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Review

Environmental Impact of Lead-Acid Batteries: A Review of Sustainable Alternatives for Production and Recycling Based on Life Cycle Analysis

Dimas Alberto Pincay-Pilay [1,*] and Eugenio F. Carrasco [2]

[1] Department of Chemical Engineering, School of Engineering, University of Santiago de Compostela, Campus Vida, 15705 Santiago de Compostela, Spain
[2] Department of Chemical Engineering, Faculty of Sciences, University of Santiago de Compostela, Campus Terra, 27002 Lugo, Spain; eugenio.fernandez@usc.es
* Correspondence: dimasalberto.pincay@rai.usc.es

Abstract

Lead-acid batteries (LAB) continue to be one of the most widely used energy storage technologies worldwide, especially in the automotive sector and in backup systems. However, their use is a significant source of lead and sulfuric acid pollution, with negative impacts on the environment and human health. This review analyzes the environmental and health effects of LAB manufacturing, use, and recycling, and evaluates sustainable alternatives through life cycle analysis. A search was conducted in the Multidisciplinary Digital Publishing Institute (MDPI), Science Direct, and Springer databases, yielding more than 247 documents, from which 84 technical and scientific articles were selected, mostly from the last five years, excluding duplicates and irrelevant texts or those in languages other than English. The results reveal that conventional pyrometallurgical processes release between 30 and 50 kg of lead fumes per ton processed, causing concentrations of up to 5000 mg/kg of Pb in soils near informal plants, exceeding international limits by more than 25 times. In contrast, closed-loop hydrometallurgical technologies reduce emissions by more than 70% and increase secondary lead recovery, making them an environmentally friendly option. It is concluded that the sustainability of the LAB system requires technological innovation, effective regulation, and extended responsibility within an eco-friendly circular economy model.

Keywords: lead-acid batteries; pollution; waste; sustainability; recycling; life cycle

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1. Introduction

Lead-acid batteries (LAB) are crucial for powering different devices, especially in the automotive industry [1]. As global demand for vehicles increases, their use is also expected to rise [2]. However, industrial lead processing remains a major source of environmental pollution and health risks. In addition, this process increases the carbon footprint derived from extraction, production, and recycling throughout the battery's life cycle analysis (LCA) [3].

Lead is a naturally occurring toxic metal present in the Earth's crust, whose extensive use throughout history has had serious impacts on ecosystems and human health [4]. According to the World Health Organization [5], lead has no biological function in the body, and exposure to it, even at low levels, can affect the nervous system, kidneys, and cognitive development in children. Lead pollution is estimated to cause more than 900,000 deaths worldwide each year, making it one of the ten most dangerous chemicals to public health [5]. The main sources of contamination include mining, smelting, manufacturing, and recycling, as well as the improper disposal of products containing lead, including LAB [6,7]. Environmental studies estimate that anthropogenic activities have released around 300 million tons of lead into the environment over the last five centuries [8].

Currently, more than 85% of global refined lead is used in the manufacture of LAB, which are used primarily in the automotive industry, photovoltaic systems, and uninterruptible power supplies [9,10]. The global market value of these batteries reached $37.98 billion in 2023, with a projected compound annual growth rate of 4.6% through 2030, driven by the expansion of the automotive and renewable energy sectors [10,11]. However, the production and recycling of LAB represent one of the largest industrial sources of lead and sulfuric acid pollution, generating emissions and leachates that contaminate various environmental matrices [12–14]. In Latin America, Africa, and Southeast Asia, the lack of environmental controls and the high degree of informality in recycling processes exacerbate the risk of human exposure and environmental degradation [8,15]. In contrast, industrialized countries such as the United States, Canada, and members of the European Union have successfully established recycling systems with recovery rates exceeding 95%, thanks to robust regulatory frameworks and low-impact technologies [16]. In Ecuador, although regulatory changes have been implemented, the comprehensive management of used batteries remains deficient due to limited traceability, insufficient control of the informal sector, and low adoption of clean technologies. The lack of adequate recycling and environmental monitoring infrastructure increases the vulnerability of exposed communities, especially in industrial areas or hazardous waste disposal sites [17–19].

Several authors have proposed methodologies for improving LAB production, such as the "one shot" method, which optimizes sulfuric acid consumption and increases battery durability, reducing their ecological footprint [20,21]. However, studies on technological efficiency and sustainability in the LAB cycle are scarce and fragmented, limiting the development of evidence-based policies. Furthermore, to date, there are no reports of studies that have comprehensively addressed the impact of the production, use, and recycling of LAB and their waste on the environmental matrices of water, soil, and air, or their direct relationship with human health in terms of pollution levels and exposure to heavy metals. Most existing studies focus on isolated aspects, such as the energy efficiency of the recycling process, electrochemical performance, or the use of secondary lead, leaving aside a comprehensive view that connects these stages of the life cycle with the associated environmental and social damage. Likewise, no detailed assessments have been found on mitigation and control strategies based on LCA, a key tool for quantifying and comparing impacts from raw material extraction to final disposal. In this context, this research develops a comprehensive review of LCA applied to LAB, analyzing their environmental footprint, their performance in production and recycling, and the current regulatory framework, also contrasting them with international experiences and more sustainable management models. The novelty of the study lies in the integration of a technical, environmental, and regulatory approach that allows for the identification of critical deficiencies in the current management of LAB and the proposal of improvement strategies based on the principles of sustainability, extended producer responsibility, and circular economy, aimed at reducing the ecological and health impacts of the LAB system.

2. LAB Manufacturing Industry

The LAB manufacturing industry continues to be a key player in the global energy storage market due to its low cost, operational robustness, and high capacity, maintaining significant demand despite the growth of alternative technologies. In 2023, the value of the global LAB market stood at around USD 38 billion, and compound annual growth is forecast to be around 4.6% until 2030, driven by automotive applications, photovoltaic systems, and backup power supplies, with the Asia-Pacific region accounting for more than 50% of global revenue [10]. These figures explain why the industry continues to absorb most of the refined lead: approximately 85% of the world's refined lead is currently used in the production of LAB, making this sector a strategic consumer of the metal and a source of environmental and public health risks when operational controls are insufficient [9].

Production flows also show that, while developed countries have consolidated comprehensive recovery and recycling schemes with return rates of over 95% [22], in many emerging economies, the value chain has high levels of informality in collection and recycling, which amplifies the externalization of environmental impacts to vulnerable communities. In Latin America, LAB production and recycling are concentrated in a few formal industrial plants and a broad network of informal actors [23]. Recent studies and reports on national cases show that Brazil and Mexico have more developed industrial capacities and regulatory programs that allow for the integration of closed-loop schemes, while other countries (Peru, Ecuador, and Colombia) face gaps in infrastructure, enforcement, and traceability of end-of-life batteries [24].

