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Impact of lead acid battery industry wastes on environment and their management in India: A review

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Abstract
Lead (Pb) is used in many industries including the lead acid battery industry (LAB), lead recycling, and Sensor development. Among these, the lead-acid battery industry is the major industry in the world. For the economic development of a country the demand for motorized vehicles that use lead acid batteries as a source of energy is increased. The estimated total global emission of Pb from lead battery industries was 4 million tonnes per year (13% from use, 65% from waste management and recycling, and 22% from production,) from 1970 to 2010. The amount of Pb released was 25% more than the lead produced. In India, the lead reserve is about 2.2 million tonnes which is 2.5% of the world lead. India has 500 battery recycling units with a volume of 2.1 million tonnes per year. After recycling, the secondary lead of about 1.25 tonnes per year was produced. "Itai-Itai" disease occurred in Japan in the 1930s and "Minamata disease" in Japan in the 1950s was heavy metals poisoning the food chains. Around 800 million children around the globe are affected by Pb at more than 70 polluted sites. Among this, 275 million children were affected in India which accounted for 30% of the total children population in India. To prevent the emission pollution control equipment needs to be installed in the LAB industry on Pb-contaminated sites in India. This review focuses on the various effects of Pb on the environment and human health with their management strategies.

Keywords: Air pollution, Contamination**,** lead acid battery wastes, management, soil pollution, water pollution

Introduction

Pb is a blue-white lustrous metal with an atomic number of 82, a boiling point of 1749°C (2022 K), a melting point of 327.46°C (600.61K), and a density of 11.34 g/cm^3. Therefore, it has been described as a heavy metal. Lead is a non-biodegradable, hazardous metal. Lead is highly hazardous to human health but humans have been extracting lead for more than 6000 years. In 1859, the discovery of Lead-acid batteries revolutionized the field of battery technology, leading to limitless valuable applications. The significant use of LABs is a reliable source of rechargeable energy for most four-wheelers, yachts, submarines, uninterruptible power supplies, and common household devices (Khan Mutasim Billah Life and Al Bari, 2022) [18]. There are two different types of lead acid batteries depending on the construction method (flooded and sealed). Flooded lead acid battery (Pb-Cd battery, Pb-Sb battery, Pb-C battery), the electrode is completely immersed in the electrode and periodically filled with water for proper functioning. In a sealed lead acid battery (gel-based LAB, Deep cycle LAB) the electrolyte is static. Between 2001 and 2013, the number of vehicles in India skyrocketed from 55 million to 159.5 million, sparking a surge in the demand for lead-acid batteries. The lead acid battery market in India currently experiences a remarkable growth rate of 16.5%, as reported by Technavio in 2014. By 2020, India is projected to become the third-largest vehicle market. These batteries can be recycled and reused after 3 to 4 years of use. The increase in government schemes for solar and wind energy has also increased the need for lead-acid batteries in India. To meet this demand, used lead-acid batteries (ULAB) need to be recycled. The recycling rate of Pb in India is 85% by 2020. The primary producers of Lead Acid batteries in India are Hindustan Zinc Limited and the secondary producers are India Lead Limited (24000MT), Thrupathy Chemicals Limited (10000 MT), and Associated Pigments Limited (15000 MT). There are 180 authorized Recycling units and 860 Secondary smelters in India. More than 50% of the Pb demand in the world was met by Secondary lead production (Varshney, 2020) [44]. The Used Lead Acid battery contains about 10.5kg of lead. Among these, 98% of lead is recycled. Recycling of these batteries leads to the release of lead dust, fumes, and SO_2. Indian lead plants release wastewater that contains 615 times more Pb than the permissible limit of Indian regulation.

For recycling, lead acid batteries are collected from three categories such as starting-lighting-ignition (SLI) batteries used in automobiles containing 70% lead, Batteries for electric vehicles, and UPS containing 15% lead (Fujimori *et al.,* 2016) [8]. Lead Smelting is the principal process in which the metal Lead metal is removed from impurities. At extreme temperatures, lead fumes are emitted into the atmosphere which settle on the soil and affect human health. The Used Lead acid battery was recycled by Electrometallurgical method which is the conventional method of lead recycling in India. Lead from the spent batteries was extracted by crushing, sieving, dissolution, and electrowinning. However, this method leads to the emission of solid, liquid, and gaseous effluents while crushing the battery, segregation of non-metallic parts resulting in the release of fumes and lead dust (Fig.1) which may lead to acid rain. Fe has been utilized to attract sulfur compounds, while Cu, a metal commonly present in battery poles as well as antimonial alloys.

In developing countries, the production and recycling of lead-acid batteries lead to most cases of lead poisoning. Pb exposure has led to a 21% increase in deaths in India since 1990 (IHME, 2017) [16]. Out of the 500 toxic sites evaluated by Pure Earth India, 80% of the sites were found to have high levels of heavy metal contamination. Tamil Nadu is among the top three states with the most lead-poisoned children. Workers in the LAB industry have blood lead levels 10 times higher than healthy individuals of the same age. Owing to the emission of lead wastewater on land the death of several cattle in Delhi was observed. This highlights the severity of the issue and the potential large-scale impact of Pb. Pb exposure from contaminated water and soil puts children at a high risk of reduced intelligence. Therefore, a proper understanding of pollutants and their impacts from lead acid batteries is required with proper management practices in India.

