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ENVIRONMENTAL AND ECONOMIC BENEFITS OF LITHIUM-ION BATTERY RECYCLING IN NIGERIA

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Abstract
Global mobile phone use has risen sharply, with Nigeria among leading users. Indiscriminate battery disposal harms the environment and wastes valuable metals. This study investigated the benefits of lithium battery recycling in Nigeria. The study utilizes rechargeable battery data from the Nigerian Communications Commission (NCC) from 2010-2025 on mobile GSM subscriptions by using the SIM-to-user ratio model equation and Nigerian population data. This equation divides the total connected lines by a factor of 1.85 to account for multiple SIM ownership, and applies a 50% redundancy factor to reflect subscriber churn. Metal recovery values were calculated using a recycling efficiency of 80%- and 3-years battery lifespan. Polynomial regression models were developed for the forecast. Findings indicated that relationship between waste lithium batteries (WLB) and GDP is a quadratic function of time, while their per capita gave a polynomial model. The resulting breakdown of the quantities of heavy metals in WLB (lithium, cobalt, and nickel) forecasted from 2013-2053 is estimated to be 7871.72, 3502.31, and 2691.83 tons, respectively. The economic and environmental loss of the three metals if there is no recycling from 2026 to 2053 was estimated at around $174.39 million with an uncertainty range of ±15% due to commodity price volatility, and about 36,951 hectares of land out of 92,376,900 hectares in Nigeria.≈0.04%). The findings encourage building waste battery recycling plants in Nigeria, creating more jobs, improve revenue, and environmental conservation. The major limitation of this study is the assumption of a constant growth rate for mobile phone users.

Keywords
Circular economy, Economic analysis, Lithium-ion batteries, Mobile phones, Recycling

1. INTRODUCTION

There has been a global increase in mobile phone users, of which Nigeria is not an exception. One of the major components of these mobile phones is the energy storage device (Batteries), which uses electrochemical principles. This power source for mobile phones cannot only integrate into traditional energy infrastructure and provide 24-hour service for electricity demand, but also collect and store energy during times when demand is high. In addition, the battery can also make this stored energy available for use during periods of high demand from intermittent renewable technologies like solar and wind [1-3]. Large- and small-scale battery solutions that can supply storage capacity to technologies ranging in size from multi-megawatt production assets to small-scale solutions have been incorporated into battery technology as it has developed to fulfil this need [4-6].
Batteries are broadly classified as either non-rechargeable (primary) or rechargeable (secondary). Non-rechargeable batteries are discarded once their chemical energy is exhausted, while rechargeable batteries can

be recharged hundreds or thousands of times. Lithium-Ion is the industry standard for portable gadgets (laptops, cellphones) and electric cars due to its high energy density and good charge retention [7].

Since the 1990s, Lithium-Ion Batteries (LIBs) have been sold commercially [8-12]. Global smartphone sales increased at an average annual pace of about 76.07 million units between 2007 and 2023 [13]. In 2020, mobile phone users in Nigeria were estimated to be around 190 million [14]. Lithium-ion batteries generate and store energy through the continuous movement of lithium ions. A standard LIB cell consists of four primary internal components: an anode, a cathode, a separator, and an electrolyte, alongside current collectors and an external protective casing. Strategic metal combinations are utilized in lithium-ion battery assembly. The most essential are lithium, which facilitates the movement of charge, and cobalt, nickel, and manganese, which dictate energy density and stability. Copper and aluminum are also used as structural current collectors inside the battery. The average life of the majority of primary batteries is estimated to be 1.8 years, with the sales of secondary lithium chemistry batteries accounting for 24 % of all batteries by weight [15].

When compared to a battery composed completely of raw materials, the cost savings from battery recycling could range from 43% to 90% [16]. According to reports, more than 90% of the economic value of a spent LIB is made up of the following elements: cobalt (39%), lithium (16%), copper (12%), graphite (10%), nickel (9%), aluminum (5%), and manganese (2%) [17]. However, most solid waste in Nigeria ends up in landfills, with only about 12% recycled [18]. The value associated with valuable metals used in the manufacture of LIBs is being lost from the Nigerian economy. While the lifespan of a mobile phone is theoretically 10 years, consumers generally update their phones more frequently than the maximum operating life. There is enormous potential to recover value from waste LIBs instead of losing them to landfill or overseas; the costs associated with collection, transport, sorting, dismantling, and the changing chemistries of these batteries should always be considered when designing processing technology for battery recycling. Other consequences of spent batteries from mobile phones can also include materials with varying levels of toxicity, such as cadmium, beryllium, mercury, hexavalent chromium, brominated and chlorinated flame retardants, and gallium arsenide. The components of a mobile phone do not pose a threat during their use. However, growth, disposal, and treatment of a mobile phone at the end-of-life must be considered to ensure that toxic materials do not pose a threat to human health and the environment [19-20].

More recently, it was forecasted that LIB waste is growing at a rate of 12 % each year in Nigeria, and given the associated fire and/ or explosion risk with LIB, there is a need to assess collection and processing infrastructure for end-of-life LIB [21]. However, more recent data gathered by the same author indicated that the 2015 forecast was underestimated due to a lack of pertinent data, and an annual growth rate of 19-22 % was more realistic for LIB waste. LIB waste generation forecasting in 2016 predicted that 3,300 tonnes in 2016 would increase to 137,000 tonnes by 2036 (medium growth projections) as a result of per capita consumption of handheld and rechargeable equipment, the introduction of EVs and the concurrent production of waste EV batteries, and increasing use of solar and photovoltaic panels.

A report reviewing Nigeria's capacity to manage hazardous wastes concluded that the country's general e-waste infrastructure would remain adequate only until 2034. However, this general capacity does not extend to lithium-ion batteries (LIBs). The same report noted that Nigeria lacks any specific LIB collection, transfer, or treatment infrastructure, relying instead on the collection and separation of mixed battery types, disposal to landfill, or exporting for recycling. The report recommended that the hazards associated with handling, management, disposal, and transport of LIB in Nigeria be assessed, along with the collection techniques and processing infrastructure for Nigeria to meet future waste treatment and resource recovery. Reinforcing this concern, a subsequent report concluded that "there is an immediate need to improve processing infrastructure capacity for handheld Li- ion batteries in Nigeria" [22].

The escalating volume of spent lithium-ion batteries (LIBs) from mobile phones poses a critical waste management challenge in Nigeria, driven by inadequate processing infrastructure, substantial economic value lost to landfills or exports, and the designation of spent batteries as a policy priority. While prior studies address general e-waste or global recycling trends, a critical gap remains: no predictive model links mobile phone adoption to spent LIB generation within the Nigerian context. This study's novelty lies in integrating polynomial regression modelling of mobile phone adoption with economic and environmental assessments using Nigerian Communications Commission data. Accordingly, the objectives are to develop a mathematical model projecting mobile phone usage through 2050, determine annual waste LIB volumes generated by users, explore the relationship between per capita LIB waste and GDP, analyze the economic value of recoverable components, and provide consequences on the environment if waste LIBs are not recycled in Nigeria.

2. MATERIALS AND METHOD

2.1. Data Collection

The GSM market in Nigeria, the largest in Africa by population and economic activity, was regulated by the Nigerian Communications Commission (NCC). Four major mobile network operators dominated the market:

MTN, Airtel, Globacom (GLO), and T2 Mobile (formerly 9Mobile). To determine the quantity of waste lithium-ion batteries (LIBs) generated in Nigeria, this study utilized the number of SIM cards registered with the NCC from 2010 to 2022. The number of mobile phone users was estimated using the SIM-to-user ratio model presented in Equation (1).

$$\text{Mobile Phone Users} = \frac{\text{Mobile GSM Connected Lines} \times 0.5}{1.85} \quad (1)$$

The divisor of 1.85 was adopted from the GSMA [23] report for emerging markets to account for multiple SIM ownership. However, because not all registered GSM subscribers remained active, a 50% redundancy factor was applied. This factor was justified by three empirically documented conditions in the Nigerian market: (i) high rates of multiple SIM ownership, with 66% of mobile phones in Nigeria containing dual SIM cards [24]; (ii) significant subscriber churn; and (iii) strict regulatory audits, such as the National Identity Number (NIN) linking mandate, which deactivated non-compliant lines. The 50% value represented a conservative midpoint between the 66% dual-SIM ownership rate and the 34% single-SIM ownership rate, thereby providing a balanced estimate of active users. This study focused on mobile cell phones as the primary source of recoverable lithium batteries due to the high volume of users in Nigeria, unlike electric vehicles (EVs), which remained in their infancy in the country.

2.2 Determination of Waste Lithium-Ion Battery Generation

To determine the number of waste lithium batteries generated by mobile phone users, a three-year minimum lifespan was assumed, as specified in [25]. This assumption was further supported by [26], whose survey of Lagos, Nigeria, indicated that approximately 62.3% of users changed their phones within one to two years, thereby disposing of spent batteries, while 37.7% changed their phones after two years. Additionally, 30.7% of respondents had not changed their phones in the previous two years, suggesting that they likely replaced only the battery. Based on these empirical findings, a three-year lifespan was adopted, assuming that all mobile phone batteries used in 2010 reached their end-of-life by 2013. This allowed for the determination of the quantity and tonnage of waste LIBs up to 2025.