The manufacture of LAB for automotive use is a complex process involving multiple physicochemical operations, from the receipt of lead alloy ingots to the shipment of the final packaged product for distribution. Figure 1 shows a typical production flow, which begins with the smelting of lead ingots and ends with the packaging and distribution of batteries. The process begins with the shipment of lead ingots, often from regions such as Europe. Emissions from the maritime transport of these essential raw materials are the first critical point of environmental impact. The burning of fossil fuels in cargo ships contributes significantly to the carbon footprint of the supply chain [25]. The lead ingots then undergo an oxidation reaction during which they are converted into lead oxides (PbO) that are used in the active paste to coat the plates. This stage is a major source of fine particle and metal fume emissions, especially if the process lacks adequate air capture and filtration systems. Exposure to lead compounds must be strictly controlled, as they are highly toxic to the environment and humans [26,27].

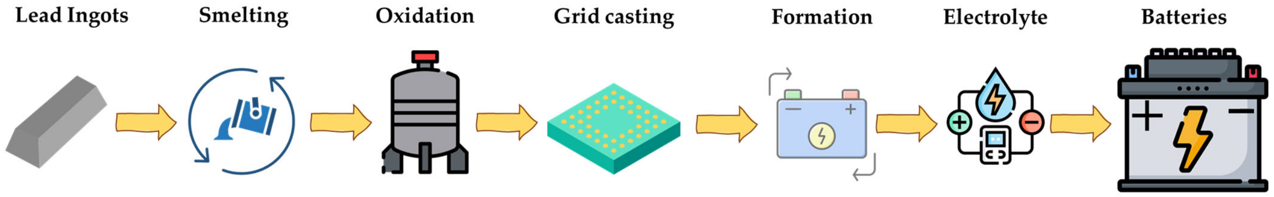

Figure 1. Diagram of the LAB production process.

At the same time, lead is melted in grids and coated with PbO paste; gas emissions during the melting stage for grid manufacturing are another source of environmental impact. Lead smelting furnaces, especially if they are not very efficient, can release sulfur oxides (SO_2), lead fumes, and PM10 or PM2.5 particles, which endanger human health and the environment [28]. The wet paste plates undergo a curing and drying process, usually using heat generated by combustible gas. Once the battery plates have been cured, they are assembled into cell arrays with separators between them. These are welded and sealed inside a plastic container, after which the terminals that will connect the battery to its container are fused [29]. For the initial charging of the battery, the system is filled with electrolyte (sulfuric acid diluted in distilled water) and then immersed in tanks filled with water to prevent overheating; this stage generates hydrogen and oxygen emissions due to electrolysis. If not properly ventilated, this step can pose a risk of explosion and indoor air pollution [30].

Finally, after the electrolyte is adjusted, the batteries undergo quality testing to verify that they are properly charged and ensure that they meet the intended design requirements. Although their direct impact is less intense, these stages are part of the product's LCA and must be taken into account in a comprehensive sustainability assessment.

Advances in the LAB Production Industry

In recent years, the LAB manufacturing industry has undergone a gradual transition towards more sustainable production models, driven both by environmental requirements and the need to improve the sector's efficiency and competitiveness. Technological advances are concentrated in two key areas: the optimization of metallurgical and recycling processes, and electrochemical innovation in cell design. Both approaches converge in reducing the environmental footprint, extending product life, and decreasing hazardous waste, in line with circular economy and industrial decarbonization trends [31,32].

In the metallurgical field, the main development is the replacement of traditional pyrometallurgy, which operates at temperatures above 1000 °C and generates SO_2 and metal particle emissions, with low-emission hydrometallurgical and hybrid pyrometallurgical technologies. Hydrometallurgical processes allow for the selective recovery of lead through leaching, desulfurization, and crystallization, obtaining high-purity products and minimizing slag generation. According to [31], the adoption of hydrometallurgical schemes in pilot plants has reduced fine particle and sulfur oxide emissions by more than 70% compared to conventional methods. In addition, the use of closed circuits to regenerate reagents and recycle sulfuric acid solutions reduces the demand for raw materials and the volume of toxic effluents [33].

These advances not only improve environmental performance but also the economic efficiency of recycling. By recovering metallic lead and sodium sulfate as commercial by-products, modern processes optimize energy balance and reduce operating costs. Likewise, the incorporation of online control technologies and emission sensors has enabled real-time monitoring of lead concentrations in gases and wastewater, strengthening regulatory compliance in regions where environmental enforcement is increasing, such as the European Union or China [34].

At the same time, electrochemical advances in LAB cell design are focused on improving the efficiency and durability of electrodes. The introduction of doped or chemically modified carbon materials in negative electrodes (such as nitrogen-doped or NH_4Cl-modified carbon) has been shown to improve conductivity, sulfation resistance, and deep charge capacity [35]. These modifications reduce the frequency of replacement and, therefore, the generation of lead waste, contributing to the sustainability of the product's LCA. Other innovations in LAB manufacturing aim to optimize energy efficiency by recovering waste heat generated during the curing and drying of plates and other thermal stages of the process. In practice, this involves capturing hot air or exhaust gases from the melting furnace, dryers, or curing processes and directing them to heat exchangers or thermal recovery systems (air-to-air, air-to-water, or organic Rankine cycle-based systems to recover low/medium temperature energy) [36]. The recovered heat is used to preheat drying air, heat process water, or feed furnace preheaters, thereby reducing primary energy demand and improving the overall thermal efficiency of the plant. In addition, many facilities are complementing these measures with renewable energies applied to thermal stages, for example, photovoltaic systems that supply electricity for pumps, fans, and backup electric heaters, and biomass-fired boilers or heaters to partially replace fossil fuels in curing and melting processes [37]. The combination of WHR (waste heat recovery) with renewable sources can significantly reduce fossil fuel consumption and CO_2 emissions associated with LAB production.

Together, these advances constitute a new generation of high-performance, low-environmental-impact LAB, where technological efficiency, environmental control, and industrial sustainability converge. The trend toward digitization and intelligent process management using sensors and predictive analytics marks the next evolutionary step for the sector, in pursuit of green and competitive manufacturing in the face of emerging energy storage technologies.

3. Environmental Impact of LAB Production and Use

The informal production, use, and repair of LAB are persistent and locally intense sources of lead (Pb) and associated by-products (sulfuric acid, slag, dust) that contaminate multiple environmental matrices and affect human health [28]. Even though LAB are highly recyclable and the formal sector has achieved high recovery rates in developed regions, the combination of traditional industrial processes, informal waste management, and regulatory gaps creates pollution "hot spots" whose intensity and extent vary with the technology used and the degree of environmental control [38]. In this regard, it is necessary to address the impact of pollutants generated in the production and use of LAB in various environmental matrices (Figure 2).