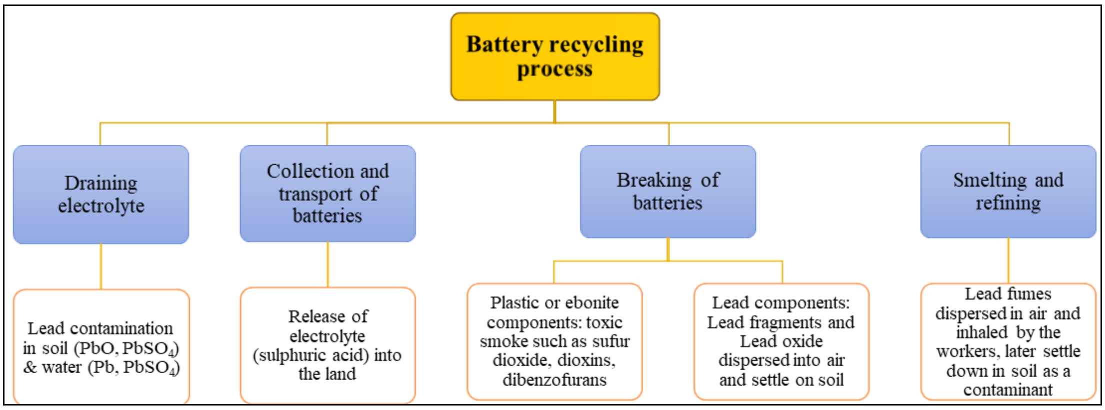

Fig 1: Schematic diagram illustrates the process at which Pb is discharged during battery recycling

1. Lead industrial effluent properties

The raw effluent from the lead acid battery industry had a pH of 2 which is extremely acidic, while the COD, BOD, TDS, and TSS of the effluent were 347 mg L^{-1}, 950 mg L^{-1}, 3100 mg L^{-1}, and 275 mg L^{-1} respectively (Table 1). The treated effluents from the industry had a higher BOD value of 74.6 mg L^{-1} and TDS of 1945 mg/L. While treating the effluent all inorganic matter was removed. The effluents released from the lead acid battery contained a Pb concentration of 1.21 mg L^{-1} which was beyond the permissible limits of the WHO, EPA, and Indian Standards (Table 3). The pH of the effluent released from the LAB industry is extremely acidic. However, the COD, BOD, and turbidity of the effluents exceeded the standard values (Table 1). Owing to the acidic nature of the effluent, Pb becomes soluble in water and leaches to groundwater. This nature of effluents leads to severe damage to aquatic organisms and poses a threat to human health when released into the environment (Meshram *et al.*, 2020) [26].

Table 1: Physicochemical characteristics of effluents (Korrapati *et al.*, 2017) [19]

Parameter	Effluent analyzed value	Indian standard for effluent discharges
Temperature	14°C	
PH	2.34	5.5 to 9.0
COD (mg L^{-1})	448	250
BOD (mg L^{-1})	173	30
Turbidity	163.4NTU	20 NTU

Table 2: Characteristics of battery-making industrial wastewater (Mansoorian *et al.*, 2014) [25]

Wastewater characteristic	Level in effluent
Electrical conductivity	4.5 mS cm^{-1}
pH	2.8
Zinc (Zn)	3.2 mg L^{-1}
Lead (Pb)	9 mg L^{-1}
Sulphate	5 mg L^{-1}
Iron	2.3 mg L^{-1}

Several processing sections are responsible for carrying lead into the effluents, specifically the paste mixing, curing, and formation of plates. Wastewater contains elevated concentrations of inorganic salts such as Pb, sulfates, chlorides, and arsenic (Table 2). Industrial wastewater contains large amounts of chlorides which significantly disrupt the natural ecological balance. The Pb concentrations in the effluent before and after treatment (Fig.2) varied significantly.

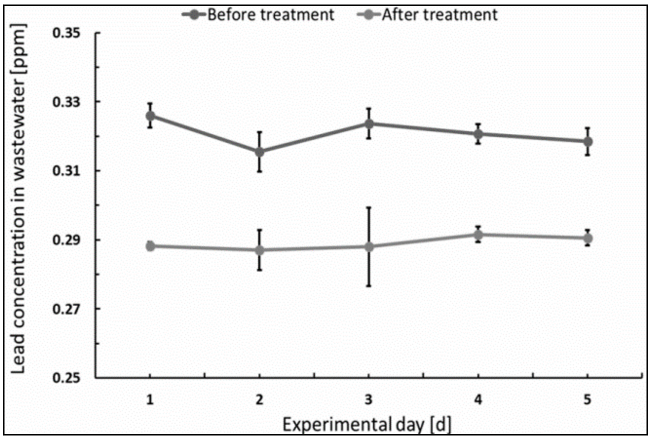

Fig 2: Lead concentration in LAB industry effluent before and after treated (Otieno *et al.*, 2022) [29]

1.1. Lead emission standards

Table 3: Effluent Discharge Standards by WHO

Parameters	Tolerance limit values			
	Discharge into inland water		Discharge into coastal water	Discharge into public sewers
	Sensitive water	General water		
pH	6.0-8.5	6.0-9.0	5.5-9.0	5.5-10.0
TSS (mg/L)	20	50	150	500
Lead (mg L^{-1})	0.1	0.5	1.0	5.0

2. Impacts due to lead acid battery on soil and environment

Lead has been recognized as a major environmental pollutant on a global scale. Pb is released into the ecosystem through paints, ceramics, pipes, solder, leaded gasoline, batteries, ammunition, mining, smelting, and refining. Moreover, the recycling of used lead-acid batteries and the lead smelting industry have been identified as the primary and third leading polluters among the top ten worst polluting industries. A single battery contained an average of 10 kg lead. The Pb industry also releases Cd, Cr, and As which are contained in lead-bearing ores and are used as additives. These harmful metals are released into the land, air, and water which finally enter the body via direct and indirect contact. Once it enters the environment, it lingers menacingly for a long period. In developing countries, over 3000 people in the community have been exposed to elevated levels of Pb from several sources, and according to the Centre for Justice, Governance, and Environment, this has resulted in the deaths of 20 individuals since the opening of the facility (Otieno *et al.*, 2022) [29]. Lead acid battery pollution has become a major concern in India, with significant impacts on both the ecology and human health. Improper recycling techniques used in India result in widespread exposure to lead particles through various stages of the recycling process and impact the soil, air, water, and humans (CPCB, 2017) [6].