2.3 Model Development for Future Projections

Based on historical trends in waste LIB generation from 2013 to 2025, we developed polynomial regression models to forecast future generation. The methodology for determining these equations involved fitting polynomial functions of time to the historical waste LIB data, with the polynomial degree selected based on the highest coefficient of determination (R^2) value. This approach captured the non-linear growth patterns observed in the data. The study utilized GDP and population data for Nigeria to obtain a model equation describing how waste lithium battery generation per capita was influenced by GDP per capita. GDP data were sourced from the World Bank's World Development Indicators database, and GDP per capita was calculated by dividing the total national GDP by the annual population estimate. This analysis provided insight into the influence of the Nigerian economy on spent LIB generation. Microsoft Excel 2016 and R 4.4.2 were used for the analysis.

2.4 Metal Composition and Economic Valuation

Valuable metals including cobalt (5–20%), nickel (5–10%), and lithium (5–8%) were identified in spent LIBs by [27]. The higher range of these percentages was used to calculate the tonnage of each metal in the waste LIB stream, rather than the mean values. This conservative approach was adopted because the study sought to estimate the maximum potential economic value recoverable from recycling, thereby providing an upper-bound estimate that would be most relevant for investment and policy decisions. The quantities of lithium, cobalt, and nickel in annual cell phone battery usage were projected up to 2053.

The economic value of these metals was calculated using an 80% recycling efficiency rate. This efficiency was determined based on industry-standard recovery rates reported in the literature for hydrometallurgical and pyrometallurgical recycling processes [8, 10]. The 80% figure represented a conservative estimate, as commercial-scale recycling facilities typically achieve recovery rates between 70% and 95% depending on the specific technology and material. The total recoverable value for each metal was calculated by multiplying the total tonnage by the market price per ton and then applying the 80% efficiency factor. Metal prices were obtained from London Metal Exchange (LME) spot prices for the corresponding years.

2.5 Environmental Impact Assessment

It is important to clarify that this study did not involve the collection of primary environmental data. Rather, the environmental impact assessment was a theoretical evaluation of the potential consequences of unrecycled waste LIBs in Nigeria, based on existing data and published literature. The study considered the economic and environmental effects of not recycling waste LIBs and of applying a circular economy approach to waste lithium batteries, taking into account national lithium deposits and their refinement.

The land area potentially affected by improper disposal was estimated based on the assumption that one tonne of metal contamination affects one hectare of topsoil. This assumption was derived from the soil contamination thresholds reported by [28], who established that lithium concentrations exceeding 500 mg/kg

render soil polluted, and [29], who identified cobalt toxicity thresholds of 50 mg/kg in agricultural soil. A hectare of topsoil at 15 cm depth weighs approximately 2,000 metric tonnes. Therefore, if one tonne of a toxic metal were uniformly distributed within this soil volume, the resulting concentration would exceed established phytotoxic thresholds, thereby justifying the 1:1 tonne-to-hectare ratio as a conservative indicator of potential land contamination.

3. RESULTS AND DISCUSSION

3.1 Empirical Results

The results of the data collected from the Nigerian Communications Commission (NCC) on mobile phone usage from 2010 to 2025 and 2026 to 205 are shown in Fig. 1. The data from 2026 to 2050 were extrapolated using the polynomial regression model.

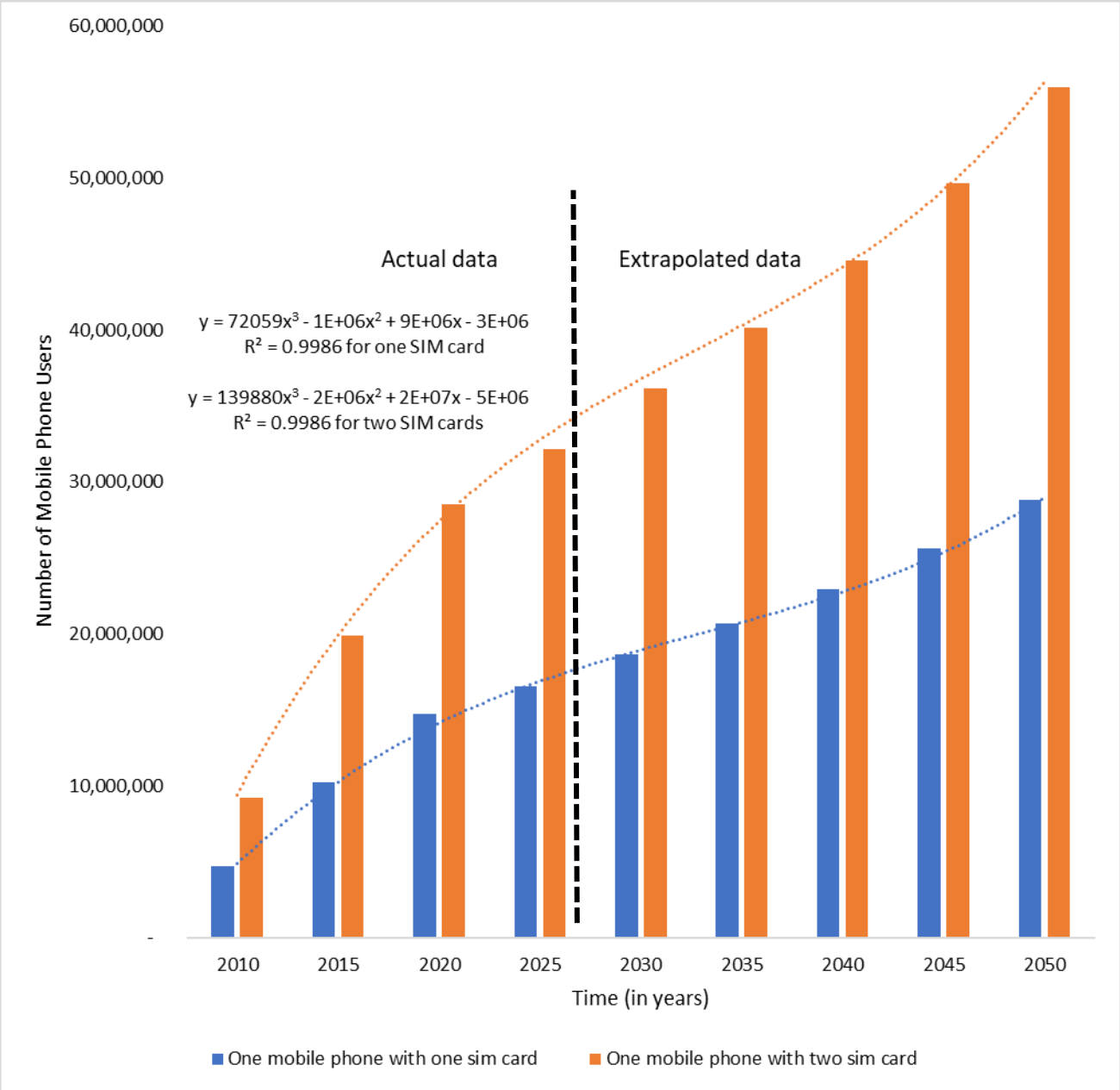


Fig. 1. A forecast of mobile phone users with single and dual SIM cards in Nigeria

The number of mobile phone users increased from approximately 13 million in 2010 to 58 million in 2025, yielding a compound annual growth rate (CAGR) of approximately 10.5%, calculated as:

$$\text{CAGR} = \left(\frac{58{,}000{,}000}{13{,}000{,}000}\right)^{\frac{1}{15}} - 1 = 0.105$$

This growth rate was used as the basis for projecting mobile phone adoption through 2050.

The amount of Cobalt, lithium, and Nickel in waste LiBs is shown in Fig. (a) and (b) for expired batteries from (2013 - 2033) and (2034 - 2053), respectively. The amount of Cobalt, lithium, and Nickel was calculated from battery data from 2010 to 2050, while 3 years battery lifespan is assumed, thereby generating data from 2013 to 2053 for expired batteries.

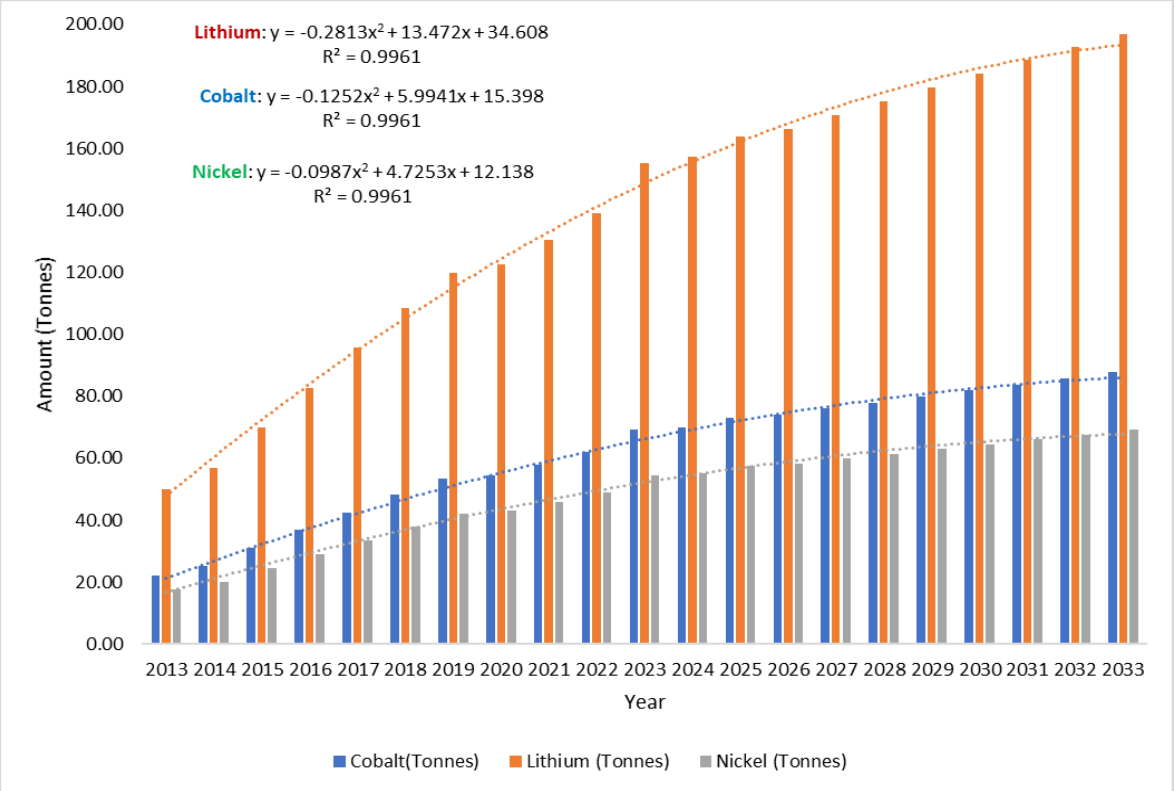


Fig. 2a. Variation in Lithium, Cobalt and Nickel from spent LiB from 2013 to 2033