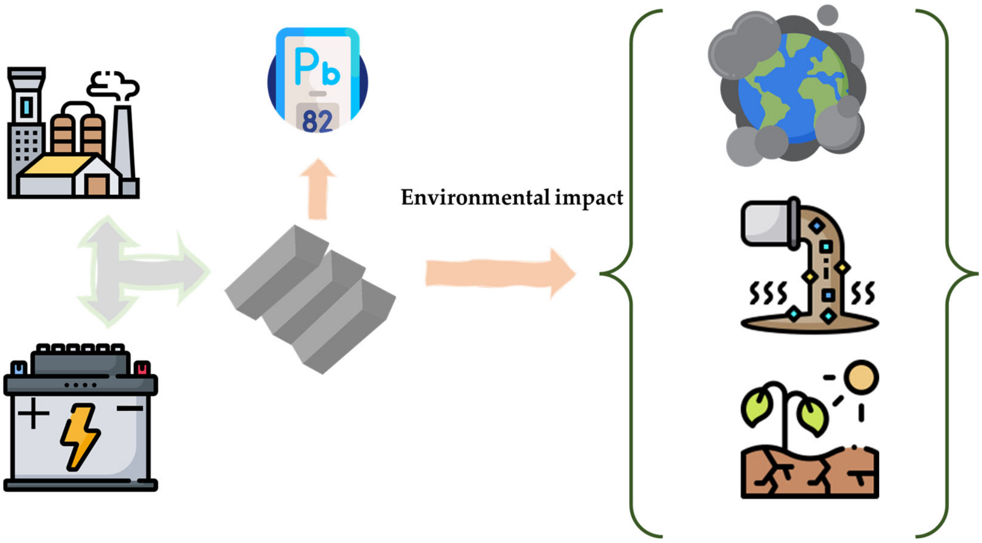

Figure 2. Extent of the environmental impact caused by poor management of LAB.

Figure 2 shows the environmental impact that the production, use, and recycling of LAB can have on the air, soil, and water matrices. It can be seen that the main pollutant derived from these batteries is Pb. The following section discusses the levels of contamination reported in the environmental matrices.

3.1. Environmental Matrices

3.1.1. Soil

The manufacture, prolonged use, and improper disposal of LAB constitute one of the most persistent anthropogenic sources of soil contamination on a global scale, mainly due to the release of lead (Pb) and associated compounds such as sulfates, oxides, and acid electrolyte residues [39]. The soil acts as a final receptor for these emissions, both through atmospheric deposition and leaching from industrial slag and effluents, becoming a toxic sink with a long half-life. During the manufacturing stage, smelting, oxidation, and curing processes generate fine particles of lead and oxides that are deposited in areas surrounding industrial plants, affecting the surface fraction of the soil. While in informal recycling, the manual opening of batteries, the burning of pastes, and the disposal of slag directly and locally aggravate the pollutant load [31]. The concentrations recorded in soils near production or recycling plants vary widely, but the most recent studies agree that they exceed international reference values by several orders of magnitude. In Bangladesh, for example, ref. [26] reported concentrations in the order of 966 mg/kg of Pb in soils adjacent to LAB repair shops, while in China, average values in the order of 2000 mg/kg have been observed in industrial areas near formalized plants [17]. In comparison, the US Environmental Protection Agency proposes a limit of 200 mg/kg for residential soils, and even 100 mg/kg in areas with multiple sources, which shows the magnitude of the pollution derived from this industry [40]. In Latin American regions, where informal or semi-formal recycling processes predominate, the situation is no different: in Peru and Mexico, sites have been identified with soil Pb concentrations exceeding 5000 mg/kg, with direct impacts on local communities and agricultural ecosystems [41].

The mechanisms that explain this persistence are related to the low mobility of lead in neutral conditions and its strong adsorption to clay, carbonate, and organic matter fractions in the soil. However, the presence of sulfuric acid and a decrease in pH (common in areas contaminated by electrolyte spills) increase the solubility and mobility of the metal, favoring its vertical migration to deeper horizons or its incorporation into groundwater [34]. This phenomenon is particularly concerning in tropical soils or in environments with high rainfall, where leaching accelerates the transport of Pb and its regional dispersion. On the other hand, open-pit smelting and waste burning generate fine particles (<10 µm) that, after being deposited, enrich the surface layer of the soil with Pb, As, and Sb compounds, increasing the bioavailability of the metal to plants and soil organisms. The persistence of Pb in the soil is quite high, since its half-life can exceed 700 years under low leaching conditions, which means that the contamination generated today will continue to affect future generations [42]. In addition, lead interferes with soil biogeochemical processes by inhibiting microbial enzymes, reducing soil respiration, and altering the bioavailability of essential nutrients such as Zn, Fe, and Ca, causing a cascading effect on agricultural productivity [43].

The ecological and socioeconomic consequences are equally severe. In agricultural areas near LAB smelting centers, high levels of Pb have been detected in high-consumption crops, compromising food security. For example, ref. [26] found concentrations in vegetables that exceeded the maximum limits allowed by the WHO, evidencing the transfer of the metal to the food chain. Soil contamination not only reduces fertility and microbial diversity, but also generates economic losses due to the unitability of agricultural land, the cost of remediation, and the health effects of chronic exposure. In urban areas, contaminated soils act as secondary sources of exposure for children through household dust, which contributes to increased blood Pb levels [44]. These effects are more pronounced in regions where informal recycling lacks controls on emissions, storage, or final disposal. From a comparative perspective, the data show that the magnitude of contamination depends on the level of industrial formalization. In modern plants with emission control and slag management technologies, Pb concentrations in adjacent soils rarely exceed 500 mg/kg, while informal sites record levels up to 100 times higher, according to the Department of Toxic Substances Control [45]. This difference demonstrates the mitigation potential of adopting clean processes such as hydrometallurgy or low-emission pyrometallurgy, which reduce dust generation and allow for the recycling of reagents and effluents [33]. However, the restoration of already impacted soils remains a complex and costly challenge. The most effective techniques include physical removal and replacement of the topsoil, encapsulation, and assisted bioremediation, although their effectiveness varies depending on the depth and initial concentration of the contaminant [44]. In Bangladesh and Nigeria, the removal of 15–30 cm of contaminated soil has been shown to reduce surface Pb levels by more than 80%, although the effects on human health cannot be completely mitigated, requiring complementary actions such as education, environmental cleanup, and continuous monitoring [46].

3.1.2. Air

The LAB industry generates atmospheric emissions that represent one of the main sources of air pollution from lead (Pb) and fine particles in industrial and urban environments. During ingot smelting, oxidation for the production of lead oxides (PbO), and initial battery charging, gaseous compounds and metallic particles are released, affecting both the indoor air of the plants and the surrounding atmosphere. These emissions contain metallic lead, lead oxides, sulfates, antimony (Sb), arsenic (As), and sulfur dioxide (SO_2), which can remain suspended or settle on the ground and nearby vegetation, generating multiple long-term exposures [34]. In plants with inadequate controls, Pb levels in the air can reach values above 50 $\mu g/m^3$, well above the limit recommended by the US Environmental Protection Agency (EPA) (0.15 $\mu g/m^3$ of Pb in ambient air), demonstrating the high risk of contamination associated with the industrial process [47].