2.1. Impact on air

The production of lead-acid batteries can liberate Pb particles, acid mist, and lead fumes (PbO & Pb) into the air, contributing to air pollution in the vicinity of manufacturing plants. Dust on the industrial floor or equipment is the major contributor to the release of lead into the air. When the plates are brushed and the casing process along the assembly line generates minuscule lead particles that disperse into the air as small droplets. Additionally, the factory utilizes filters to remove lead dust however, during the cleaning process, a significant amount of dust laden with lead is released into the air (Otieno *et al.*, 2022) [29]. Furnaces and smelters release dust particles high in metallic compounds, which can have harmful effects on workers. When the discharged acid on land evaporates leads to the formation of Acid mist causing damage to the air layer. The smelting process also releases dust particles and fumes containing Cu, Cd, As, Hg, Sb, and Pb which leads to their accumulation in soil and inhalation by humans. During the winter season in India, the atmosphere has a Pb concentration of $1 \mu g\ m^{-3}$ which is many times higher than the standard (0.1-$0.3\ \mu g\ m^{-3}$) (Ettler and Johan, 2014) [7].

2.2. Impact on water

Lead is carried out into waterbodies during the burning of lead gasoline, lead plumbing (Pb), smelting of lead acid batteries ($PbSO_4$), and mining of lead from its ore. The washing of the factory floor, particularly during the formation and pasting stages, results in wastewater contaminated with lead being directly discharged into water bodies. When the water body is acidic the soluble Pb concentration is high causing acute diseases in human health and accumulating in fish (Akhtar, 2022) [2]. The lead particles settle and accumulate in the soil percolating into the groundwater by dissolution which leads to contamination. The pH of water bodies near the used lead acid battery recycling industry ranges from 0.59 to 6.54. The surface water near the recycling facility has a very low pH of 0.59 which is hazardous to ecosystem and aquatic organisms. This low pH of water is due to the informal discharging of Sulphuric acid from the ULAB (Schismenos *et al.*, 2021) [36]. The concentration of heavy metals in the water bodies was beyond the permissible limit of WHO. The heavy metal concentrations of the water bodies near the ULAB facility followed an increasing order of Se<AS<Cd<Ni<Sb<Cr<Pb<Mn<Cu<Zn (Oloruntoba *et al.*, 2021) [28].

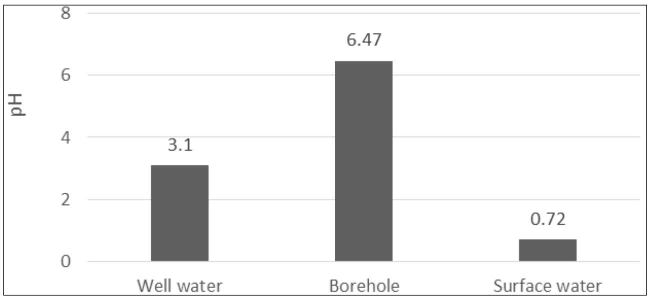

Fig 3: pH of water from ULAB

2.3. Impact on soil

Soil is the main source of Pb exposure in children. Sulfuric acid (H_2SO_4) from battery recycling depresses the pH of soil and water below 2. Pb recycling leads to the release of Pb from the sludge of battery remains as $PbSO_4$, PbO, and PbO_2 which were disposed into the soil. Inadequate residue disposal and LABR seriously polluted soil in developing countries. The lead (Pb) present in soils near the industrial premises results in solubilization and migrates to different locations when exposed to acidic water (Gottesfeld *et al.*, 2018) [10]. It results in the infiltration of Pb into soil profiles leading to contamination of groundwater surpassing the permissible limit for drinking. The concentration of heavy metals in the agricultural environment around the lead acid battery industry had a high concentration of Cr, Zn, Pb, and Cd which led to the accumulation of Pb on the plants that grew on the polluted soils. The Pb is stored in soil uptake by plants and accumulates in fruit and leaves. It accumulated in the animals, children, and adults in rural areas causing various disorders. The concentrations of heavy metals in the plant grown on ULAB industry-polluted soil followed the increasing order of Se<Cr<Cu<Sb<Mn<Zn<Pb (Oloruntoba *et al*., 2021) [28]. Due to the pollution of soil by the lead acid battery industry, the biological activity of soil is reduced. A study led by Adekunle *et al.* found that *Amaranthus cruentus L.*, a type of vegetable, showed a substantial increase in the accumulation of lead (Pb) and cadmium (Cd) as the level of soil contamination increased in a greenhouse experiment. This highlights the potential danger of consuming vegetables contaminated with heavy metals, as it can lead to the development of chronic illnesses (Otieno *et al.*, 2022) [29]. The Pb accumulation in soil leads to the reduction of microbial activity, microbial biomass C and N which increases the invertase activity of Soil biota. Pb contamination of soil affects the ecosystem at various trophic levels and causes various disorders.

2.4. Impact on humans

Out of 800 million children affected by elevated blood lead levels globally, 275 million resided in India alone which is

30% of the total children population in India. The 23 states in India had the blood lead level beyond 5 µg/dL. Among these Jharkhand, Uttar Pradesh, Bihar, Chhattisgarh, Madhya Pradesh, and Andhra Pradesh had the blood lead level of more than 7 µg/dL.