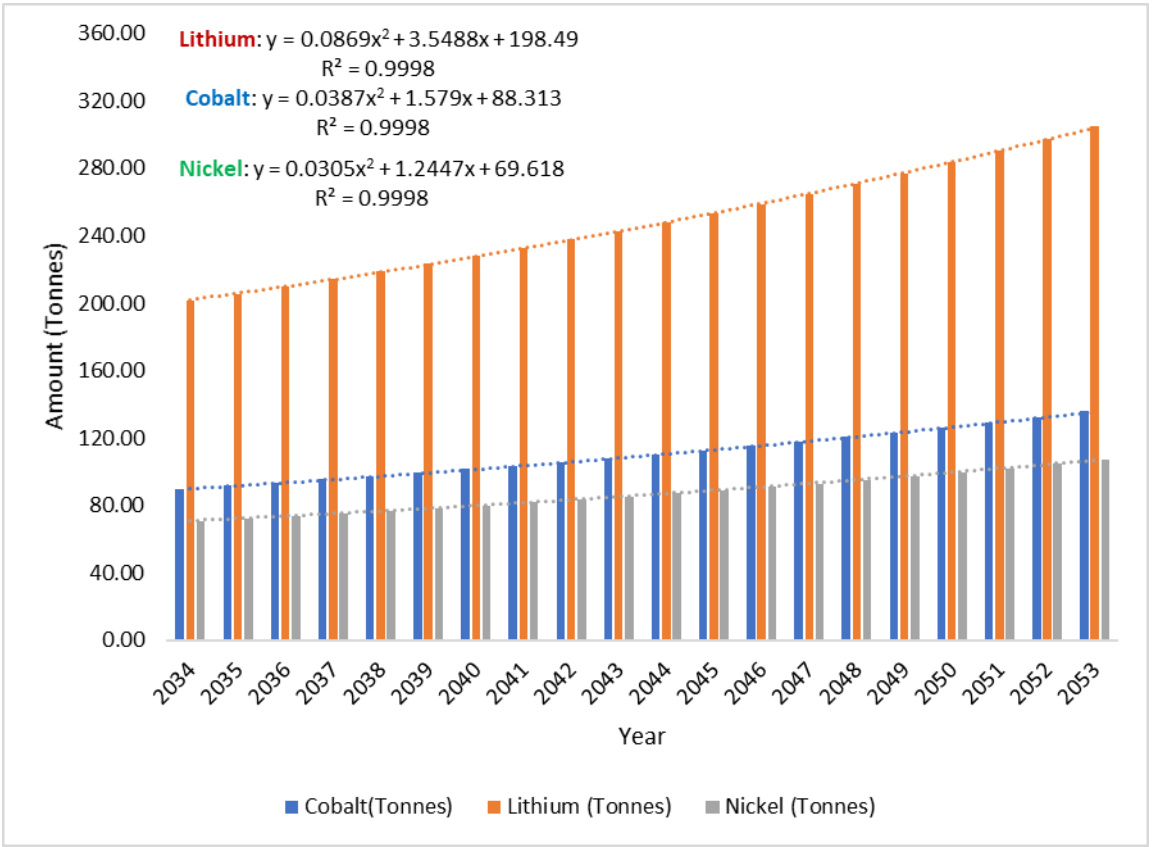


Fig. 2b. Variation in Lithium, Cobalt and Nickel from spent LiB from 2034 to 2053

The quantities of cobalt, lithium, and nickel recovered from spent lithium-ion batteries (LIBs) are presented in Fig. 2a for the period 2013 to 2033 and in Fig. 2b for the period 2034 to 2053. These projections were derived from mobile phone usage data spanning 2010 to 2050, with a three-year battery lifespan assumed, thereby generating the waste LIB stream from 2013 to 2053. As illustrated in Fig. 2a, lithium exhibited the highest accumulation rate among the three metals, increasing from approximately 34.6 tons in 2013 to 173.2 tons by 2033, following a quadratic trend ($y = -0.2813x^2 + 13.472x + 34.608$, $R^2 = 0.9961$). Cobalt followed with an increase from 15.4 tons to 87.7 tons over the same period ($y = -0.1252x^2 + 5.9941x + 15.398$, $R^2 = 0.9961$), while nickel rose from 12.1 tons to 68.4 tons ($y = -0.0987x^2 + 4.725x + 12.138$, $R^2 = 0.9961$). Fig. 2b presents the forecast for 2034 to 2053, where lithium continued its upward trajectory, rising from 198.5 tons in 2034 to 334.5 tons by 2053 ($y = 0.0869x^2 + 3.5488x + 198.49$, $R^2 = 0.9998$). Cobalt increased from 88.3 tons to 133.8 tons ($y = 0.0387x^2 + 1.579x + 88.313$, $R^2 = 0.9998$), and nickel rose from 69.6 tons to 111.8 tons ($y = 0.0305x^2 + 1.2447x + 69.618$, $R^2 = 0.9998$). The high coefficients of determination ($R^2 > 0.99$) for all six models confirm the strong polynomial fit of the projected trends. Across both periods, lithium consistently represented the largest fraction of recoverable metals, followed by cobalt and nickel, underscoring the economic significance of lithium recovery from spent mobile phone batteries in Nigeria.

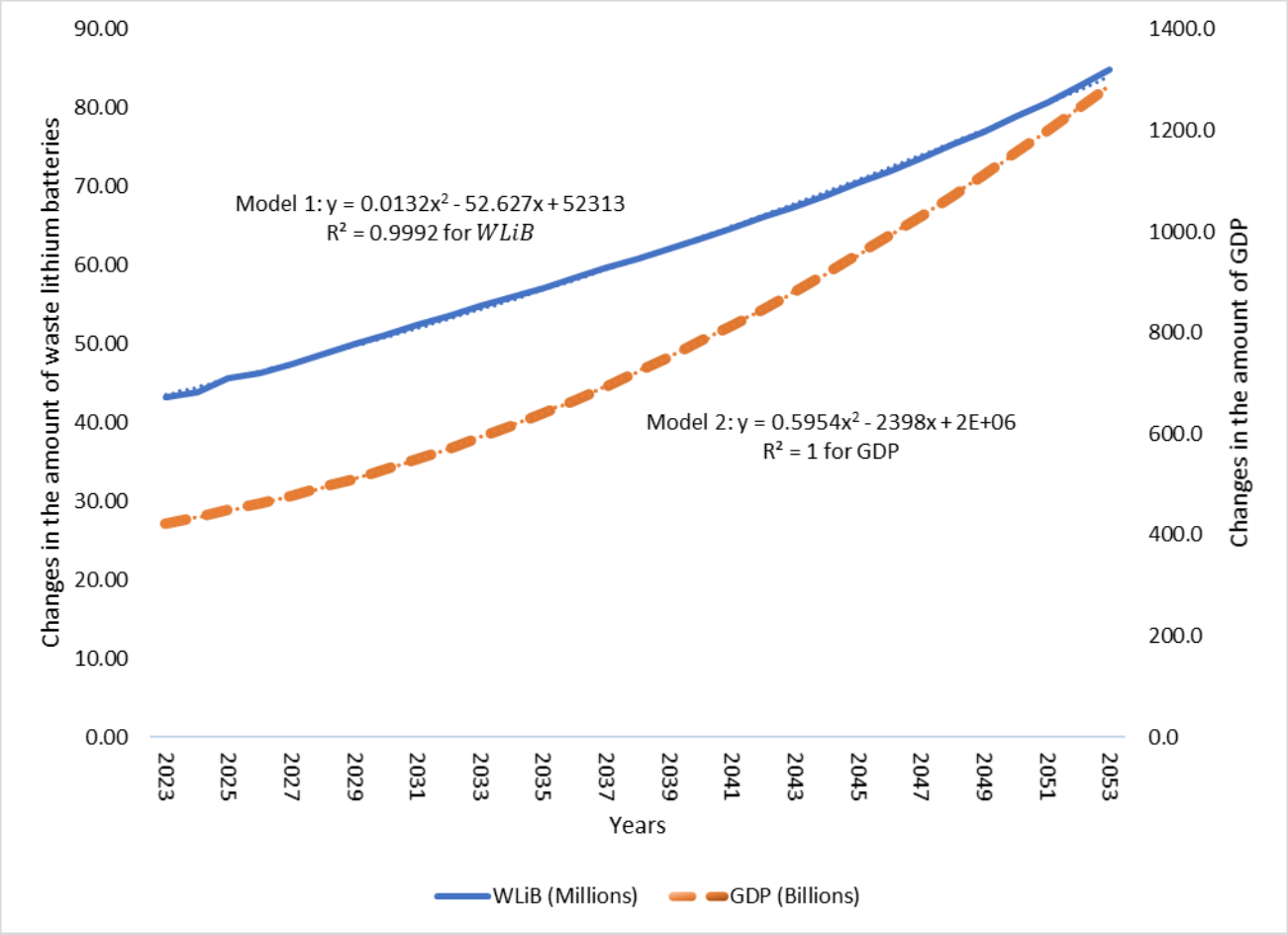


Fig. 2. Changes in the amount of waste lithium batteries and GDP over 3 decades using model equations

Fig. 3 illustrates the projected trajectories of waste lithium batteries (WLB) and Gross Domestic Product (GDP) over a 30-year horizon. Due to disparate scales, a secondary axis was used to compare their growth. The results yielded two second-degree polynomial model equations serving as the mathematical foundation for the projections. Model 1 ($y = 0.0132x^2 - 52.627\ x + 52313$) indicates that WLB generation follows an accelerating, upward-curving trajectory. The positive quadratic coefficient (0.0132) signifies that the rate of accumulation increases annually, projecting a rise from 45 million units in 2022 to nearly 85 million by 2052 ($R^2 = 0.9992$). This exponential rise reflects the growing global adoption of electric vehicles and electronics reaching their end-of-life phase.