The effects of this pollution are both local and regional. At the local level, workers and communities near manufacturing plants or informal recycling facilities suffer direct exposure through inhalation of contaminated air or dust deposition in the domestic environment. In regions such as South Asia and West Africa, atmospheric lead concentrations in informal reuse areas have been detected that exceed maximum permissible levels by 100 to 200 times, highlighting the absence of filters and ventilation systems [26,42]. In China, ref. [17] documented that air emissions of Pb and SO_2 from a LAB plant could disperse up to 3 km from the site, with a direct correlation to atmospheric concentrations in adjacent areas. Fine particles (PM10 and PM2.5) not only pose a respiratory hazard, but also act as vehicles for the regional dispersion of lead, contributing to the contamination of other environmental matrices. In addition, the release of secondary gases, such as sulfur dioxide (SO_2) and nitrogen oxide (NO_X), derived from the combustion of liquefied gas or coal during the curing and drying of plates, increases the load of atmospheric pollutants and enhances the formation of acid rain, affecting ecosystems on a large scale [23].

Informal recycling of LAB exacerbates this situation, as the open burning of plastic covers and electrolyte residues generates black smoke laden with toxic organic compounds and heavy metals. Studies in peri-urban areas of Nigeria, Bangladesh, and Peru report air concentrations 10–30 times higher than the permissible limit, which has led to episodes of mass poisoning and deterioration of air quality in neighboring communities [44].

In this context, air pollution from waste derived from the LAB industry continues to be a global environmental and health challenge, especially in regions where production and recycling are carried out without control. The air, as a dynamic matrix, acts as the main vehicle for the dispersion of pollutants, connecting point emissions from plants with diffuse contamination of soils, waters, and ecosystems. The adoption of clean technologies, the formalization of recycling, and regulatory strengthening are essential steps to reduce the atmospheric burden of lead and mitigate its impact on public health and the environment.

3.1.3. Water

Water is one of the most vulnerable matrices to contamination from the manufacture, use, and improper disposal of lead-acid batteries, due to the high solubility of certain lead compounds (Pb^{2+}, $PbSO_4$, PbO_2) and their chemical persistence in aquatic environments. Liquid emissions and leachates generated in LAB plants are significant sources of lead input into water bodies, affecting surface water, groundwater, and urban drainage networks [48]. In industrial stages, effluents originate mainly from equipment washing, cooling, pickling, and residual acid neutralization processes, which contain Pb concentrations that can exceed 50–200 mg/L, well above the discharge limits set by the World Health Organization (0.01 mg/L for drinking water) and the United States Environmental Protection Agency (0.015 mg/L) [5]. In regions where industrial plants lack adequate treatment systems, these effluents are discharged directly into water bodies or infiltrated into the soil, contaminating local aquifers and supply networks [49].

Improper handling in final disposal B also exacerbates the impact of LAB on water bodies. During manual battery opening, the electrolyte (diluted sulfuric acid, ~4–5 mol/L) is poured directly onto the ground or into storm drains, creating a double threat: acidification of the environment and the simultaneous release of Pb and other heavy metals. A decrease in pH below 3 dramatically increases the solubility of lead, favoring its transport in solution to groundwater and subsequent dispersion [44]. In countries such as Nigeria, ref. [42] reported Pb concentrations of 1.6 to 5.4 mg/L in wells near artisanal recycling areas, while in Bangladesh, levels of up to 11 mg/L have been found in adjacent surface waters [26]. In Latin America, recent studies show contamination of water wells and streams in rural areas with concentrations ranging from 0.3 to 2.5 mg/L, which directly compromises agricultural and domestic water use [41].

The mechanisms of dispersion and accumulation of lead in aquatic environments are complex. A significant portion of the released Pb is associated with suspended particles and dissolved organic matter, forming Pb–humate or Pb–carbonate complexes that tend to sediment, accumulating at the bottom of rivers, lagoons, and estuaries [50]. This sedimentary fraction can be resuspended during floods or hydrodynamic disturbances, causing chronic contamination of the system. In anoxic environments, the reduction of PbO_2 and interaction with sulfides favor the formation of PbS, a less soluble compound but potentially unstable in the face of changes in pH or redox potential. Thus, bodies of water near LAB plants or landfills act as dynamic reservoirs of lead, capable of releasing the metal again under variable environmental conditions. Water contamination is also reflected in aquatic biota: filter feeders, fish, and aquatic plants accumulate lead in their tissues, with bioaccumulation factors ranging from 100 to 5000, depending on the species and environmental conditions [51]. The ingestion of these contaminated organisms represents an indirect route of human and ecological exposure, generating neurotoxic and cardiovascular risks.

Water pollution by LAB also has implications for drinking water quality and food safety. In rural communities without treatment infrastructure, the use of contaminated groundwater has led to alarming increases in blood Pb levels, especially in children. For these reasons, modernized LAB production plants have been implemented, featuring closed hydrometallurgical processes, sulfuric acid recovery, and internal water recycling. These measures can reduce water consumption and pollutant load by more than 80% [31]. However, the adoption of these technologies in developing regions remains limited for economic and regulatory reasons.

3.2. Human Health

Recent research provides clear evidence that the manufacture and improper disposal of LAB not only contaminates soil, air, and water, but also generates cumulative risks that affect biota and human health, especially in communities near production plants or informal recycling facilities. Table 1 shows the levels of Pb contamination derived from LAB and its ecological and human health effects. The type of exposure and sources of contamination are also shown.

Table 1. Reported concentrations of lead in various environmental matrices contaminated by LAB, and their ecological and health effects.

Environmental Matrix	Ubication	Concentrations	Polluting Sources	Ecological and Health Effects (Type of Exposure)	References
Soil	China	30.4–41.3 mg/kg	Slag deposit in LAB industrial park	Moderate cumulative contamination, potential bioaccumulation in crops and water (community exhibition)	[50]
	Bangladesh	966 mg/kg	Artisanal battery recycling, plastic burning, electrolyte dumping.	Extreme pollution, mass poisoning (community exhibition)	[26]
	Bolivia	2400 mg/kg	Disposal of slag and metallurgical waste	Persistent urban pollution, affecting family gardens (community exhibition)	[52]
	Mexico	>5000 mg/kg	Semi-industrial recycling workshops and uncontrolled smelters	Degraded agricultural soils, chronic exposure of children, Pb in vegetables (15–30 mg/kg) (community exhibition)	[41]
Air	USA	$0.3–2 \times 10^{-6}$ mg/L	Smelting and improper disposal in residential areas	73% of children >5 µg/dL Pb in blood (occupational exposure)	[45]
	China	2.4×10^{-6} mg/L	Formal recycling of LAB, smelting, and oxidation of Pb	Non-carcinogenic risk, higher exposure in children (3.46×10^{-2} mg/kg day) (occupational exposure)	[53]
	Czech Republic	50×10^{-6} mg/L	Casting, oxidation, plate curing, and handling of PbO	Respiratory and neurological risk, high occupational exposure (occupational exposure)	[23]
Water	China	0.5–2 mg/L	Dissolution of PbO_2 and $PbSO_4$ in industrial effluents	Bioaccumulation in fish and invertebrates, enzymatic alteration, and oxidative stress (community exhibition)	[34]
	Nigeria	1.6–5.4 mg/L	Electrolyte and slag leachate spills	High bioavailability (45–50%), degradation of agricultural soils, anemia in children (community exhibition)	[42]
	Bangladesh	3.8 mg/L	Acid leaks and leaching into aquifers	High presence in children's health biomarkers (community exhibition)	[44]
	Bangladesh	11 mg/L	Artisanal battery recycling, plastic burning, electrolyte dumping	Local acid rain, mass poisoning (community exhibition)	[26]