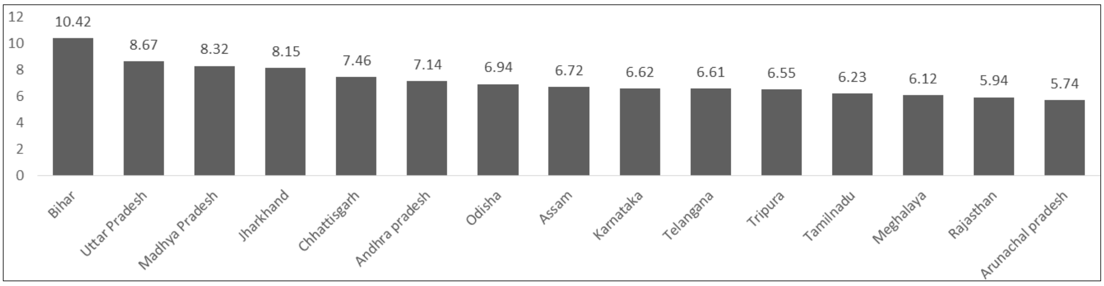

Fig 4: Average BLL (µg/dL) prevalence across various states in India (IHME, 2017) [16]

Recycling used lead-acid batteries ranked first in Pb contamination, followed by industrial estates, mining and ore processing, smelting, tanneries, and dumpsites (Abdelbasir, 2021) [1]. These industries pose a significant risk to over 32 million individuals and low and middle-income countries alone responsible for 7 to 17 million Disability Adjusted Life Years (DALYs). In particular, used lead-acid battery recycling alone accounts for 2 to 4.8 million DALYs. The concentration of Pb levels in the blood, urine, and hair of employees in the lead acid battery industry was at very high concentration in developing countries (Fig.4). The inhabitants of the village near the lead acid battery recycling industry had a blood Pb level of 14-122 µg dL^{-1} which exceeds the maximum threshold level of 10 µg dL^{-1}. The employees in the plate-cutting area had a high concentration of blood Pb level (BLL) followed by pasting, executive, and assembly sections (Khan Mutasim Billah Life and Al Bari, 2022) [18].

Lead can pass in humans through ingestion and inhalation. The principal entry of Pb is through inhalation and it accumulates in the erythrocytes, soft tissues (kidney, brain, bone marrow), and mineralized teeth (teeth and bone). Reticulocytosis is a major problem among lead acid industry workers. Pb pollution can also disrupt essential cell functions like metabolism, respiration, membrane transport, and protein synthesis, resulting in the death of cells (Korrapati *et al.*, 2017) [19]. Lead Poisoning in humans is called Plumbism which causes Learning Difficulties, Delay in Development, Loss of Appetite, irritability, Fatigue, Vomiting, Hearing loss, and Constipation in children (Table 4). Increased blood pressure, memory difficulties, muscle and joint pain, Abdominal pain, headache, Reduced sperm count in adults, and Miscarriage in pregnant women (Schismenos *et al.*, 2021) [36]. If the symptoms are untreated it leads to Infertility, Nervous system damage, Kidney/Liver damage, Irreversible brain damage, and Unconsciousness or death (Table 4).

Table 4: Clinical effects on humans with levels of Pb concentrations in blood

Blood Pb Concentration (µg dL^{-1})	Impact on health
<5	Children: Decline in IQ, cognitive ability, and academic success, increase in problem behaviors and have been diagnosed with attention deficit hyperactivity disorder, decreased fetal growth All ages: Weak kidney function and a decrease in the production of delta-aminolaevulinic acid dehydratase (ALAD) and development of anemia
<10	Delayed puberty Adults: Hypertension, increased risk of cardiovascular-related mortality, higher risk of spontaneous abortion and preterm birth
>20	Children: Anaemia
>30	Children: Reduced speed of neural signalling
>40	Children: Hinder haemoglobin production Adults: Peripheral neuropathy, Neuro-behavioural effects, Abdominal colic
>50	Adults: Hinder haemoglobin production Children: Severe neural problems
>60	Children: Abdominal colic
>90	Children: Encephalopathy
>105	Children: Severe neurological features
150-460	Children: Death

3. Management strategies

Lead is one of the most hazardous metals in the world for humans, soil, and air. Due to emissions of Pb from industries and recyclers lead to various difficulties like disorders in humans, accumulation in soil and plants, and leaches into the groundwater (Huang *et al.*, 2021) [14]. So, to prevent these extreme impacts on health and the ecosystem the primary and secondary Pb-producing industries should set up certain management strategies and treat the pollutants emitted from the source. Recycling of used lead acid batteries by authorized recyclers was an efficient method to reduce the pollution of ecosystem and human health from Pb. The Solid waste from the lead acid battery industry (Mainani *et al.*, 2022) [24] was ETP produces Sludge (74 kg/hr), Battery processing produces Glass mats (9.9 MT/10 days), Grid plates while processing (contains Lead oxide), Acid paste in pasting section and Pb paste. The different management strategies followed in industries of developed countries to prevent these Pb emissions were described.

3.1. Pb recycling process

Currently, the predominant methods for managing lead in the metal industry are hydrometallurgy and fire-gold metallurgy. Fire-gold metallurgy utilizes two different approaches. The first step involves pre-desulfurization, with subsequent reduction of lead through low-temperature smelting (Tang *et al.*, 2019) [42]. Both of these methods can be carried out using blast furnaces or reflectors without the need for direct coal burning (Hanif *et al.*, 2020) [13]. The hydrometallurgy method comprises of two models solid-phase electroreduction of lead and pre-desulfurization-electrolytic precipitation. After being treated with sodium hydroxide or ammonium carbonate (Xie *et al.*, 2020) [48], the lead paste formed from the solid phase electrolysis will adhere to the negative plate (cathode) and the solid phase lead bloom will eventually be reduced to metallic lead (Huang *et al.*, 2021) [14]. To effectively remove sulfur, first perform electrolyte precipitation and then evaporate the desulphurization solution once leaching is complete.

3.2. Effluent Treatment Plant (ETP)

Effluent Treatment Plant is a crucial component of the chemical processing industry. ETP encompasses several key units such as the neutralization tank, equalization tank, clarifier, rotary vacuum filter, and pressure sand filter. These chemical processes result in unwanted residues that contribute to high levels of TDS, COD, TSS, leady effluent, and heavy metals (Li *et al.*, 2019) [23]. The treatment plant receives two types of waste: acidic waste and leady waste, which are treated simultaneously (Gu *et al.*, 2020) [11]. Acidic waste is obtained from various sources and is equalized in the equalization tank before being pumped into the neutralization tank where the waste is treated with lime to neutralize acidity (Akhtar, 2022) [2]. Meanwhile, the leady effluent is filtered through a pressure filter press to remove the lead paste, which is then stored in a separate tank. The stored effluent is then treated and the deposit is stored in the Pb water filtrate tank. In addition, the sludge from the clarification process is pumped into a rotary vacuum filter press to remove excess water through the use of vacuum technology and then the sludge is dried and sent for secure landfilling (Asiwal *et al.*, 2016) [4]. The industry also adopted demineralization, Reverse osmosis, coagulation, precipitation, and electrodialysis techniques to lower the concentration of Chloride in the wastewater.

