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Lithium-ion Battery Recycling Industry: Demands, Challenges, Growth, Revenue, and a Circular Sustainable Economy

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ABSTRACT

There has been an increase in the usage of lithium-ion batteries (LIBs) all over the world, and this is projected to continue in the near future. The increasing use of LIBs resulted in a significant increase in the number ofspent LIBs added to the waste stream. There is an immediate and urgent need for disposal methods that are safe, kind to the environment, and inexpensive from a financial perspective for LIBs. The fact that billions of LIBs are thrown away every year even though only a small number of businesses recycle these batteries makes this evident when one considers the difficulty and poor yield of recycling. Collecting, transporting, sorting into battery chemistries, separating metallic and non-metallic materials, shredding, neutralizing hazardous compounds, smelting, and purifying recovered metals are all part of the raw material process.The economic feasibility of this industrial process is one of the most significant challenges to be overcome in recycling used batteries. Reusing LIBs in a financially viable manner is becoming more important, although the paths to profitability remain elusive. The management of trash LIBs has been attempted by several countries, and several methods have been developed to recycle waste LIBs and reduce environmental dangers. The valuable materials contained can be reused by improving their electrochemical performance. Recycling may be a feasible economic option; however, its extent dependsmainly on factors such as transport distances, wages, pack design, and the recycling process. In conclusion, this article intends to offer a helpful reference for the management, scientific research, and industrial application of spent LIBs recycling to achieve economic and environmental advantages.

Keywords: Lithium-ionbattery, Recycling, Battery economics, Circular sustainable development

I. INTRODUCTION:

Li-ion batteries (LIBs) have recently continued to be a focus of research due to their high specific energy, high cell voltage, strong capacity retention, and minimal self-discharge.Portable electronic gadgets like smartphones, laptops, and more recently electric automobiles, which all use LIBs, have considerable advantages as a consequence of the development of thesetinier and more lightweight LIBs[1-4]. The development of commercial LIBs throughout the past couple of years required the combined efforts of a large number of very gifted researchers and engineers over the 1990s. This endeavor was not an instant triumph. After then, a considerable amount of work was placed into further improving LIB's performance, which finally led to a huge advance being made. The production of LIBs of the next generation, which can meet the rising demand for energy storage in the form of electric automobiles, which have grown more popular over the course of the last several years, requires additional research to be carried out. This is due to the increased popularity of electric vehicles over the last many years.

LIBs are constructed using the cathode, the anode, the electrolyte, and the separator, which are the four standard components. The relative weights of these components are given as a proportion of the battery's overall mass (g of material/g battery) as shown in Figure 1: 7 % cobalt, 7 % lithium, 4 % nickel, 4 % manganese, 11 % copper (33 % cathode material), 5 % aluminum, 16 % graphite, and 3 % conducting carbon, together with a 3 %polymer separator, 11% battery casing, and 16 % electrolyte. Commercial LIBs use a wide range of cathode chemistries, such as $LiCoO_2$, $LiMn_2O_4$, $LiFePO_4$, and $LiNi_{xy}Co_xMn_yO$, among others. Graphite and its composites are often used in the manufacturing of anodes.Polyvinylidene fluoride (PVDF) and styrene-butadiene rubber (SBR)are used as a binder by mixing with solvent N-methyl pyrrolidone (NMP). In the LIBs sector, micrometer-sized separators made of polyethylene (PE), polypropylene (PP), and PE/PP have been marketed and used extensively[5-6].These microporous separators protect the cells from any risk of damage that may arise at any stage of the processing procedure.