The information presented in this table shows a duality in exposure patterns: on the one hand, occupational exposure, concentrated among workers in foundries or recycling workshops, and on the other, community exposure, which affects populations living near these industrial or informal centers.

Soil acts as the main sink and reservoir for lead in community exposure. In Mexico, semi-industrial workshops and uncontrolled facilities generate concentrations exceeding 5000 mg/kg [41], which indicates severe contamination that compromises food safety and child health. These values exceed the limits established by the WHO (200 mg/kg for residential soils) by more than 25 times. In Bolivia, urban soils reach up to 2400 mg/kg, affecting family gardens and exposing communities that depend on subsistence agriculture [52]. In Asia, Bangladesh has recorded levels of 966 mg/kg, accompanied by documented cases of mass poisoning due to environmental and dietary exposure [26]. These results show that community exposure depends not only on proximity to emission sources, but also on local socioeconomic conditions and the degree of environmental regulation.

In terms of air, the highest levels of Pb are reported in work environments, which exposes workers to occupational exposure. For example, up to 50×10^{-6} mg/L has been detected in the Czech Republic [23] and 2.4×10^{-6} mg/L in China [53], both associated with PbO smelting and oxidation processes. These concentrations pose a high occupational risk, particularly through the inhalation of fine particles (<10 µm), which can penetrate deep into the respiratory tract and cause neurological and hematological damage. In informal settings, such as artisanal workshops in Africa or Latin America, emissions are often even higher, although systematic measurements are not always available. Air pollution also affects nearby communities (community exposure). In the United States, for example, values between 0.3 and 2×10^{-6} mg/L around residential areas exposed to obsolete smelters caused 73% of children to have blood Pb levels above 0.05 mg/L [45]. This trend is repeated in densely populated urban areas of Lagos (Nigeria) and Douala (Cameroon), where air and household dust values exceed international standards and confirm a transition from occupational exposure to chronic community exposure.

Water, meanwhile, represents a secondary but no less important route of exposure. In Nigeria and Bangladesh, concentrations between 1.6 and 11 mg/L have been reported [26,42], result of electrolyte leaks and industrial leachates. These values exceed the maximum Pb limit allowed for drinking water by more than 100 times. Water pollution promotes bioaccumulation in fish and aquatic organisms, creating risks through food consumption, especially in fishing communities. Lead mobility increases in acidic conditions ($pH < 5$), amplifying its bioavailability and toxicity, with documented effects such as oxidative stress, enzymatic alterations, and liver damage in wildlife and even in humans exposed over the long term.

Socioeconomic Factors and Environmental Inequality

Lead exposure linked to the production and recycling of LAB is deeply influenced by socioeconomic factors: poverty, informal employment, regulatory gaps, and deficits in education and health services. These variables act as risk multipliers, increasing the likelihood that both workers and residential communities will suffer high and prolonged exposure [54]. With regard to poverty and economic dependence on informal recycling, in many contexts in Latin America and Africa, battery recycling and scrap metal recovery are a critical source of family income. Economic necessity drives activities in homes and yards without emission controls or protective equipment, increasing both occupational and community exposure. These patterns are associated with higher levels of Pb in household dust, soil, and locally grown food, with direct consequences for child health (cognitive deficits, developmental delays) and adult health (kidney disease, hypertension). Recent studies and reviews emphasize that informality reproduces cycles of intergenerational vulnerability [55]. In addition, informal work and the absence of labor protections play a major role, as artisanal workshops and informal recycling centers often operate outside regulatory frameworks. The lack of protective equipment, engineering controls, and environmental monitoring results in constant respiratory and dermal exposure; workers have blood Pb levels that often exceed reference thresholds, increasing the risk of anemia, neurotoxicity, and reproductive effects. The literature indicates that the formalization and certification of plants with closed-loop technologies significantly reduce emissions and the body burden of Pb.

On the other hand, spatial inequality and lack of environmental governance are associated with insufficient oversight. Regulatory gaps allow pollution hotspots to persist in marginalized neighborhoods. This produces hotspots with soils containing hundreds or thousands of mg/kg of Pb and children with dangerous blood levels, with recurring evidence in field studies in regions such as Agbogbloshie (Ghana), peri-urban neighborhoods in Latin America, and informal sites in Asia and Africa. Remediation requires public policies that integrate public health, industrial controls, and extended producer responsibility [56]. Finally, the combined effect of social determinants and environmental exposure translates into high costs in health and human capital: loss of IQ in children, increased cardiovascular disease, and higher mortality attributable to Pb pollution. Recent global reports and reviews estimate that the burden of disease associated with this heavy metal is substantial and overrepresented in low- and middle-income countries.

To reduce exposure mediated by socioeconomic determinants, integrated interventions are recommended: (i) formalizing recycling chains and transferring closed-loop technologies; (ii) education programs and economic alternatives for informal workers; (iii) community biomonitoring and soil remediation in hot spots; (iv) regulatory enforcement and extended producer responsibility mechanisms. These measures should be designed with a focus on environmental justice and community participation to ensure effectiveness and equity.

4. Sustainable Alternatives to Mitigate the Environmental Impact of LAB

Every activity or process inevitably generates environmental impacts, whether through the use of resources, the emission of pollutants, or the alteration of natural conditions throughout its life cycle. Therefore, it is vitally important to assess the environmental impacts that contribute to climate change, ozone depletion, ozone generation, eutrophication, acidification, and other indicators used in LCA. For example, one option that would help minimize the impact of lead on the ecosystem is the recycling of used LAB electrodes using innovative, low-cost, energy-efficient, and environmentally friendly technologies capable of effectively desulfurizing the plates. Figure 3 shows the life cycle of LAB, including recycling processes that can be implemented as sustainable alternatives.

It can be seen that recycling processes can be sustainable (Figure 3), provided that the principles of LCA, social responsibility, and circular economy are applied.