3.3. Air pollution control technologies

Efficient air emission control technologies, such as filters made of fabric, electrostatic precipitators, and scrubbers, were implemented to minimize the level of contaminants in the process off-gas before their release into the environment (Kalender, 2019) [17]. Notably, these wet scrubbers showed a 90% success rate in eliminating harmful substances such as acid mist, particulate matter, and lead fumes. Additionally, stacks are carefully situated at a height of 30 meters above ground level to prevent the spread of pollutants. The gravity settlers (MK720 and MK 820) and filter bags (PK720 and PK820) were the two streams in a system for the industry metal recycling furnace and indoor air furnace. The filter bag PK720 filters Tl, Pb, and Na while PK820 filters Na, Cu, Fe, Pb, and Ca in large amounts. During the refinery process impurities such as Sn, Sb, Cu, Al, Bi, Ni, Zn, Fe, As, and Ag were released into the environment by various chemical processes (Garche *et al.*, 2017) [9] was trapped by the filter bags. The gravity settlers contain large amounts of Sb and Cl. The efficiency of particle removal by gravity settlers and filter bags was 99.91%. So, industries should equip these systems to prevent the emission of contaminants into the surrounding air.

3.4. Remediation of contaminated soil

3.4.1. Acid leaching

Soil leaching is one of the widely used mitigation techniques for heavy metal-contaminated soils because it is a permanent remediation process, has stable remediation efficiency, and short time (Rajendran *et al.*, 2022) [32]. Inorganic acids possess a potent dissolving effect and are also capable of complexing, making them a suitable and cost-effective solution for removing lead from soil. When HCl with a concentration of 6 mol L^{-1} was applied to soil having a Pb intensity of 64,195 $mgkg^{-1}$ showed an 83% efficiency for Pb remediation (Vu *et al.*, 2019) [46]. However, it should be noted that a lower concentration of HCl, such as 1 mol L^{-1}, yielded a 35% efficiency for remediation of contaminated soil. Increasing the concentration of HCl may enhance remediation and cause potential harm to the soil's chemical, physical, and biological properties (Xiao *et al.*, 2022) [47].

The method was highly successful in eliminating Pb from the soil but less successful in lowering the Pb concentration in soil below the standard values. The concentration of heavy metals was reduced below the standard for human health. The alkaline contaminated soils contain inorganic lead compounds in an insoluble divalent state such as $PbCO_3$, PbS, $Pb(OH)_2$, and $Pb_3(CO_3)_2(OH)_2$. So, it was challenging to remove the contaminants using deionized water (Mansoorian *et al.*, 2014) [25]. For acid leaching citric acid (CA) and HCl had the finest leaching effects. In ideal conditions, 0.2 mol L^{-1} HCl could effectively remediate at a rate of 70.3%. The Pb level in the washed soil was recorded at 2388 mg kg^{-1}, and a leaching solution of 0.05mol L^{-1} CA reduced the Pb content of soil from 8043 mg kg^{-1} to 3732 mg kg^{-1}, making up 53.7% of the original amount (Asiwal *et al.*, 2016) [4].

$$2H^+ + Pb(OH)_2 \longrightarrow 2H_2O + Pb^{2+}$$

$$2H^+ + PbCO_3 \longrightarrow H_2O + Pb^{2+} + CO_2$$

$$6H^+ + Pb_3(CO_3)_2(OH)_2 \longrightarrow 4H_2O + 3Pb^{2+} + 2CO_2$$

However, the remediation ability of Citric acid was slightly lesser than HCl. More significantly, the CA solution resulted in a post-leaching soil pH of 6.97, compared to the much more damaging pH value of 3.88 with HCl, indicating that CA causes less harm to the soil. Citric acid was more suitable for leaching than HCl for lead-contaminated soil because the pH was maintained after remediation of the soil (Xiao *et al.*, 2022) [47].

3.4.2. Chelation extraction technique

According to Turner, proper use of EDTA resulted in over 95% removal of lead from LBRS soil. Additional studies by Clifford *et al*. showed that anhydrous ammonia combined with EDTA was effective in eliminating 94-95% of Pb from soil spiked with $Pb(NO_3)_2$, while aqueous EDTA was able to eliminate 98% of Pb from the same soil. This is due to the high stability constant of 10^{18} for the lead-EDTA complex, which allows it to effectively dissolve difficult-to-soluble lead compounds and extract lead exchanged within the soil (Palden *et al.*, 2020) [30]. The issue with the formation of the Pb-EDTA complex is competition with other metals in the soil, as observed with other metals present in the soil. Fe^{3+} form complexes with EDTA which had a stability constant of 10^{25}. Thus, the treatment of soil encompassing high Fe^{3+} ions was difficult with EDTA.

3.4.3. Thermal treatment
Exide Corporation was working on a revolutionary technology called the Super High-Temperature Metals Recovery (SHTMR) system, which aims to remediate soil contaminated by the LBRS site. This innovative approach has been officially recognized by the Environmental Protection Agency (EPA) as an ideal treatment method for the Battery Breaking site (Krishnan *et al.*, 2021) [20]. With a sealed plasma-arc furnace that can operate in various modes (oxidizing, reducing, or neutral), the SHTMR system utilizes a high temperature of 36,000°F generated by nitrogen, argon, or recycled furnace off-gas. During this process, the lead compounds are volatilized by the extreme temperatures within the reactor, and the resulting off-gas is then collected, making it possible to recover the lead (Pichler and Antrekowitsch, 2017) [31]. This efficient process yields three distinct products. The first is a stream of off-gas metals with a boiling point below 3200°F, the second consists of metals that remain in solid form and sink to the bottom of the molten alloy in the reactor. These metals are extracted intermittently by tapping. The third and final stream is a stable oxide slag that remains on top of the molten alloy. This slag is also intermittently tapped and forms a dense and environmentally friendly product that passes strict EPA leachability tests. The SHTMR process greatly reduces the production of harmful compounds often associated with traditional incineration methods.