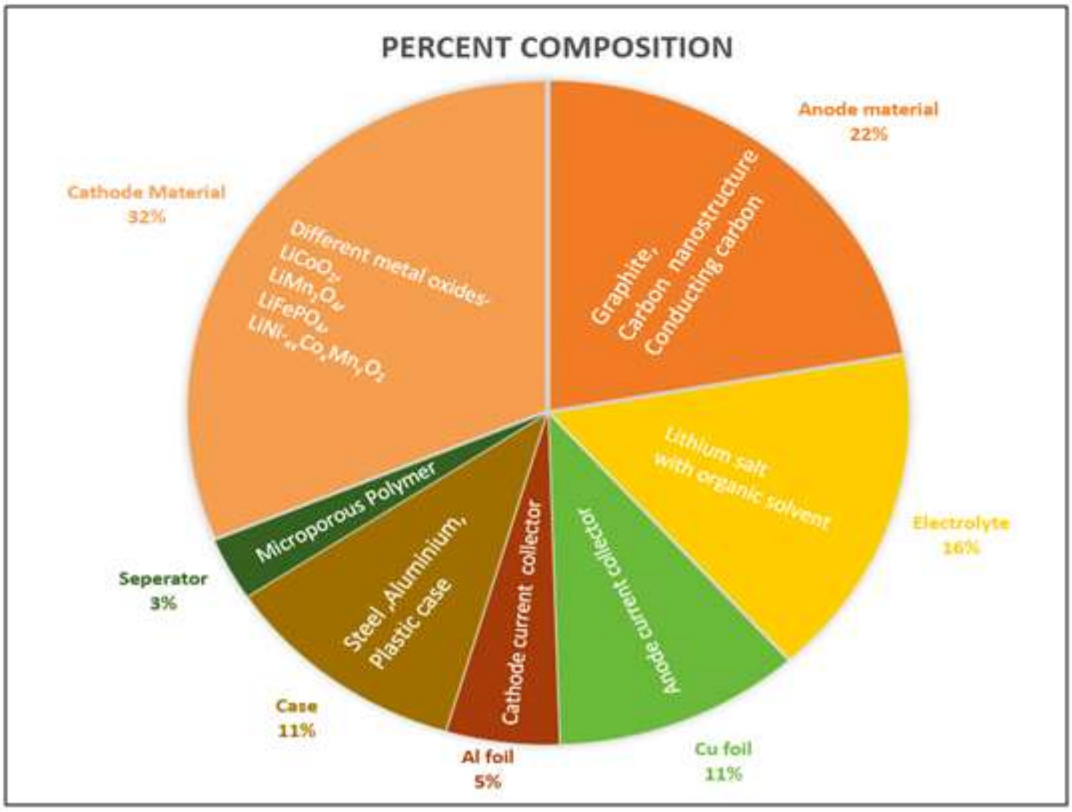


Fig.1Typical percent composition of LIBs

LIBs are built by connecting the appropriate Li-ion cells in series (to increase voltage) or parallel (to increase current), or by combining the two. A module may include a large number of battery cells. A battery pack might be built from a variety of components. A standard Tesla vehicle's battery pack contains 7104 cells and has an energy capacity of 85 kWh. The main Li-ion cell typically consists of a positive electrode(cathode) and a negative electrode (anode). Both of these electrodes come into touch with a lithium-ion-containing electrolyte. A separator, which is often a microporous polymer membrane, separates the electrodes. This kind of membrane does not let the passage of electrons, but it does permit the passage of lithium ions.[7]Figure 2 depicts the inner cell structure of typical LIB. In addition,Polymer electrolytes, gel electrolytes, and ceramic electrolytes are some of the other types of electrolytes that have been investigated for use in LIBs.