Currently, the most widely used methods in this field are pyrometallurgy and hydrometallurgy. The pyrometallurgical technique requires temperatures above 1000 °C, which generates significant environmental impacts, including sulfur oxide emissions (approximately 70 kg/t) and lead fumes (between 30 and 50 kg/t) [34]. This technique also uses alkaline or organic reagents for the desulfurization of the LAB paste used [33].

Hydrometallurgy has emerged as a clean and efficient alternative to pyrometallurgy in LAB recycling because it allows lead to be recovered through selective dissolution and electrodeposition, reducing SO_2 and PbO emissions and the generation of hazardous slag. While traditional pyrometallurgical processes (based on high-temperature smelting with coal or coke) emit between 1.8 and 2.7 t CO_2 equivalent/t Pb recovered, hydrometallurgical systems, which use acid leaching and electrodeposition, generate only between 0.4 and 0.8 t CO_2 equivalent/t Pb, reaching values below 0.3 t CO_2 equivalent/t Pb when electricity comes from renewable sources [29,57].

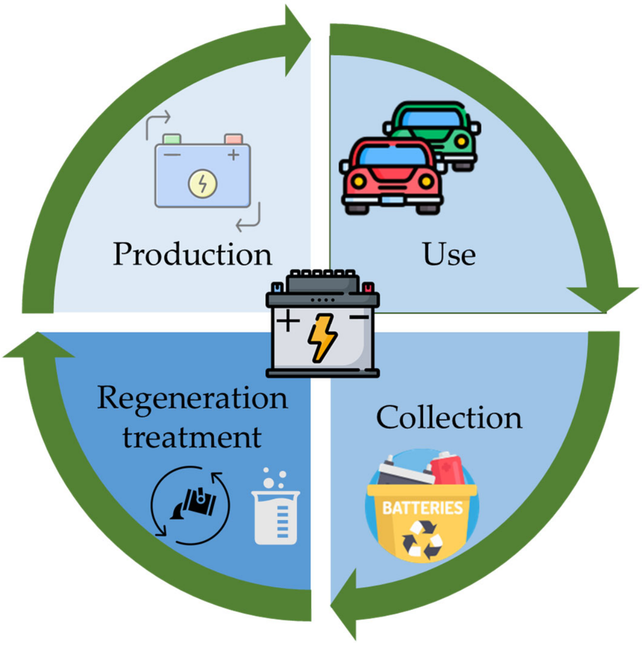

Figure 3. Application of sustainable alternatives in the life cycle of LAB.

In this regard, Table 2 compares recycling technologies with quantitative data on the environmental, technical, and economic performance of the main LAB recycling alternatives.

Table 2. Technological alternatives for LAB recycling, with their recovery rates, environmental impact, and estimated costs.

Technology	**Lead Recovery Rate (%)**	**Carbon Footprint (t CO_2-eq/t Pb)**	**SO_2 and PbO Emissions (kg/t Pb)**	**Energy Demand (GJ/t Pb)**	**Estimated Cost (USD/t Pb)**	**Environmental Advantages**	**References**
Conventional pyrometallurgy	90–98	1.8–2.7	22–35	6.5–8.2	600–900	Mature technology; high metallurgical efficiency	[29]
Advanced pyrometallurgy (with emission control)	95–99	1.2–1.6	8–12	5.5–6.5	850–1100	40–50% reduction in emissions with filters and heat recovery	[58,59]
Hydrometallurgy (acid leaching and electrowinning)	96–99	0.4–0.8 ($\leq$0.3 with renewable electricity)	<5	3.0–4.2	1000–1300	70–80% lower CO_2 and SO_2 emissions; Pb purity > 99.9%	[57]
Informal (artisanal recycling)	60–85	4.0–6.5	>50	Variable	200–400	Low upfront cost; locally accessible	[60]

In conclusion, LCA confirm that the overall impact of the hydrometallurgical process is between 55% and 70% lower than that of pyrometallurgy in terms of climate change, acidification, and human toxicity [61]. Likewise, if 50% of global pyrometallurgical recycling were replaced by hydrometallurgy, annual emissions from the sector would be reduced by approximately 3 million tons of CO_2, consolidating this technology as a key pillar towards a low-carbon circular economy model.

However, the applicability of hydrometallurgical processes in developing countries faces economic, technological, and structural barriers that limit their scalability and financial viability. It should be noted that the establishment of hydrometallurgical plants requires substantial capital investment (anti-corrosion equipment, neutralization and electro-winning systems) and high recurring operating costs (reagents and effluent treatment). Recent LCA studies and techno-economic analyses show that these costs can represent a significant fraction and increase the sensitivity of the project to energy and reagent prices [57]. In addition, hydrometallurgy often requires considerable feedstock volumes to achieve economies of scale: in markets in underdeveloped countries dominated by artisanal workshops and volumes < 5000 t/year, reagent recovery and energy efficiency do not allow for competitive profitability compared to informal or pyrometallurgical processes. Dependence on a stable and cheap electricity supply increases financial risk in regions with unreliable grids, and the need to import acids and extractants increases logistics and operating costs (cases documented in Africa and Latin America). Added to this is the absence of support policies (green subsidies, soft loans) and limited demand for "green secondary lead" in local markets, factors that reduce incentives for clean investments. Recent technical reviews indicate that the combination of these barriers (financial, infrastructure, regulatory, and capacity) makes hydrometallurgy a technically attractive but economically difficult option to scale up without public interventions and market mechanisms that internalize environmental costs [62]. In view of this, it is possible to suggest the implementation of recycling strategies that combine the aforementioned technologies with disassembly and staggered utilization techniques [63–65], in order to achieve highly efficient use of resources and protection of the environment.

Growing global energy needs and environmental damage have driven the search for sustainable energy sources and storage technologies. With this objective in mind, ref. [66] reviewed the environmental indicators developed in recent years that were considered suitable for use at the corporate level to evaluate manufacturing processes and products, classifying them into four main groups: energy and material flow indicators; indicators with a territorial dimension; LCA indicators; and environmental risk assessment indicators. Ref. [67] found that integrative and single-index indicators, such as the ecological footprint or carbon footprint, were the most attractive to companies, although further progress is needed in this area to combine scientific knowledge with the simplicity required at the business level to track and communicate environmental data [35,68]. The carbon footprint is a measure of the total greenhouse gases emitted directly or indirectly by a person, organization, event, or product, and is generally expressed in tons of CO_2 equivalent [69,70]. This indicator allows us to assess the environmental impact of our daily activities and promote actions to reduce these emissions.