Similarly, Model 2 ($y = 0.5954x^2 - 2398x + 2000000$) describes GDP growth. Mirroring WLB, GDP exhibits a positive quadratic coefficient (0.5954), forecasting an increase from approximately 400 billion to over 1,300 billion, with an R^2 of 1. The comparative analysis reveals a strong positive correlation between economic expansion and hazardous electronic waste generation. The parallelism of the curves suggests that as economic activity intensifies, so does the disposal of lithium battery technologies, with the most

significant increases for both variables occurring between 2040 and 2052. These findings have profound implications for waste management policy. The accelerating generation of WLB suggests that current linear frameworks will be insufficient. Policymakers must utilize these predictive models to scale up recycling infrastructure and implement circular economy strategies, underscoring the urgent need to decouple economic growth from resource depletion and waste generation.

The results in

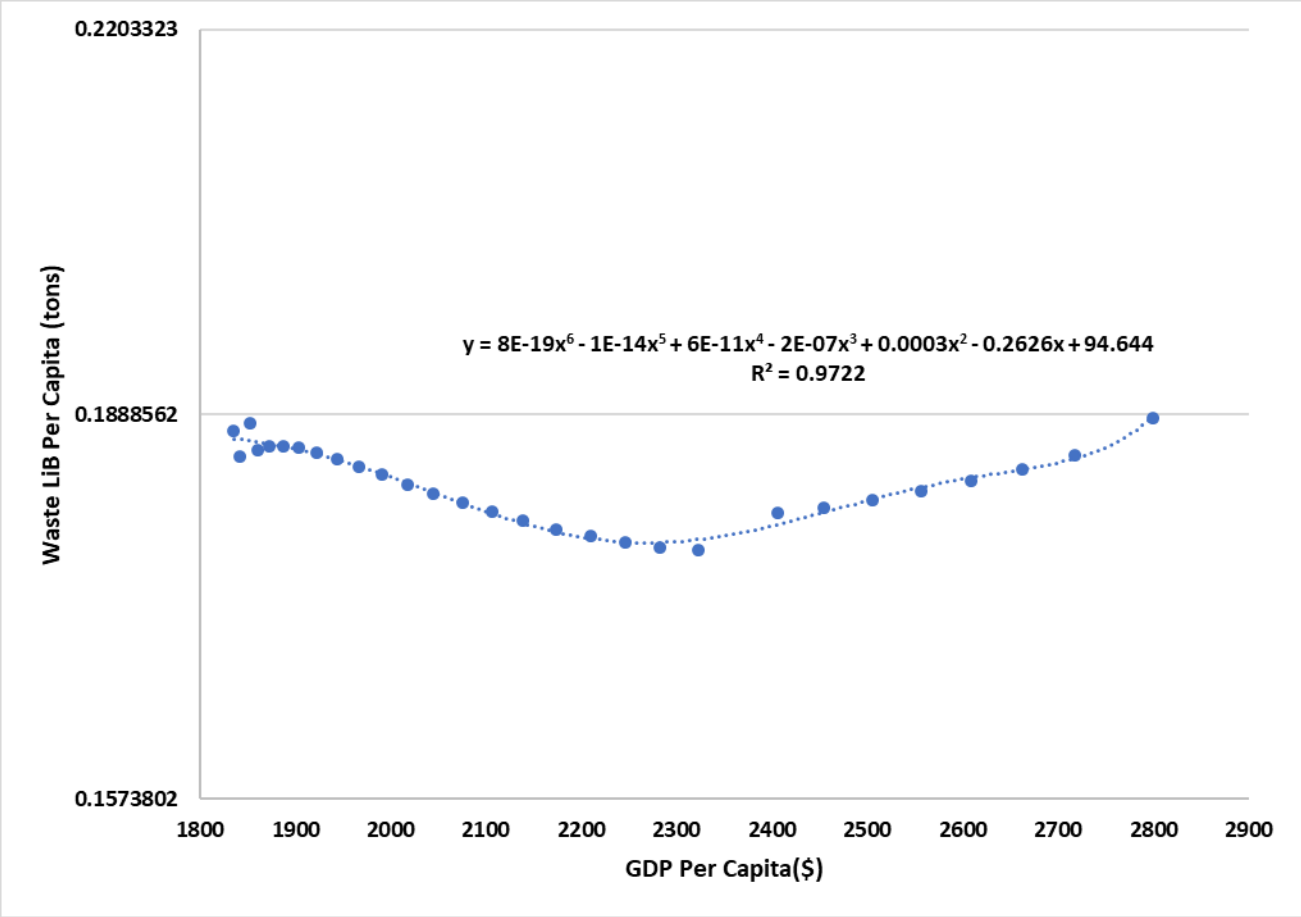


Fig. **3** indicate the effects of GDP Per Capita on Waste LiB Per Capita,

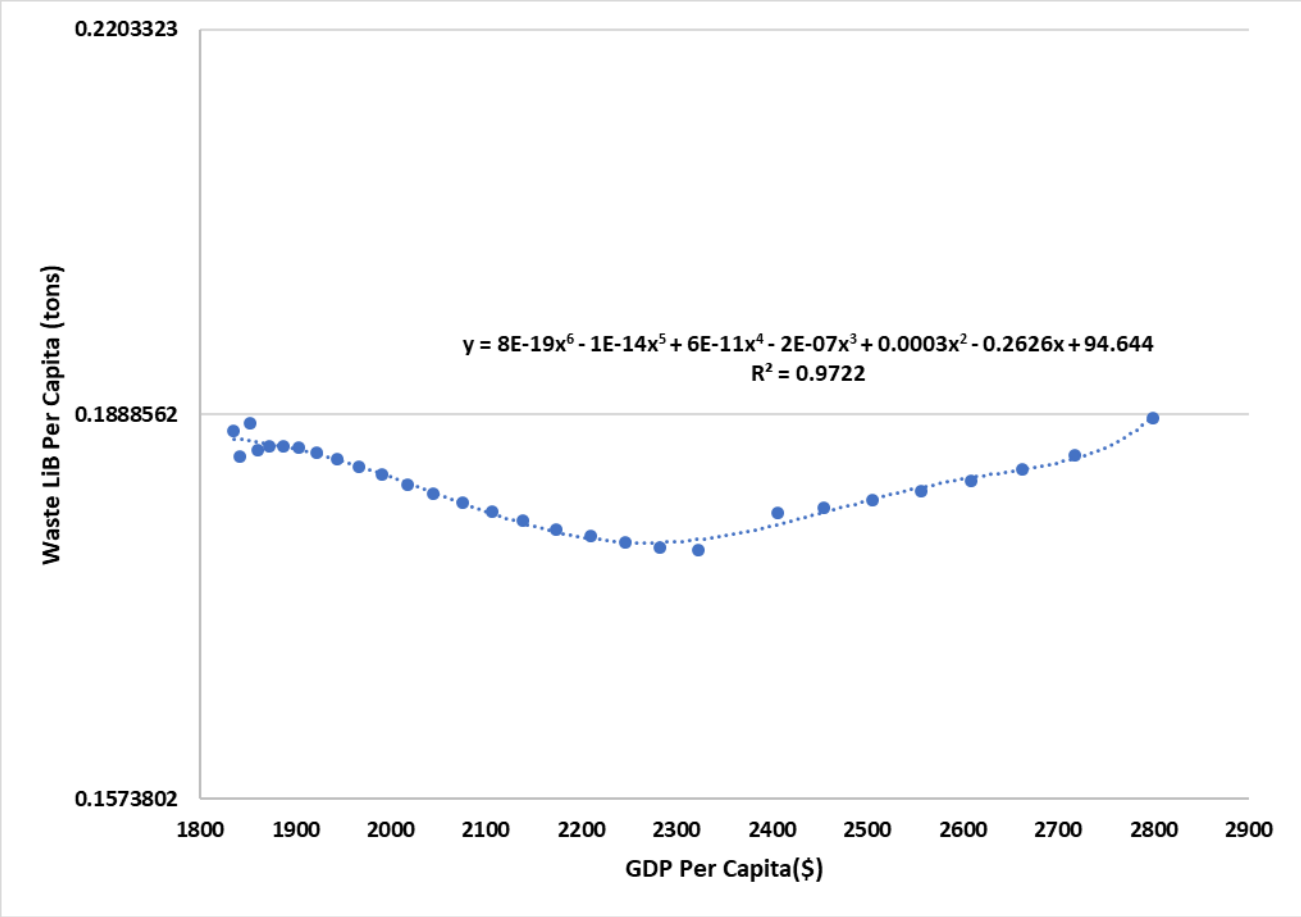


Fig. 3. Effects of GDP Per Capita on Waste LiB Per Capita

Fig. 4 illustrates the non-linear relationship between GDP per capita and per capita waste lithium batteries from mobile phones. The data were modelled using a 6th-degree polynomial regression, which yielded a high coefficient of determination (R^2 = 0.9722), indicating that the model explains a substantial portion of the variance in the dataset. The curve exhibits a distinct U-shaped trajectory: initially, waste generation declines as GDP per capita increases from $1,850, reaching a minimum point at approximately $2,300 per capita. Beyond this inflection point, the trend reverses, and waste generation begins to rise again as GDP per capita approaches $2,800.

