative was picked up at the 20th session of AMCEN in July 2025 in Nairobi and is reflected by the Decision on Strengthening Chemicals and Waste Governance in Africa conference, which "encourage[s] member states, to establish a multistakeholder initiative to develop standards to the environmental sound management of used lead acid batteries" (AMCEN 2025). The seed for regional exchange is therefore planted, and it is recommended that this regional dynamic be grown into an impact-oriented initiative with steering and ownership by regional players.

Supply chain due diligence

As laid out in the policy recommendations above, sector upgrade strategies largely depend on well-planned and implemented strategies at the national level, including the introduction and enforcement of minimum standards, sanctions against polluting recyclers, implementation of the polluter-pays-principle, and adequate and proactive reactions of plant managers.

However, it is important to recognize that many African nations have limited domestic demand for lead, which means that much of the recycled lead is exported to international markets. In that context it is strongly encouraged to treat lead as a commodity with potentially high human rights and environmental contamination risks when sourced from countries with insufficiently developed safeguards. Subsequently, it is advisable for buyers of lead as well as lead-containing products to engage in robust supply chain due diligence, adopting approaches like those used for monitoring so-called conflict minerals.

In fact, market demand serves as an important additional lever for systematic sector upgrades, complementing the impact of regulatory measures. It is essential to emphasize that implementing supply chain due diligence should not automatically result in the cessation of lead purchases from all sources in low- and middle-income countries. Instead, the focus should be on understanding and leveraging the potential role that lead markets can play in driving positive change.

Improved monitoring

The application of sensor-based remote monitoring technologies, such as those used for tracking stack emissions, measuring air quality within production halls, and conducting fenceline air monitoring, is already a well-established standard in many industrialized nations. These systems have demonstrated their effectiveness in supporting environmental oversight and regulatory compliance. It is increasingly important that similar approaches be adopted in low- and middle-income countries, where the benefits of such monitoring can be substantial for both public health and environmental protection.

When implementing these technologies, it is crucial to ensure that the models selected are both affordable and robust. Additionally, these monitoring systems should provide a live data link to relevant authorities, enabling real-time oversight. Integrating video data from the production site can further enhance transparency and accountability. To maintain the integrity of the monitoring process, it is advisable to establish co-access for a neutral third party, which can play a vital role in providing independent quality assurance and verifying the accuracy of the data collected.

However, it is important to recognize that sensor-based remote monitoring should not be viewed as a substitute for in-person facility audits or for critical health assessments such as blood lead testing. Instead, these technologies should be regarded as complementary tools that enhance the overall effectiveness of environmental management and worker safety programs. By combining remote monitoring with on-site inspections and health screenings, stakeholders can achieve a more comprehensive view of the sector and determine areas for critical focus.

The role of international donors and experts

In many low- and middle-income countries, resources for effective oversight are limited, even though regulatory staff are often highly motivated and committed. Local institutions generally possess solid technical capabilities, although these may not always be specific enough for assessing ULAB plants or designing targeted policies. Support works best when aligned with national priorities and when it reinforces rather than replaces domestic expertise. Strong national ownership in these countries already provides a solid base, and international partners can add value by facilitating cooperation, dialogue, and regional alignment where structural barriers exist.

The strategy sometimes pursued by international donors and organizations of taking over the roles, responsibilities, and functions of local institutions and experts should be firmly avoided. While international specialists may deliver quick results, this approach risks undermining national ownership and reducing the likelihood that measures will be sustained once external support ends. It is more effective to expand domestic expertise and strengthen organizations that can adapt knowledge to local contexts and select suitable engagement approaches. Research and consultancy efforts supported by international partners should therefore be designed to build national and regional capacities as part of a gradual exit strategy.

Any strategy for sector improvement requires sustained financing across multiple agencies, reflecting the complexity of the value chain and the number of institutions involved. Similar needs exist at regional and continental levels, where cooperation is often limited. Local experts and organizations are best placed to guide reform processes and should be centrally involved in designing and coordinating measures for improving ULAB management.

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