3.4.4. Solidification / Stabilization (S/S)
The focus of Solidification/Stabilization was to limit the lead mobilization pathways in soil such as soil runoff and dust (Shen *et al.*, 2019) [39]. Initially, S/S reduces the effect of Pb by immobilizing it, later the S/S monolithic massages lead to weathering of the mass which again releases Pb into the pathways causing health impacts. The weathered dust contains a high amount of absorbable $PbCO_3$.The traditional Stabilization process converts the Pb salts in soil into Pyromorphite ($(Pb_5(PO_4)_3Cl)$ (Ren, 2023) [33]. Pyromorphite is the lead phosphate mineral which is highly insoluble. So, the pre-treatment of soil by spreading phosphatic fertilizer leads to the formation of Pb into Pyromorphite. When the Pb-contaminated soil was applied with rock phosphate reduced the bioavailability of Pb to various organisms. After the formation of Pb phosphate the soil was solidified with cement which prevents the erosion loss of Pb during weathering of S/S monolith.

3.4.5. Electrokinetic Treatment
Electrokinetic treatment is a process that takes place in situ by passing a low direct current (DC) among electrodes buried in the soil (Li *et al.*, 2020) [22]. The contaminants in soil migrate due to electromigration (ion transport) and electroosmosis (neutral compound transport). The Pb-contaminated soil should be pre-treated with EDTA which acts as a chelating and wetting agent (Table 5) and forms a water-soluble anionic complex with Pb and Cr then convert it into a smaller soil portion. These anionic complexes are electromigrated towards the anode where they accumulate into a small soil volume. The sandy loam soil had a Pb removal efficiency of 63.3%and slow permeable soil had an efficiency of 90.7%.

Table 5: Properties of the wetting agents used for Pre-treatment (Ng *et al*., 2016) [27]

Wetting agent	Chemical full name	Concentration (M)	Molecular weight (g mol^{-1})	Solubility in water (g/100ml)	Density (g/cm^3)	Function
NaNO3	Sodium nitrate	0.01	84.99	91	2.26	Electrolyte
Citric acid	Citric acid monohydrate	0.1	210.14	59	1.54	Complexing agent Electrolyte Soil acidification
EDTA	Ethylene diamine tetra acidic acid disodium salt	0.1	372.24	10	1.01	Electrolyte Soil alkalisation Chelating agent

3.4.6. Electrocoagulation process
The process involves the use of electrical currents to produce hydroxide metal flakes, extracting them from wastewater. The anodes are made up of aluminum or ferrous materials. Through electrochemical oxidation, metal cations are formed at the anode, while hydrogen is produced at the negative electrode (cathode) (Voutetaki *et al.*, 2023) [45]. The elimination of Pb and Zn from wastewater includes oxidation of iron (Fe) to ferrous ions and electrolysis on the anode surface leads to the synthesis of oxygen (O_2) which converts ferrous ion (Fe^{2+}) to ferric ions (Fe^{3+}) and production of poly hydroxide, Hydroxide and poly-ferrous hydroxide precipitate.

$$Fe_{(s)} + 2H^+ \longrightarrow Fe^{2+}_{(aq)} + H_{2(g)}$$

$$Fe_{(s)} + 6H_2O_{(l)} \longrightarrow Fe(H_2O)_4(OH)_{2(aq)} + 2H^+ + 2e^-$$

$$\text{Overall reaction: } Fe_{(s)} + 6H_2O_{(l)} \longrightarrow Fe(H_2O)_4(OH)_{2(s)} + H_2$$

$$\frac{Pb}{Zn}(aq) + \text{Iron hydroxide floc} \longrightarrow \frac{Pb}{Zn}\text{- Fe precipitate complex}$$

Employing chemical sedimentation, lead, and zinc were successfully eliminated through the formation of hydroxide (OH^-) ions at the cathode during electrolysis of water and through the co-sedimentation of steel and iron hydroxides. In direct current, the optimal exclusion rates for Pb and Zn were 97.2% and 95.5%, respectively, when using iron rod electrodes93.2% and 92.5% when using stainless steel rod electrodes, at a current density of 8 and 6mA/cm^3(Otieno *et al.*, 2022) [29]. The optimal length of electrolysis time was found to be 30 minutes for iron rod electrodes and 40 minutes for stainless rod electrodes. When considering energy consumption and electrode usage, alternating current was found to have the lowest operation cost. Additionally, it was found that alternating current produces less sludge than direct current (Mansoorian *et al.*, 2014) [25].

3.4.7. Bioremediation method

Many different forms of lead can be found in soil, each with its level of movement, toxicity, and availability to living organisms like animals, and plants (Hussein and Alatabe, 2019) [15]. The composition is impacted by various processes such as immobilization, absorption and desorption, precipitation and dissolution, complexation, ion exchange, biological mobilization, and plant absorption (Srivastava *et al.*, 2022) [40]. Some common forms of lead in soil include ionic lead (Pb(II) as $PbSO_4$), lead-metal oxyanion complexes, and oxides and hydroxides. Phosphates, carbonates (at a pH above 6), hydroxides/oxides, sulfides, and pyromorphite forms are among the most stable forms (Rigoletto *et al.*, 2020) [34].

Lead can be uptake by plants through the leaves or roots, and is then either stored in the leaf tissue or transported through the cell membranes. It is believed that this transportation is assisted by plasma membrane channels i.e., Ca-channels (Collin *et al.*, 2022) [5]. Lead may bind to ion-exchangeable sites on the cell walls and form external deposits, particularly in the form of lead carbonate. At higher concentrations, the metal hinders the activity of chlorophyll-producing enzymes, causing a decline in photosynthetic potential and overall plant growth. As a result, RWC is reduced, potentially leading to stomatal closure.