Another alternative solution is LCA, a widely used approach to examine the potential impacts of large-scale battery production, use, disposal, and recycling [32]. LCA is, in other words, a way of quantifying the direct and indirect environmental burdens associated with a product or service [71]. It is also a useful framework for exploring environmental trade-offs between different technologies that provide comparable services. However, applying LCA to batteries is difficult for a variety of reasons, ranging from methodological choices to the scarcity of primary data on battery manufacturing. Nevertheless, it is certainly an option for monitoring the environmental impacts of lead use. Regarding LCA methodology, ref. [32] argue that to date there has been no consensus on how to analyze the environmental impact of batteries or how to communicate the results. Relevant studies use a wide variety of system boundaries, functional units, primary data sources, impact categories, midpoints, and life cycle inventories, making cross-comparisons between different technologies difficult and limiting the ability of LCA to provide a feedback loop for early scientific research and technological development. Ref. [72], following this same line of thinking, introduced the concept of sustainability through a discussion of the LCA of battery recycling. Their study supports LCA as a methodological framework for estimating and evaluating the environmental impacts attributable to a product or service throughout its life stages.

It is also proposed to comprehensively improve the LAB system, as this would help balance human and socioeconomic development with environmental protection. Such improvement depends on understanding the anthropogenic lead cycle, i.e., the movement of lead through the four stages of human activity: primary production (mineral extraction), manufacturing, use, and waste recycling. The study by [73] found that, in the specific case of China in 2014, the primary production and manufacturing stages had the greatest negative environmental impact compared to other stages of the cycle.

Among other alternatives reviewed was the one described by [31] in their analysis of a more sustainable method for recycling spent lead batteries. They state that the traditional sodium desulfurization process for used LAB is beneficial to the environment but is limited by its poor economic viability, as the cost of the desulfurizer is much higher than the value of the desulfurization by-products. This study proposes a novel closed-loop presulfurization process for lead paste that uses only lime as an indirect desulfurant, producing sodium sulfate as a by-product and regenerating sodium hydroxide as a direct desulfurant, providing a clean, practical, and viable LAB recycling method with significant environmental and economic benefits.

Between 30% and 40% of LAB used in China are recycled by companies that are not licensed to handle hazardous waste. Combined with ineffective collection and storage, these conditions further exacerbate the problem. One proposed interim measure is to ban or consolidate small-scale plants while large-scale recycling plants are built [30]. Ref. [35] describes an alternative production process whereby LAB performance can be significantly improved by incorporating carbon materials into the negative electrodes.

In summary, the transition to sustainable management of LAB does not depend solely on technological innovation, but also on the systematic integration of environmental assessment tools. The literature reviewed emphasizes the need to standardize methodologies, improve data transparency, and incorporate economic and social indicators to achieve a comprehensive assessment. Furthermore, the expansion of environmentally superior technologies, such as closed-loop hydrometallurgical systems and low-temperature desulfurization processes, requires appropriate regulatory frameworks and incentives that favor their large-scale adoption. In conclusion, the current state of LAB recycling represents a turning point toward aligning industrial development with environmental responsibility. The reviewed data demonstrate that cleaner technologies, supported by robust life cycle methodologies, can significantly reduce the ecological footprint of lead-based energy systems. This convergence between technological innovation and environmental assessment sets the stage for the next section of the study, which focuses specifically on LCA.

Life Cycle Analysis of LAB Recycling

LCA allows us to identify the impacts generated at each stage of a product's development. Based on this assessment, it is possible to propose effective actions to control and reduce these effects. This methodology is used to examine and evaluate the inputs, outputs, and impacts associated with a production system, service, or item throughout its entire life cycle. In the case of LAB, their durability depends on the number of charge and discharge cycles they can withstand at a given discharge depth. The shallower the depth, the greater the number of cycles the battery can perform, which directly affects its service life [74,75].

At the end of the LAB recycling LCA, the lead is separated and sent to recycling plants, where the metal is usually refined for future use [14]. In brief, the lead recovery process involves crushing and removing the battery at room temperature and removing the paste from the lead grids, plastic casing, and any acid residue [76]. Traditional pyrometallurgical processes are then used to recycle the refined lead from the lead paste; this is the main pollution-emitting unit in the entire production line. Pyrometallurgical processing of WBA is the main technology used worldwide due to its advantages in terms of short processing time, low equipment investment, and high yield [77].

However, technological alternatives for LAB recycling differ significantly depending on the technological basis, the functionality of the recycling plant, the country, and the

LCA approach implemented. In this regard, Table 3 presents a comparative compilation of various studies and technical reports on LCA applied to LAB recycling.

Table 3. Considerations and objectives of sustainable alternatives for LAB recycling.

Localization	Findings	Goal	References
Vietnam, Uruguay, and Malaysia	High lead exposure in formal and informal industries; lack of strategic efforts to understand sources of exposure	To analyze how formal and informal industries contribute to lead exposure in Vietnam, Uruguay, and Malaysia	[8]
Nigeria	The flow of materials and substances from used LAB and their implications for environmental quality in Nigeria revealed that battery pastes are heterogeneous, with only lead exceeding the 1000 mg/kg total threshold limit concentration	To study the environmental implications of the flow of materials and substances from the used LAB	[42]
Peru	There are no engineering controls or adequate regulations for LAB management	To design and implement a robust legal framework that clearly defines the responsibilities of each stakeholder involved in LAB management and provides for effective sanctions on those who fail to comply with the established quality and safety standards	[78]
Brazil	Identification of the mechanisms that drive recycling programs and proposal of an explanatory framework	To examine how regulations and sustainability strategies implemented by LAB manufacturers are coordinated with various stakeholders involved, promoting economic development, social well-being, and environmental protection	[24]
China	High technological efficiency in LAB recycling, with high occupational risks due to lead exposure	To strengthen and update workplace safety policies to ensure safe and healthy work environments	[22,79]
Bangladesh	Environmental pollution due to improper management of lead-containing elements.	To institute controls in the LAB recycling process to prevent environmental pollution	[80]
Europe	More than 99% of LAB are recycled for reuse in manufacturing new batteries.	To promote the circular economy through complete and efficient recycling.	[16]
Africa	Lack of regulation in recycling and emissions management; significant environmental risks.	To identify regulatory gaps and instigate improvements in recycling regulations.	[15]

LCA studies and material and substance flow analyses (MFA/SFA) on LAB show a clear pattern: where there is an integrated collection and recycling infrastructure and strong regulatory frameworks (e.g., the Unites States and much of Europe), the system functions as a closed loop, utilizing waste, drastically reducing the need for primary lead, and the intensity of impacts associated with extraction. In the United States, a recycling rate of 99% is reported for LAB, demonstrating a robust circular economy in the industry, preventing 160 million batteries from ending up in landfills each year and creating a model of sustainability with almost zero waste [81]. In Europe, efficiencies reported by Eurostat show that most countries far exceed the minimum efficiency target (65%) and several achieve >90% in useful recycled material yield. These recovery levels explain why many

LCAs show significant reductions in CO_2 emissions and energy consumption when the scenario incorporates formal recycling and high reuse of secondary lead.