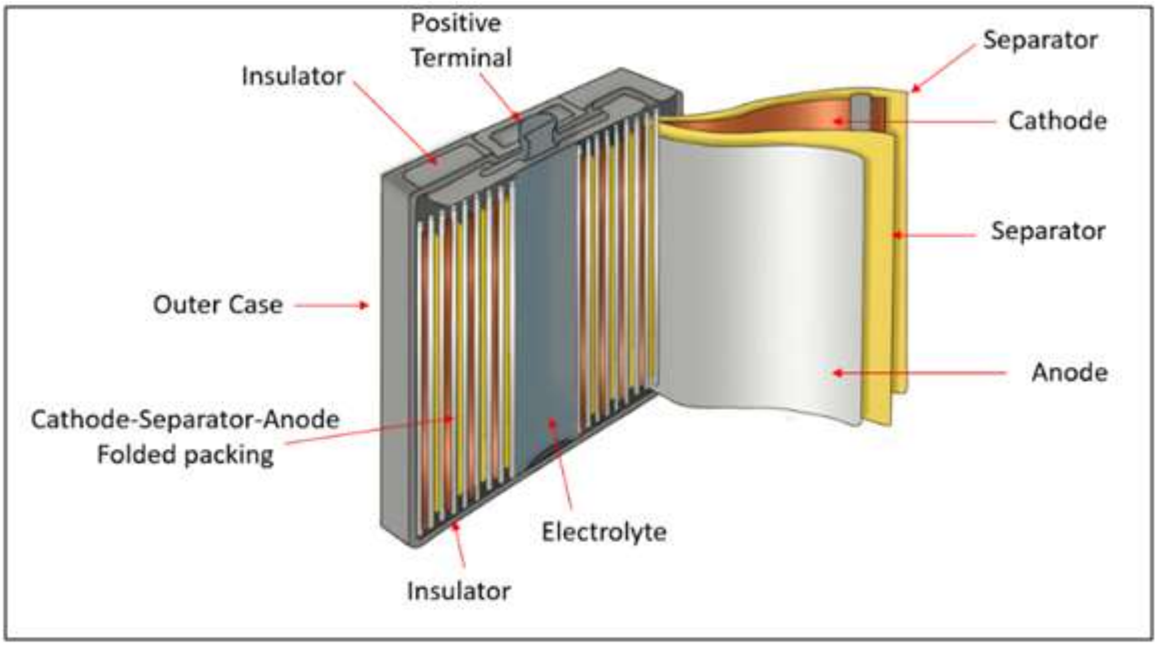


Fig.2LIB's internal cell structure

The current battery manufacturing process consists of three major steps: preparing the electrodes, assembling the cells, and activating the battery electrochemistry. To create a homogenous slurry, the active electrode material, conductive carbon, and binder are first thoroughly combined in a solvent. PVDF cathode binder is dissolved with NMP, whereas SBR anode binder is dissolved with carboxymethyl cellulose (CMC).The current collector Al foil (for cathode) and Cu foil (foranode) is coated on both sides with liquid using a slot die before the solvent is evaporated using drying equipment. Common organic solvent NMP for cathode slurry requires significant emission restrictions because of its toxicity. Due to the necessity for cathode production, a solvent recovery technique is necessary during drying, and 20–30 % of the recovered NMP is lost during battery production.After completing all of these operations, the electrodes are imprinted and cut to match the cell's design[8].The electrodes are dried in vacuum furnaces to eliminate any remaining solvent. Electrodes' moisture levels will be checked after drying to avoid side reactions and cell damage. Figure 3 depicts the whole LIB manufacturing process.