3.4.8. Phytoremediation

It is the in-situ process of remediation that immobilizes, transforms, and extracts contaminants mostly heavy metals from soil or water-using plants. Plants uptake nutrients that are present at very low concentrations through their roots by the synthesis of chelating agents or by pH modifications. The capacity of the plant to uptake heavy metals from the soil is determined by the Bioconcentration factor (BF). BF (C_p/C_{so}) is defined as the ratio of heavy metal concentration in plants (C_p) to the heavy metal concentration in soil (C_{so}). The amount of element stored and translocated into plants is the Translocation factor (TF) which is the ratio of metal concentration in the aerial parts (C_s) to the roots (C_r) (Lago-Vila *et al.*, 2019) [21]. If the TF value is more than 1 then the metals are translocated from the root to the shoots, when the TF value is less than 1 then the metals are immobilized in the root. Phytoremediation methods can be categorized based on how they remove pollutants. These methods include phytoextraction, where plants absorb contaminants from the soil into their tissues, phytodegradation, which involves the degradation of organic contaminants by plants, Rhizofiltration, where plant roots are used to clean contaminated water by adsorbing pollutants onto the outer layer and adsorbing them through specialized proteins (membrane proteins), phytostabilization, where plants reduce the bioavailability of pollutants in soil over their roots, and phytovolatilization, which relies on the volatilization of pollutants by plants (Subhashini and Swamy, 2013) [41].

Some herbs such as *Stachys arvensis*, *Conyza sumatrensis, and Cyperus* sp., while some shrubs like *Chromolaena odorata, and Barrington asiatica* were used as the phytoremediators for lead-contaminated soil because these plants accumulate >1000 mg/kg in a shoot. *Catharanthus roseus* is known to effectively accumulate lead in its roots, making it a valuable option for phytostabilization treatments (Table 6). The accumulative properties of this plant were identified with a BF (bioconcentration factor) greater than 1 and a TF (translocation factor) less than 1 (Zhang *et al.*, 2022) [49]. Similarly, *Acacia saligna* and *Eucalyptus rostrate* also primarily accumulate lead in their roots with a TF of less than 1. In contrast, *Conocarpus erectus* accumulates lead mainly in their shoots with a TF greater than 1 (Subhashini and Swamy, 2013) [41]. Additionally, *A. saligna* exhibits a higher Pb content in the biomass (Table 6). Although *A. saligna* and *E. rostrata* showed higher levels of lead in their roots, the above-ground tissues also resulted in significant concentrations of the metal. Hence, *Acacia saligna*, *Conocarpus erectus*, and *Eucalyptus rostrata* had the potential to be Pb hyperaccumulators.

Table 6: Phytoremediation carried out on Pb-contaminated soils (Rigoletto *et al.*, 2020) [34]

Plant Species	Results	Study
Cytisus scoparius	Pb Accumulated mainly in roots, so it acts as a Pb phyto-stabilizer (TF < 1, BF > 1)	(Lago-Vila *et al.*, 2019) [21]
Herbs: Sonchus arvensis, Co. sumatrensis, Cyperus sp. Shrubs: *C. odoratum, B. asiatica*	Hyperaccumulators: accumulate Pb in shoots which were 10–500 times higher than normal plants (Pb -5 mg/kg) shoot accumulation > 1000 mg/kg Perennial shrubs were highly preferable	(Rotkittikhun *et al.*, 2006) [35]
H. annuus (sunflower)	BF < 1, it was not an accumulator but an excluder	(Alaboudi *et al.*, 2018) [3]
C. roseus	Accumulator (TF<1 and BF > 1 in roots), it is used as phytostabilization	(Subhashini and Swamy, 2013) [41]
Trees*: C. erectus*	Pb Accumulation mainly in shoots	(Alaboudi *et al.*, 2018) [3]
E. rostrata, A. saligna	hyperaccumulators (above-ground tissues have high Pb, no decrease in biomass)	
B. juncea L. (Indian mustard), 80 types	Genotypes IM-24 and IM-32 had TF >1andaccumulated more Pb than other varieties	(Gurajala *et al.*, 2019) [12]

3.4.9. Bioremediation by Fungi and Bacteria

Leung defines bio-remediation as the process of transforming harmful pollutants into less dangerous or non-hazardous chemical compounds (Fig.5). This technology uses microbes to remove, or alter pollutants present in soil, sediment, air, and water. Biostimulation encompasses utilizing natural processes to enhance pollutant breakdown, either by optimizing environmental factors like oxygen levels, temperature, and pH or by introducing additional inorganic or organic nutrients (Sevak *et al.,* 2021) [37]. On the other hand, bioaugmentation entails introducing laboratory-grown microbial cultures to boost the existing microbial communities at a site and facilitate the breakdown of pollutants.