This observed pattern shows that in the lower GDP range (up to $2,300), increased economic prosperity may correlate with improved waste management efficiencies or reduced consumption intensity. However, the subsequent increase in waste generation at higher GDP levels implies that beyond a certain threshold, the volume of discarded batteries begins to scale positively with wealth, likely driven by higher consumption rates and shorter device replacement cycles. It is important to note that while the model captures this curvature effectively, the specific turning point at $2,300 represents a lower-middle-income bracket by international standards, rather than a 'very high-income' status. Therefore, the 'decoupling' of wealth from waste often observed in advanced economies is not yet evident within this specific dataset range.

While the polynomial fit is statistically strong for the observed data range, the use of a 6th-degree polynomial introduces the risk of overfitting, potentially capturing random noise rather than a purely generalizable trend. Thus, while the model provides a valuable relationship of the correlation between wealth and waste within this specific GDP range, the long-term projections and the characterization of the $2,300 threshold as 'high-income' require further validation with extended datasets.

The economic value of the valuable metals found in spent LiBs, such as Cobalt, lithium, and nickel, for the various years is calculated using a recycling efficiency of 80%. The results are shown in **Error! Reference source not found.** and **Error! Reference source not found.** show the economic value of cobalt, nickel, and lithium from 2013 to 2033 and 2034 to 2053.

Table I: Economic Value of Metals in Mobile Phone Battery Waste from the Year 2013-2033.

Metal	Tonnage of Metal (Tons)	Value of Metal per Ton ($)	Total Value of Metal ($)	Total Value of Metal Using Recycling Efficiency ($)
Cobalt	1293.55	28,550.00	36,930,994.08	29,544,795.27

Lithium	2907.36	15,343.30	44,608,547.00	35,686,837.60
Nickel	950.62	16,863.00	17,195,738.81	13,756,591.04

Source: Value of metals in mobile phones (Nwachukwu [27])

Table II: Economic Value of Metals in Mobile Phone Battery Waste from the Year 2034-2053

Metals	Tonnage of Metal (Tons)	Value of Metal per ton ($)	Total Value of Metal ($)	Total Value of Metal using recycling efficiency ($)
Cobalt	2,208.76	28,550.00	63,060,195.10	50,448,156.08
Lithium	4,964.36	15,343.30	76,169,725.38	60,935,780.30
Nickel	1,741.21	16,863.00	29,361,967.39	23,489,573.91

Source: Value of metals in mobile phones (Nwachukwu [27])

Presented in Table I and Table II are the estimated values (in Dollars) of the studied metals [27]. It shows that Waste lithium batteries in Nigeria from 2013-2033 have 1293.55 tons of recoverable Co with an estimated value of $36.9 million at a unit price of $28,550. Also, 2907.36 tons of recoverable Li, at a unit price of $15,343.30, is estimated at a total value of $44.6 million. In addition, 950.62 tons of recoverable Ni, at a unit price of $16,863, is estimated at a total value of $17.2 million. The total value of the metals will be $98.7 million.

From 2034-2053, the waste lithium batteries in Nigeria have 2,208.76 tons of recoverable Co with an estimated value of $63 million at a unit price of $28,550. Also, 4,964.36 tons of recoverable Li, at a unit price of $15,343.30, were estimated at a recoverable value of $76.2 million. In addition, 1,741.21 tons of recoverable Ni, at a unit price of $16,863, were estimated at a recoverable value of $29.4 million. The total value of the metals will be $168.6 million. If the recycling efficiency of 80% was used, the total value of Co would be $50.4 million, the total value of Li would be $60.9 million, and the total value of Ni would be $23.5 million. The total value of the metals will be $134.9 million. Li had the highest recoverable value, followed by Co and Ni.

From 2013-2033, it can be deduced that a huge amount of money (foreign exchange) was lost due to the lack of recycling of spent lithium batteries, while from 2034-2053, it can be deduced that a huge amount of money (foreign exchange) can be generated from the recycling of spent lithium batteries.

3.2 Environmental Effects of Waste Lithium Battery

Poor or negligent handling and disposal of spent batteries contaminate the air, water, and soil, as shown in the figure below. Both human health and organisms at different trophic levels are directly threatened by the battery material's toxicity. Although leaching, battery disintegration, and degradation have been identified as pollution pathways, violent events like fires and explosions are also important [30]. Spent LIBs are regarded as hazardous wastes because heavy metals may pose a risk to human health and the environment. Numerous environmental compartments will be significantly impacted by the processing and disposal of LIBs, as well as their characteristics (such as chemistries). Reactive salts, volatile organic electrolytes, and additives are among the many compounds found in LIBs. Since the latter are frequently trade secrets, little is known about their toxicity and combustion products. Furthermore, when battery fires are combined with biogas from landfills, the hazardous materials may leak into the soil, groundwater, and surface water or emit toxins into the atmosphere. When released, they can be hazardous to the environment on their own or in conjunction with other contaminants. Fig. 5 illustrates potential cross-contamination between several compartments as well as expected pollution pathways (derived from the processing and disposal of EoL LIBs) to the environment. After being liberated from LIBs, pollutants may move from one compartment to another. For example, heavy metals may be carried into the soil or groundwater outside of the original location by dumpsite leachate. However, if a battery leaches into open land, heavy metals could end up in a neighboring lake or river with the rain.

3.2.1 Soil

When spent lithium batteries are disposed of in the ground, hazardous substances like lithium salts, organic solvents, and heavy metals (like cobalt and nickel) leak into the soil, poisoning plants, contaminating groundwater, and endangering animals [31]. The main dangerous reaction that happens when a lithium-ion battery electrolyte seeps into the ground is between moisture and the lithium salt, lithium hexafluorophosphate ($LiPF_6$) in Equation (2). The highly poisonous and corrosive hydrofluoric acid (HF) produced by this reaction deteriorates soil quality and puts groundwater safety at risk. Lithium salts (such as $LiPF_6$) dissolved in organic solvents (such as ethylene carbonate, $C_3H_4O_3$) make up a typical battery electrolyte [32].

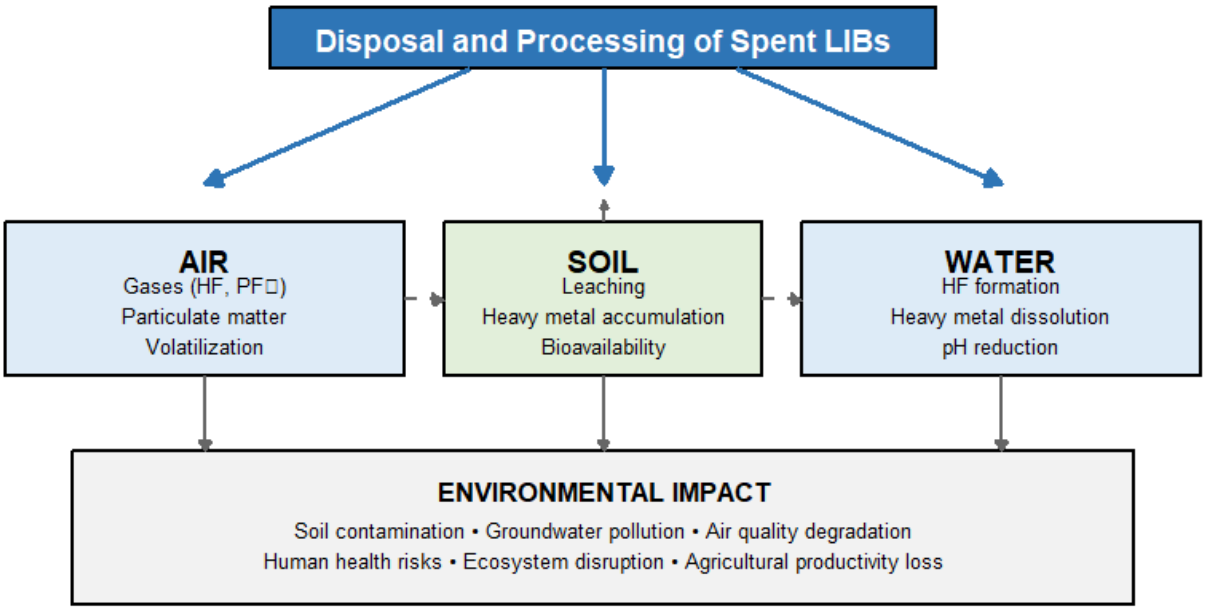


Fig. 5. Conceptual framework of pollution pathways from spent lithium-ion batteries into environmental compartments

The following gradually occurs when this liquid comes into contact with the water (H_2O) that is naturally present in soil: When the lithium salt comes into contact with water, it degrades. Hydrofluoric acid (HF) and phosphorus pentafluoride (PF_5) are produced.

$$LiPF_6 + H_2O \rightarrow POF_3 + 2HF + LiF \quad (2)$$

Soil moisture continues to react with the byproduct POF_3. This produces even more phosphoric acid (H_3PO_4) and hydrofluoric acid (HF) in Equation (3).

$$POF_3 + 3H_2O \rightarrow H_3PO_4 + 3HF \quad (3)$$

Lithium Cobalt Oxide ($LiCoO_2$), the main cathode component of discharged lithium-ion batteries, degrades in the soil. The solid $LiCoO_2$ leaches out when exposed to naturally occurring soil acids and moisture, releasing harmful Co^{2+} ions into the environment in accordance with the following reaction in Equation (4).

$$2LiCoO_2 + 8H^+ \rightarrow 2Li^+ + 2Co^{2+} + O_2 + 4H_2O. \quad (4)$$

A single trigger quantity of lithium does not exist. Concentration determines soil pollution. Geogenic (natural) background levels in unpolluted soil range from 1 to 200 mg/kg. When lithium concentrations surpass 500 mg/kg (0.0005 tons/kg), the soil is deemed polluted. Lithium interferes with plant growth and seeps into groundwater at this concentration.