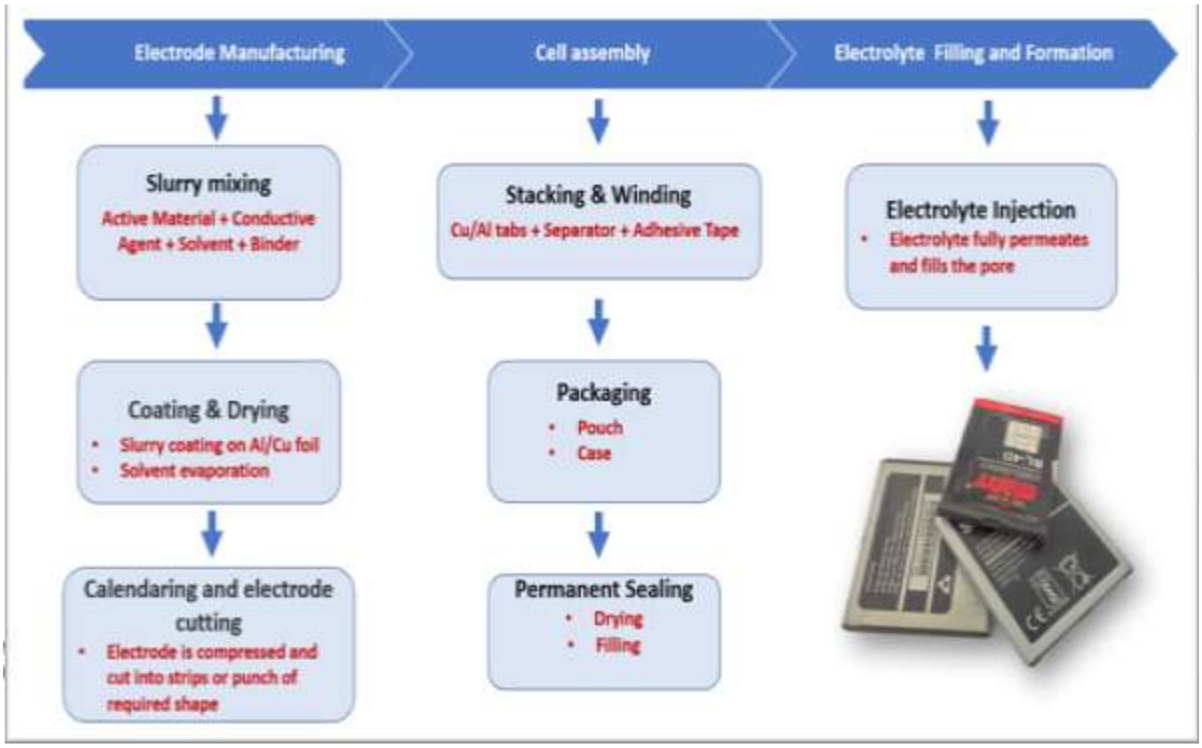


Fig.3 Manufacturing procedure involved in the production of LIBs

LIBs are undergoing rapid development, mostly as a direct result of the increasing demand for automobiles that are powered by electric batteries. This need is only going to grow in the near future. There has been an increased demand for this in the previous several years. In 2009, about 1,34,000 metric tonnes worth of energy storage capacity was introduced into markets all around the globe. This is about comparable to the storage of 25.6 GWhworth of energy. It reached around 218 GWh in 2019, which is equal to more than 1.2 million tonnes. Moreover, this quantity is projected to reach roughly 2500 GWh in 2030, which is equivalent to more than 12.7 million tonnes of carbon dioxide emissions[9-10].

Due to the rise in LIB applications, there has been a proportionate rise in the quantity of used LIBs that have been disposed of in the waste stream. The need for LIB disposal techniques that are secure, economical, and ecologically responsible is evident and urgent. However, substantial amounts of batteries are often buried or burned as a form of disposal. These approaches are not ecologically friendly. The main causes of the expansion of this problem are the lack of appropriate limitations and laws, as well as the absence of national battery collecting and recycling programs. It is probable that this will have a negative impact on the community's health as well as the environment's value. Furthermore, it is likely that this will have a negative impact on the creation of new LIBs.

Technology has to be developed in order to enable a recycling system for LIBs that is both resource-efficient and economically viable. It is challenging to make an accurate prediction about the LIBs' potential to be recovered over the long run since these batteries are complex systems with constantly evolving designs and materials. There have been various strategies for recycling that have been created or put into operation, and each of these strategies has its own mix of advantages and disadvantages[11].

This review article is a comprehensive description of the requirements of the LIBs recycling business, in addition to its challenges, growth, and revenue, as well as its contribution to a sustainable and circular economy. In addition, this article gives a short overview of LIBs waste recycling and treatment techniques, analyses those approaches from a technical and economic perspective, and discusses the current status of LIBs waste management. This review is a valuable resource that has the potential to be put to use in a number of different settings, including the recycling of old LIBs, scientific research, and industrial uses.

II. RECYCLING DEMANDAND PROCESS:

The need for recycling is often brought to people's attention at a wide range of various points. Even though recycling is something we are required to do, there is a significant chance that most of us are unaware of the additional benefits that come along with it. Following are some of the points that can help explain why the recycling industry is in such high demand in liberal countries.