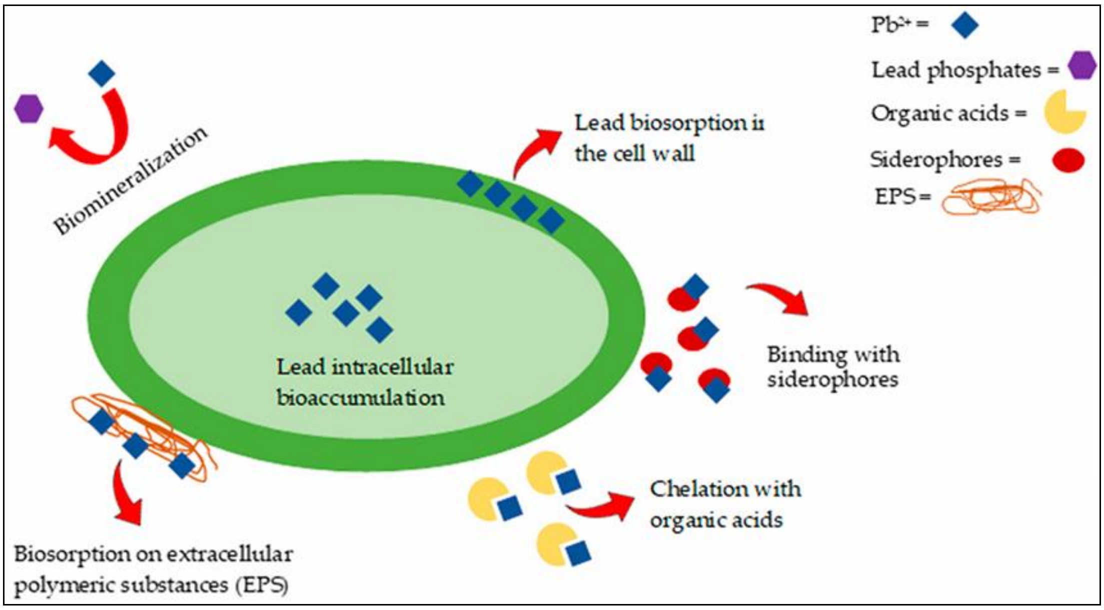

Fig 5: Mechanisms in bioremediation of Pb by bacteria and fungi (Rigoletto *et al*., 2020) [34]

A significant discovery of two fungi, *Paecilomyces javanicus and Metarhizium anisopliae* found in a prior lead mining site (Table 7). These fungi possess the remarkable ability to convert metallic lead into chloropyromorphite. Altering the pH and temperature, the highest absorption rate (21.5%) of lead by *Aspergillus niger* at a pH range of 4 to 5.4 was observed (Shan *et al.,* 2023) [38]. While the absorption efficiency of fungi decreased at higher pH levels, due to metal accumulation within cell walls or the formation of micro precipitates inside the cells. *A. Niger* showed a maximum biosorption efficiency of 45.5% at 37°C. The bacterium *Rhodobacter sphaeroides* alters the chemical composition of lead, effectively rendering it biologically inactive (Table 7). This was achieved through the production of Pb (SO_4), present in the surrounding culture medium, and lead sulfide, formed by the bacterium through the desulfhydrase enzyme. *Kocuria flava* achieves a similar result by chelating lead with calcite, promoted by the high levels of urease it produces. This process reduces the bioavailability of lead and its potential impact on the environment. During the bioremediation process bacteria undergo several mechanisms to store Pb and protect them from Pb i.e., Efflux mechanism, Biosorption, exopolysaccharides, precipitation and biotransformation of Pb, bioaccumulation and sequestration of Pb, oxidative stress management, siderophore complexation and Metallothionein (Tiquia-Arashiro, 2018) [43].

Table 7: Bioremediation of Pb through bacteria and fungi (Rigoletto *et al*., 2020) [34]

	Species	Mechanism
Bioremediation via fungi	*M. anisopliae,* *P. javanicus*	Sedimentation of lead as chloropyromorphite
	T. viride, A. niger, P. chrysogenum	Sedimentation of lead phosphate and biosorption
	P. bilaiae, A. niger	Chelate with Low molecular weight organic acids (LMWOAs)
	P. chrysosporium	Chelate with active functional groups Pb Bind with humic substances increases pH and hinders solubility
Bioremediation via bacteria	*R. sphaeroides* *L. adecarboxylata* *K. flava*	Immobilization as inert forms Binding with EPS Chelation by calcite

4. Future prospects

It is considerable for the Indian government to strengthen regulations and effectively enforce strict standards for the recycling of lead-acid batteries. Strict penalties must be imposed on any illegal or hazardous practices. In addition, public awareness, campaigns, and educational initiatives are necessary to educate individuals, businesses, and recyclers about the detrimental effects of improper lead-acid battery disposal and the advantages of recycling. By educating citizens about the health hazards and economic benefits of responsible recycling, we can drive meaningful progress and inspire positive change. Investment should be made in the development of advanced recycling technologies that hold potential for improving the efficiency of lead-acid battery recycling. Implementing Extended Producer Responsibility (EPR) policies would hold battery manufacturers responsible for their products throughout their entire life cycle - from collection and recycling to proper disposal. With EPR in place, manufacturers would be encouraged to design batteries with recycling in mind, ultimately optimizing the recycling process.

The contaminated areas should be remediated by proper management practices and further pollution of the environment should be prevented. First, evaluate the level and origins of lead contamination. Improve recycling methods for batteries and eliminate unauthorized processing of used lead-acid batteries (ULAB). Enact regulations and establish monitoring protocols to promote lead-free processes. Formulate policy suggestions for collaboration with national and state governments, including assistance with implementation, training, and adherence to the recently established Battery Waste Management Rules of 2022. By these steps, the ecosystem and human health can be conserved.

Conclusion

Pb is a hazardous heavy metal in India primarily contaminated by the soil, air, and water by Lead acid battery industries, recyclers, and unauthorized smelters, It accumulates in large amounts on the human body especially Children are more prone to Pb exposure through the soil which leads to various disorders and finally death of the individual. The soil is contaminated by Pb through improper discharge of untreated wastewater, settling Pb particles from the air and pH is extremely acidic due to the leakage/discharging of Sulfuric acid. Pb also enters humans via inhalation of air which contains Pb particles resealed from industries. So due to the release of Pb from the Lead acid battery industry, the ecosystem is completely degraded and human health is permanently affected. To prevent this huge impact government should take action on the unauthorized smelters and backyard recyclers from which most of the pollutants are released. Later the production of LAB is only limited to particular large-scale industries that have proper waste treatment plants and pollution control equipment at all the manufacturing process. The production and recycling of LAB by small-scale industries should be stopped or the proper handling of wastes should be practised. The contaminated soil and water should be treated with proper remediation methodologies to prevent the spread of contaminants from one trophic level to another. Proper disposal of wastes should also be practiced after remediation practices.

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