According to critical limits, cobalt (Co) concentrations in agricultural soil that are more than about 50 mg/kg can harm microorganisms and stunt plant growth. Improper disposal of spent lithium-ion batteries can create serious soil toxicity, geotechnical instability, and groundwater concerns since they can emit amounts of Co up to 160,000 mg/kg.

When concentrations of high-nickel lithium-ion batteries in the soil reach 75 to 150 mg/kg, they start to have toxic effects on plants and soil, severely stunting vegetation. Uncontrolled disposal results in the transmission of heavy metals into food chains, decreased soil fertility, and changed soil stability.

The weight of a hectare of topsoil that is 15 cm deep is about 2 million kilograms (2,000 metric tonnes). From 2013 to 2033, 2907.36 tonnes of lithium in waste lithium batteries were accumulated, and about 5.8 billion kg of soil is affected. Therefore, about 2,907.36 hectares of land is affected by lithium from the indiscriminate disposal of waste lithium batteries. 1293.55 tonnes of cobalt in waste lithium batteries are accumulated, and about 25.8 billion kg of soil is affected. Therefore, about 12935.5 hectares of land is affected by cobalt from the improper disposal of waste lithium batteries. 950.62 tonnes of nickel in waste lithium batteries are accumulated, and about 6.3 billion kg of soil is affected. Therefore, about 3168.73 hectares of land is affected by nickel from the improper disposal of waste lithium batteries.

From 2034 to 2053, 4964.36 tonnes of lithium in waste lithium batteries are accumulated, and about 9.9 billion kg of soil is affected. Therefore, about 4964.36 hectares of land is affected by lithium from the indiscriminate disposal of waste lithium batteries. 2208.76 tonnes of cobalt in waste lithium batteries are accumulated, and about 44.2 billion kg of soil is affected. Therefore, about 22087.6 hectares of land is affected by cobalt from the improper disposal of waste lithium batteries. 1741.21 tonnes of nickel in waste lithium batteries are accumulated, and about 11.6 billion kg of soil is affected. Therefore, about 5804.03

hectares of land are affected by nickel from the improper disposal of waste lithium batteries. Cobalt affects the soil the most, even in small concentrations.

The environmental risk posed by heavy metals from spent LIBs is not determined solely by their total concentration, but rather by their chemical speciation and bioavailability. In soil, metals such as cobalt, nickel, and lithium can exist in various forms, including free hydrated ions (e.g., Co^{2+}, Ni^{2+}, Li^{+}), complexes with organic and inorganic ligands, and precipitates. The speciation of these metals is governed by soil pH, redox potential, organic matter content, and the presence of competing ions. For example, under acidic conditions, cobalt and nickel are more soluble and exist predominantly as free ions, which are highly bioavailable and toxic to plants and soil microorganisms. In contrast, under neutral to alkaline conditions, these metals tend to form insoluble hydroxides and carbonates, reducing their mobility and bioavailability. Similarly, lithium, which is highly soluble across a wide pH range, can readily leach into groundwater and be taken up by plants, where it interferes with physiological processes. The bioavailable fraction of these metals, rather than the total concentration, determines their potential for uptake by plants, accumulation in the food chain, and toxicity to soil organisms. Therefore, risk assessments and remediation strategies for LIB-contaminated soils must consider not only the total metal load but also the factors that influence speciation and bioavailability, such as pH, organic matter, and soil texture.

3.2.2 Air

Since lithium is bound in solid compounds in ordinary lithium-ion batteries, it does not typically become an airborne threat. However, these compounds break down if the battery is damaged, overheated, or experiences "thermal runaway," producing dangerous gases like hydrogen fluoride (HF) and highly poisonous, respirable metallic particles like nickel, cobalt, and lithium.

When battery cells overheat, the electrolyte's lithium salt (often $LiPF_6$) thermally breaks down and reacts with any remaining moisture to form hydrogen fluoride gas, which is extremely poisonous and corrosive [33].

Electrolyte Decomposition:

$$LiPF_6 \rightarrow LiF + PF_5 \quad (5)$$

Reaction with Moisture:

$$PF_5 + H_2O \rightarrow POF_3 + 2HF \quad (6)$$

Overall Hydrolysis Equation:

$$LiPF_6 + H_2O \rightarrow LiF + POF_3 + 2HF \quad (7)$$

Cobalt concentrations, which are frequently referred to in chemistries like Lithium Nickel Manganese Cobalt Oxide (NMC), can make up 5% to 20% by weight of the cathode material in typical lithium-ion batteries. This particular metal affects the air during battery fires and disposal.

Nickel usually comprises 80% to more than 90% of the cathode in high-nickel lithium-ion batteries (such as NMC 811). High nickel concentrations boost the energy density of the battery, but they also make the cathode extremely reactive with surrounding air, which increases the production of hazardous aerosols and particulate matter in the case of a fire.

3.2.3 Water

The main ways that lithium-ion batteries contaminate water are through the production of hydrofluoric acid (from moisture getting into broken cells) and the leaching of hazardous heavy metals (from incorrect disposal or firefighting runoff). The process is broken down into important chemical events because there isn't just one equation.

Hydrofluoric Acid (HF) Formation: The lithium hexafluorophosphate ($LiPF_6$) conducting salt in the electrolyte reacts with moisture that enters a lithium-ion battery when the seal is breached. Aquatic habitats are destroyed, and water pH is drastically lowered by this extremely toxic and caustic acid.

Electrolyte hydrolysis

$$LiPF_6 + H_2O \rightarrow LiF + POF_3 + 2HF \quad (8)$$

Phosphoryl fluoride reacts further with water.

$$POF_3 + 3H_2O \rightarrow H_3PO_4 + 3HF \quad (9)$$

Heavy Metal Leaching and Dissolution: Toxic transition metals, including cobalt, nickel, and manganese, dissolve into the nearby groundwater when they are dumped in landfills or come into contact with water. The dissolution of metal oxides from the cathode in acidic aqueous settings is a common way to describe this:

$$LiCoO_2 + 4H^+ \rightarrow Li^+ + Co^{2+} + 2H_2O \quad (10)$$

Depending on recycling procedures, lithium concentrations in battery wastewater can reach up to 664 mg/L. Aquatic ecosystems are drastically altered by this concentration, which is extremely hazardous to aquatic life, alters fish behavior, and hinders the development of invertebrates.

3.3 Discussion

The findings of this study demonstrate that mobile phone adoption in Nigeria will continue to rise over the next three decades, driving a corresponding increase in waste lithium-ion batteries (LIBs). The polynomial regression models developed in this study projected that waste LIB generation from mobile phones will reach approximately 7,871.72 tons of lithium, 3,502.31 tons of cobalt, and 2,691.83 tons of nickel by 2050. The economic valuation of these recoverable metals revealed that between 2013 and 2033, the total value of recoverable metals was estimated at $98.7 million, rising to $168.6 million between 2034 and 2053. Applying the 80% recycling efficiency rate, the recoverable value for the latter period was approximately $134.9 million. These findings indicated that without domestic recycling capacity, Nigeria stands to lose an estimated $174.39 million (with a ±15% uncertainty range due to commodity price volatility) in potential economic value between 2026 and 2050.

The environmental consequences of inaction were also quantified in this study. The results indicated that improper disposal of waste LIBs could contaminate approximately 36,951 hectares of land by 2050, representing about 0.04% of Nigeria's total land area of 92,376,900 hectares [34]. While this percentage appears small in absolute terms, the localized concentration of toxic metals, particularly cobalt, which affects soil at concentrations as low as 50 mg/kg, poses severe risks to soil fertility, groundwater quality, and agricultural productivity. The contamination pathways identified in this study, including the hydrolysis of lithium hexafluorophosphate ($LiPF_6$) to form hydrofluoric acid, highlighted the urgent need for proper end-of-life management. The relationship between waste LIB per capita and GDP per capita was found to be a 6th-degree polynomial function ($R^2 = 0.9722$), indicating that while waste generation initially declined as GDP per capita increased, it began to rise again beyond a GDP per capita threshold of approximately $2,300.

Based on the findings of this study, several recommendations are proposed for policymakers, industry stakeholders, and future researchers. First, the Nigerian government should mandate the establishment of dedicated LIB collection and recycling infrastructure. The current reliance on mixed battery separation and landfill disposal, as documented in the literature, is inadequate to handle the projected volumes of waste LIBs. The significant economic value identified in this study, estimated at $134.9 million in recoverable metals between 2034 and 2053, provides a strong financial incentive for investment in domestic recycling capacity.