However, the high circularity observed in regulated regions is not representative globally. MFAs/SFAs in developing countries report large losses, informal flows, and environmental leakage points that generate local toxicity burdens. In Nigeria, for example, ref. [42] quantified that between 1980 and 2014, large volumes of LAB (≈4.8 million tons accumulated during the period cited) were used and that a substantial portion—millions of tons—has reached the end of its life, with around 2.3 Mt recycled but with management practices that leave contaminant flows and variability in the composition of the pastes (lead, cadmium, arsenic) that complicate safe reconditioning. This type of operational heterogeneity increases local toxicity impacts that some LCAs tend to underestimate if they do not incorporate empirical inventories of point emissions.

China illustrates an intermediate dynamic, as it has advanced technological plants with high recovery efficiencies and technical developments (e.g., vacuum roasting and refining processes) that reduce the carbon footprint of recycling, but occupational risks and point source emissions persist, affecting workers and nearby communities when control measures are insufficient. Recent studies on occupational control and biomarkers in workers show that, although the body burden of lead has tended to decrease over time, it remains high in exposed populations and requires stricter industrial controls and occupational health monitoring [53]. This evidence highlights that environmental gains measured by LCA (e.g., lower CO_2 emissions due to primary metal substitution) must be complemented by toxicity and occupational health assessments to obtain a holistic evaluation. Bangladesh, Peru, and other countries with informal recycling highlight another recurring problem: governance and the absence of engineering controls. In places where dismantling and artisanal smelting are common, remediation interventions have been shown to reduce local environmental contamination, but follow-up studies report that blood concentrations in children or workers may take longer to decline, reflecting diffuse and historical sources of exposure. Consequently, policies that only promote clean technologies without modifying the socioeconomic chains of recycling, such as collection, incentives, and producer responsibility, do not achieve the same effect as integrated formalization and public health programs [82].

Finally, the remaining challenges are operational (improving segregation and traceability), methodological (incorporating point emissions and human exposure into LCA), and political (creating frameworks that encourage formalization and finance modernization). Recent evidence suggests that regions that combine effective policy, technical infrastructure, and health monitoring achieve the greatest environmental and social benefits; conversely, without governance, the potential circular advantage can become a persistent risk for vulnerable communities. For future LCA related to LAB management, it is essential to use MFA-empirical scenarios, report toxicity and occupational health indicators alongside climate and material emissions, and compare emerging technologies (vacuum roasting, hydrometallurgy) based on local socioeconomic feasibility. Furthermore, it should be noted that although LCA provides a useful framework for quantifying environmental impacts, it has significant limitations when assessing the informal lead-acid battery recycling sector. These limitations are based on: (i) incomplete and unrepresentative inventory data, since artisanal practices vary widely between workshops and locations, meaning that database averages do not reflect specific emissions or pollution peaks, which reduces the spatial and temporal validity of traditional LCA [83]; (ii) underestimation of diffuse emissions and exposure routes, as many LCA ignore or poorly model the release of lead into soil, household dust, and groundwater from informal processes, and therefore do not adequately quantify risks to human health and local ecotoxicity; (iii) methodological limitations in relation to social and health impacts: conventional LCAs focus on physical-chemical indicators and rarely integrate social assessments or health biomarkers (although S-LCA approaches are advancing, their application in informal contexts is still incipient and complex); (iv) problems in defining boundaries and allocation: the fragmentation of the chain (small recyclers, intermediaries, informal scrap sales) makes it difficult to allocate material flows and responsibilities, causing biases in the distribution of impacts; and (v) high uncertainty and poor traceability of countermeasures, as the benefits of interventions (e.g., formalization or clean technologies) are difficult to model accurately without longitudinal data and field studies [74], which could limit the usefulness of LCA for designing effective local policies.

5. Conclusions

This study demonstrates that LAB continue to be essential to global energy infrastructure, specifically in the automotive industry. However, their life cycle poses significant environmental and health risks if not managed properly. The data collected show that inefficient LAB production and recycling can release between 30 and 50 kg of lead fumes per ton processed, and that soils near informal plants reach concentrations of up to 5000 mg/kg of Pb, exceeding the environmental safety limits established by the WHO by more than 25 times. In addition, atmospheric emissions of SO_2 and fine particles in traditional pyrometallurgical systems are responsible for more than 40% of the ecological footprint of the LAB life cycle. In contrast, hydrometallurgical and closed-loop processes reduce gaseous emissions by more than 70% and increase lead recovery efficiency to 98%, minimizing the impact on environmental matrices. The comparative LCA studies reviewed show that countries with robust regulatory frameworks achieve recycling rates of over 95%, while in developing countries, the figures rarely exceed 60% due to informality and a lack of environmental oversight. It is concluded that the sustainability of the LAB system depends on three interconnected pillars: technological innovation (clean and efficient processes), comprehensive environmental assessment using tools such as LCA and MFA, and participatory governance that promotes traceability, environmental education, and extended producer responsibility. Moving towards a circular economy based on scientific evidence and international cooperation will transform the LAB sector into a model of energy efficiency, environmental justice, and effective reduction of lead pollution globally.

6. Future Prospects

The future of the LAB industry will depend on its ability to integrate clean technologies, circular economy strategies, and regulatory policies consistent with global sustainability goals. Future lines of research should be geared toward building a more sustainable, efficient, and eco-friendly industrial model. In the production stage, studies should focus on optimizing metallurgical processes through the development of low-emission pyrometallurgy and closed-loop hydrometallurgical processes that allow for the recovery of lead and sulfuric acid with lower energy consumption and lower gas emissions. Priority should be given to researching the use of renewable energies in thermal stages, the recovery of waste heat, and the replacement of auxiliary materials with recyclable or biodegradable alternatives. In addition, the integration of green manufacturing models and digital technologies for real-time control and monitoring can improve the efficiency and traceability of the production process. In terms of use and operational performance, future research should focus on the eco-design of batteries, incorporating lighter and more resistant materials, as well as electrodes modified with nanocarbon or graphene to increase charging capacity and durability and reduce sulfation. The development of predictive degradation and failure models based on artificial intelligence will extend the useful life and optimize the maintenance of LAB systems in electric vehicles or photovoltaic systems. Similarly, it is recommended to investigate reuse and second-life strategies for stationary or energy backup applications, reducing pressure on primary production.

With regard to recycling and final disposal, research should focus on exploring selective metal recovery through bioadsorption, nanomaterials, and low-impact electrochemical processes, comparing their environmental performance through LCA and material flow analysis. In this regard, it will be essential to develop more comprehensive LCA methodologies that integrate indicators of human toxicity, occupational health, and water footprint, as well as empirical databases adapted to local realities. Finally, the promotion of regulatory frameworks based on scientific evidence, together with the formalization of recycling and the creation of regional technology innovation centers, is emerging as a strategic field of research to close the LAB cycle in a sustainable and safe manner.

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