Second, extended producer responsibility (EPR) legislation should be enacted, requiring mobile phone manufacturers and importers to fund and manage end-of-life battery collection programs. This approach has been successfully implemented in other developing economies, such as South Africa and Kenya, where EPR frameworks have improved collection rates and reduced environmental contamination. Nigeria can adapt these models to its specific market conditions, leveraging the high mobile phone penetration rate to achieve economies of scale in collection and recycling.

Third, investment incentives such as tax breaks, subsidies, or low-interest loans should be provided to stimulate the growth of domestic recycling facilities. The comparative analysis with other African countries suggests that Nigeria lags behind in recycling infrastructure, despite being the largest mobile phone market on the continent. Public-private partnerships could be explored to mobilize the necessary capital and technical expertise.

Fourth, public awareness campaigns should be launched to educate consumers on the hazards of improper battery disposal and the importance of recycling. The study's finding that 62.3% of users change their phones within one to two years suggests a high turnover rate, which presents both a challenge and an opportunity for collection programs. Retailers and mobile network operators could serve as collection points, integrating battery take-back into existing customer service channels.

Fifth, further research is needed to address the limitations of this study. Future studies should incorporate primary surveys of consumer disposal behavior, conduct empirical soil and water sampling to validate the theoretical contamination estimates, and explore the feasibility of different recycling technologies (hydrometallurgical, pyrometallurgical, or direct recycling) for the Nigerian context. Additionally, the forecast models should be updated periodically to account for technological shifts, economic fluctuations, and policy interventions [35].

Finally, regulatory frameworks should be developed to ensure that recycling operations meet environmental and safety standards, preventing the release of toxic byproducts during processing. The findings of this study underscore the urgent need for a transition from linear disposal practices to a circular economy model, where valuable materials are recovered, environmental contamination is minimized, and economic value is retained within the national economy.

4. CONCLUSION

This study set out to develop predictive models for mobile phone adoption in Nigeria and to quantify the resulting waste lithium-ion battery (LIB) generation, economic value, and environmental consequences. The findings confirmed that mobile phone usage in Nigeria will continue to grow over the next four decades, with users projected to reach approximately 266 million by 2050. This growth trajectory, driven by a compound

annual growth rate of approximately 10.5% derived from NCC data for all mobile phone users, is higher than Statista's [36] 6.7% projection for the Nigerian smartphone market only, likely due to differences in scope and time period. This will result in a corresponding increase in spent LIBs, assuming the established three-year battery lifespan. The polynomial regression models developed in this study projected that waste LIB generation from mobile phones will reach approximately 7,871.72 tons of lithium, 3,502.31 tons of cobalt, and 2,691.83 tons of nickel by 2050.

The economic analysis demonstrated that these recoverable metals represent a significant financial opportunity. Between 2013 and 2033, the total value of recoverable metals was estimated at $98.7 million, rising to $168.6 million between 2034 and 2053. Applying an 80% recycling efficiency rate, the recoverable value for the latter period was approximately $134.9 million. Conversely, the study estimated that without domestic recycling capacity, Nigeria stands to lose approximately $174.39 million in potential economic value between 2026 and 2050, subject to a ±15% uncertainty range due to commodity price volatility. These figures underscore the urgent need to transition from linear disposal practices to a circular economy model that retains value within the national economy.

The environmental assessment revealed that improper disposal of waste LIBs could contaminate approximately 36,951 hectares of land by 2050, representing about 0.04% of Nigeria's total land area. While this percentage appears small in absolute terms, the localized concentration of toxic metals—particularly cobalt, which affects soil at concentrations as low as 50 mg/kg—poses severe risks to soil fertility, groundwater quality, and agricultural productivity. The contamination pathways identified in this study, including the hydrolysis of lithium hexafluorophosphate ($LiPF_6$) to form hydrofluoric acid, highlight the urgent need for proper end-of-life management.

Based on these findings, the study recommends the establishment of dedicated LIB collection and recycling infrastructure, the enactment of extended producer responsibility (EPR) legislation, the provision of investment incentives for domestic recycling facilities, and the launch of public awareness campaigns on battery disposal. Additionally, regulatory frameworks should be developed to ensure that recycling operations meet environmental and safety standards. Future research should incorporate primary surveys of consumer disposal behavior, conduct empirical soil and water sampling to validate the theoretical contamination estimates, and explore the feasibility of different recycling technologies for the Nigerian context.

In conclusion, this study has demonstrated that the accelerating generation of waste LIBs from mobile phones in Nigeria presents both a significant environmental challenge and a substantial economic opportunity. The models and recommendations provided herein offer a foundation for policymakers, industry stakeholders, and researchers to develop targeted interventions that address this growing waste stream. The transition to a circular economy for lithium-ion batteries is not merely an environmental necessity but a strategic economic imperative for Nigeria's sustainable development.

REFERENCES

[1] H. Marta, Y. Cahyana, M. Djali, and G. Pramafisi, "The Properties, Modification, and Application of Banana Starch," *Polymers*, vol. 14, no. 15, p. 3092, 2022, doi: 10.3390/polym14153092.

[2] C. Yeboaa, E. K. Tetteh, M. N. Chollom, and S. Rathilal, "Sustainable Solutions for Plastic Waste Mitigation in Sub-Saharan Africa: Challenges and Future Perspectives Review," *Polymers*, vol. 17, no. 11, p. 1521, 2025, doi: 10.3390/polym17111521.

[3] I. T. Bello, L. A. Jolaoso, R. A. Ahmed, and A. Bello, "Electrochemical energy conversion and storage systems: A perspective on the challenges and opportunities for sustainable energy in Africa," *Energy Reviews*, vol. 4, no. 1, Art. no. 100109, 2025, doi: 10.1016/j.enrev.2024.100109.

[4] S. Coccato, K. Barhmi, I. Lampropoulos, S. Golroodbari, and W. van Sark, "A Review of Battery Energy Storage Optimization in the Built Environment," *Batteries*, vol. 11, no. 5, p. 179, 2025, doi: 10.3390/batteries11050179.

[5] G. De Carne *et al.*, "The role of energy storage systems for a secure energy supply: A comprehensive review of system needs and technology solutions," *Electric Power Systems Research*, Art. no. 110963, 2024, doi: 10.1016/j.epsr.2024.110963.

[6] T. Jaradat and T. Khatib, "A review of battery energy storage system for renewable energy penetration in electrical power system: Environmental impact, sizing methods, market features, and policy frameworks," *Future Batteries*, vol. 7, Art. no. 100106, 2025, doi: 10.1016/j.fub.2025.100106.

[7] F. Sciatti *et al.*, "A comprehensive overview of lithium-ion batteries for electric vehicles: Materials, performance, safety, recycling, and emerging technologies," *Journal of Energy Storage*, vol. 144, Art. no. 119694, 2026, doi: 10.1016/j.est.2025.119694.

[8] M. Kaya, "State-of-the-art lithium-ion battery recycling technologies," *Circular Economy*, vol. 1, no. 2, Art. no. 100015, 2022, doi: 10.1016/j.cec.2022.100015.

[9] F. Larouche *et al.*, "Progress and Status of Hydrometallurgical and Direct Recycling of Li-Ion Batteries and Beyond," *Materials (Basel, Switzerland)*, vol. 13, no. 3, p. 801, 2020, doi: 10.3390/ma13030801.
[10] M. Rezaei *et al.*, "A review of lithium-ion battery recycling for enabling a circular economy," *Journal of Power Sources*, vol. 630, Art. no. 236157, 2025, doi: 10.1016/j.jpowsour.2024.236157.
[11] Y.-S. Chuang, H.-P. Cheng, and C.-C. Cheng, "Reuse of Retired Lithium-Ion Batteries (LIBs) for Electric Vehicles (EVs) from the Perspective of Extended Producer Responsibility (EPR) in Taiwan," *World Electric Vehicle Journal*, vol. 15, no. 3, p. 105, 2024, doi: 10.3390/wevj15030105.
[12] A. Zanoletti, E. Carena, C. Ferrara, and E. Bontempi, "A Review of Lithium-Ion Battery Recycling: Technologies, Sustainability, and Open Issues," *Batteries*, vol. 10, no. 1, p. 38, 2024, doi: 10.3390/batteries10010038.
[13] M. T. Islam and A. Ali, "Assessment of waste lithium-ion battery generation from laptops and mobile phones in Saudi Arabia: Forecasting, material recovery, and recycling profitability," *Next Sustainability*, vol. 6, p. 100202, 2025.
[14] Industry Statistics, Subscriber Data, Nigerian Telecommunication Commission, Apr. 2020. Accessed: Jul. 24, 2020.
[15] K. O'Farrell, R. Veit, and D. A. Vard, "Study into market Share and Stocks and flows of handheld batteries in Australia," Melbourne, 2014.
[16] D. Steward, A. Mayyas, and M. Mann, "Economics and challenges of Li-ion battery recycling from end-of-life vehicles," *Procedia Manufacturing*, vol. 33, pp. 272–279, 2019.
[17] M. Pagliaro and F. Meneguzzo, "Lithium battery reusing and recycling: A circular economy insight," *Heliyon*, vol. 5, no. 6, 2019.
[18] J. O. Babayemi, I. C. Nnorom, O. Osibanjo, and R. Weber, "Ensuring sustainability in plastics use in Africa: consumption, waste generation, and projections," *Environmental Sciences Europe*, vol. 31, no. 1, pp. 1–20, 2019.
[19] O. A. Alabi, Y. M. Adeoluwa, X. Huo, X. Xu, and A. A. Bakare, "Environmental contamination and public health effects of electronic waste: an overview," *Journal of Environmental Health Science & Engineering*, vol. 19, no. 1, pp. 1209–1227, 2021, doi: 10.1007/s40201-021-00654-5.
[20] Ankit et al., "Electronic waste and their leachates impact on human health and environment: Global ecological threat and management," *Environmental Technology & Innovation*, vol. 24, Art. no. 102049, 2021, doi: 10.1016/j.eti.2021.102049.
[21] P. Randell, J. Pickin, and G. Latimer, "Hazardous-Waste-Infrastructure-Needs-Capacity-Assessment," *Canberra*, 2015.
[22] P. Randell, "Waste lithium-ion battery projections," Woodend, 2016.
[23] GSMA Report, "Measuring mobile penetration - Untangling 'subscribers', 'mobile phone owners' and 'users'," 2014. [Online]. Available: https://www.gsmaintelligence.com/research/measuring-mobile-penetration-untangling-subscribers-mobile-phone-owners-and-users
[24] Bankole Oluwafemi, "How Nigeria became the world's dual SIM-card superpower," Quartz, 2022. [Online]. Available: https://qz.com/345991/how-nigeria-became-the-worlds-dual-sim-card-superpower
[25] X. Wang, G. Gaustad, C. W. Babbitt, *et al.*, "Economic and environmental characterization of an evolving Li-ion battery waste stream," *Journal of Environmental Management*, vol. 135, pp. 126–134, 2014.
[26] O. A. Babatunde *et al.*, "Mobile phone usage and battery disposal in Lagos, Nigeria," *International Journal of Applied Psychology*, vol. 4, no. 4, pp. 147–154, 2014.
[27] Chinyere Nwachukwu, Innocent Nnorom, and Christopher Onyemeziri Alisa, "Determination of Co, Li, Mn, and Ni Levels of Waste Rechargeable Batteries Collected from Aba, Nigeria," *International Journal of Applied Sciences: Current and Future Research Trends*, vol. 24, no. 1, pp. 7–27, 2026. [Online]. Available: https://ijascfrtjournal.isrra.org/Applied_Sciences_Journal/article/view/1602
[28] R. Kastori, I. Maksimović, and M. Putnikdelić, "Lithium in the environment and its effects on higher plants," *Contemporary Agriculture*, vol. 71, no. 3–4, pp. 226–239, 2022.
[29] M. Rizwan, K. Usman, and M. Alsafran, "Ecological impacts and potential hazards of nickel on soil microbes, plants, and human health," *Chemosphere*, vol. 357, p. 142028, 2024.
[30] W. Mrozik, M. A. Rajaeifar, O. Heidrich, and P. Christensen, "Environmental impacts, pollution sources and pathways of spent lithium-ion batteries," *Energy & Environmental Science*, vol. 14, no. 12, pp. 6099–6121, 2021.
[31] P. Mishra, S. Apte, and A. Mukherjee, "Sustainable lithium-ion battery waste management: assessing impacts of heavy metal fraction on soil properties and pathways to mitigation," *Sustainable Environment Research*, 2026.
[32] L. Peiseler *et al.*, "Carbon footprint distributions of lithium-ion batteries and their materials," *Nature Communications*, vol. 15, no. 1, p. 10301, 2024.

[33] E. J. Nilsson and A. Ahlberg Tidblad, "Gas emissions from lithium-ion batteries: a review of experimental results and methodologies," *Batteries*, vol. 10, no. 12, p. 443, 2024.

[34] V. Ebong, "Agricultural land use and population growth in Nigeria. The need for synergy for a sustainable agricultural production," *Journal of Agribusiness and Rural Development*, vol. 61, no. 3, pp. 261–270, 2021.

[35] S. Ahmed, N. Haleem, Y. Jamal, S. J. Khan, and X. Yang, "Recovery of lithium and cobalt from used lithium-ion cell phone batteries through a pyro-hydrometallurgical hybrid extraction process and chemical precipitation," *Journal of Material Cycles and Waste Management*, vol. 27, no. 2, pp. 925–936, 2025.

[36] Statista, "Consumer electronics – Nigeria," Statista Market Insights, Jun. 2025. [Online]. Available: https://www.statista.com/outlook/cmo/consumer-electronics/nigeria

Appendix A: R Code for the Conceptual Framework of LIB Pollution Pathways

```
# Load necessary libraries
library(ggplot2)
library(grid)
# Create a blank canvas
p <- ggplot() +
  # Set plot limits
  xlim(0, 10) + ylim(0, 10) +
  # --- Title Box ---
  annotate("rect", xmin = 2.5, xmax = 7.5, ymin = 9.0, ymax = 9.8,
           fill = "#2E75B6", color = "black", linewidth = 0.8) +
  annotate("text", x = 5, y = 9.4, label = "Disposal and Processing of Spent LIBs",
           size = 5, fontface = "bold", color = "white") +
  # --- Arrows from Title to Three Compartments ---
  # Arrow to Air
  annotate("segment", x = 4, y = 9.0, xend = 2, yend = 7.5,
           arrow = arrow(length = unit(0.3, "cm"), type = "closed"),
           linewidth = 1.2, color = "#2E75B6") +
  # Arrow to Soil
  annotate("segment", x = 5, y = 9.0, xend = 5, yend = 7.5,
           arrow = arrow(length = unit(0.3, "cm"), type = "closed"),
           linewidth = 1.2, color = "#2E75B6") +
  # Arrow to Water
  annotate("segment", x = 6, y = 9.0, xend = 8, yend = 7.5,
           arrow = arrow(length = unit(0.3, "cm"), type = "closed"),
           linewidth = 1.2, color = "#2E75B6") +
  # --- Air Compartment ---
  annotate("rect", xmin = 0.5, xmax = 3.5, ymin = 5.0, ymax = 7.0,
           fill = "#DEEBF7", color = "black", linewidth = 0.8) +
  annotate("text", x = 2, y = 6.5, label = "AIR", size = 5, fontface = "bold") +
  annotate("text", x = 2, y = 5.8, label = "Gases (HF, PF5)\nParticulate matter\nVolatilization",
           size = 3.5, hjust = 0.5) +
  # --- Soil Compartment ---
  annotate("rect", xmin = 3.8, xmax = 6.2, ymin = 5.0, ymax = 7.0,
           fill = "#E2EFDA", color = "black", linewidth = 0.8) +
  annotate("text", x = 5, y = 6.5, label = "SOIL", size = 5, fontface = "bold") +
  annotate("text", x = 5, y = 5.8, label = "Leaching\nHeavy metal accumulation\nBioavailability",
           size = 3.5, hjust = 0.5) +
  # --- Water Compartment ---
  annotate("rect", xmin = 6.5, xmax = 9.5, ymin = 5.0, ymax = 7.0,
           fill = "#DDEBF7", color = "black", linewidth = 0.8) +
  annotate("text", x = 8, y = 6.5, label = "WATER", size = 5, fontface = "bold") +
  annotate("text", x = 8, y = 5.8, label = "HF formation\nHeavy metal dissolution\npH reduction",
           size = 3.5, hjust = 0.5) +
  # --- Cross-Compartment Arrows ---
  # Air to Soil
  annotate("segment", x = 3.5, y = 6.0, xend = 3.8, yend = 6.0,
           arrow = arrow(length = unit(0.2, "cm"), type = "closed"),
           linewidth = 0.8, color = "gray40", linetype = "dashed") +
  # Soil to Water
  annotate("segment", x = 6.2, y = 6.0, xend = 6.5, yend = 6.0,
           arrow = arrow(length = unit(0.2, "cm"), type = "closed"),
           linewidth = 0.8, color = "gray40", linetype = "dashed") +
  # Soil to Air (off-gassing)
  annotate("segment", x = 5, y = 7.0, xend = 5, yend = 7.3,
           arrow = arrow(length = unit(0.2, "cm"), type = "closed"),
           linewidth = 0.8, color = "gray40", linetype = "dashed") +
  # --- Bottom Section: Environmental Impact ---
  annotate("rect", xmin = 1.0, xmax = 9.0, ymin = 2.0, ymax = 4.0,
           fill = "#F2F2F2", color = "black", linewidth = 0.8) +
  annotate("text", x = 5, y = 3.5, label = "ENVIRONMENTAL IMPACT",
```

```
        size = 4.5, fontface = "bold") +
  annotate("text", x = 5, y = 2.8,
        label = "Soil contamination • Groundwater pollution • Air quality degradation\nHuman health risks •
Ecosystem disruption • Agricultural productivity loss",
        size = 3.5, hjust = 0.5) +
  # --- Arrows from Compartments to Impact ---
  annotate("segment", x = 2, y = 5.0, xend = 2, yend = 4.0,
        arrow = arrow(length = unit(0.2, "cm"), type = "closed"),
        linewidth = 0.8, color = "gray40") +
  annotate("segment", x = 5, y = 5.0, xend = 5, yend = 4.0,
        arrow = arrow(length = unit(0.2, "cm"), type = "closed"),
        linewidth = 0.8, color = "gray40") +
  annotate("segment", x = 8, y = 5.0, xend = 8, yend = 4.0,
        arrow = arrow(length = unit(0.2, "cm"), type = "closed"),
        linewidth = 0.8, color = "gray40") +
  # --- Theme ---
  theme_void() +
  theme(
    plot.margin = margin(10, 10, 10, 10)
  )
# Display the plot
print(p)
```