2.1 Shortages in raw material supply

The quantity of raw resources that will be required to satisfy the increasing demand for LIBs is expected to rise, which will have a substantial influence on economies all over the world[12].This is especially concerning in light of the fact that there is a limited supply of essential metals like lithium and cobalt.In addition to this, it is anticipated that large quantities of discarded batteries would build up[13]. If a battery pack weighs 250 kilograms and has a lifespan of ten years, the anticipated sale of 23 million electric autos throughout theglobe in the year 2030 mightresult in 5,750,000 tons of batteries that will be retired by the year 2040.

The entire worldwide capacity for producing car LIBs will begreater than 120 GWh soon. Because of this fast expansion, it is anticipated that more than 550,000 metric tonnes of the materials used to make batteries would be required by the year 2025. Lithium, cobalt, manganese, nickel, and graphite are among these materials. In addition, LIBs are the dominant battery technology for storing power at a large scale on the grid. As the availability of renewable energy sources grows, grid-scale electricity storage will become more important. The deployment of stationary energy storage in the United States (residential, non-residential, and utility) increased by 46% year-over-year in the third quarter of 2017, measured in megawatts (MW), and LIB technologies continued to account for more than 94 % of the installed MW. On the basis of this information, it can be concluded that the transportation sector, namely electric automobiles and buses, will dominate the LIBs industry in the next years.

The mining production of materials for LIBs is currently restricted to a few places throughout the globe, which may create challenges with supply and pricing. Since there is a limited amount of these materials, their costs may rise as a result of the rising demand brought on by the widespread usage of electric cars and massive stationary storage facilities. This can interfere with manufacturers' plans and the expected expansion of the market for electric vehicles.

According to information provided by the United States Geological Survey (USGS), the worldwide production of cobalt in 2017 was 110,000 tonnes, with about 60 % of that amount originating from the Democratic Republic of Congo. China was responsible for the production of 67 % of the world's natural graphite, which totaled 1.2 million tonnes. The majority of the world's lithium was mined in Australia (44 %) and Chile (34 %), with a total output of 43,000 tonnes. South Africa (33%), China (16 %), and Australia (14%) were the three largest producers of manganese in the world. On a worldwide scale, nickel production reached 2.1 million tonnes, with the Philippines providing 11% of it, Canada 10%, Russia 9%, and Australia 8% of that total[14].In 2017, 32 nations were responsible for the whole of the world's output of these elements.It isimportant to maintain a steady and sustainable supply of these essential raw materialsbecause it is anticipated that the demand for LIBs technology will continue to rise dramatically. It is predicted that the EU would need 18 times as much lithium and 5 times as much cobalt by 2030than is currently available. This is because of the rising need for batteries to provide electricity to electric vehicles and other forms of energy storage. It is anticipated that by the year 2050, the demand for lithium will have increased to be 60 times higher, and the demand for cobalt will have increased to be 15 times higher[15].

Experts on rechargeable batteries and environmentalists feel that recycling may assist in the recovery of essential elements. Nickel and cobalt are both common cathode metals, although they are also quite costly to deal with. Throughout their existence, their prices have seen significant fluctuations. In many instances, the concentrations of manganese, lithium, nickel, and cobalt in LIBs surpass those of highly enriched ore. LIBs may also include substantial quantities of the elements listed in Table 1.Therefore, if recovered in significant amounts from wasted batteries, these metals may provide the same advantages as natural ores. Through recycling, it is possible to limit the amount of electronic trash delivered to landfills. About half of the cobalt used in the production of batteries is sourced from foreign nations, such as the Congo. Illegal mining, environmental degradation, armed conflict, and violations of human rights are all too prevalent in these nations. Recycling LIBs might aid in reducing dependency on these materials, enhancing supply chain security, and mitigating the negative effects of these batteries on people and the environment. Recycling would reduce the need for raw materials, benefiting both the economy and the environment.

Raw materials	Critical stage	Main global producers	Main EU[1] sourcing countries	Import reliance[2]	EoL-RIR[3]	Selected uses
Bauxite	Extraction	Australia (28%) China (20%) Brazil (10%) France (1%)	Guinea (64%) Greece (12%) Brazil (10%) France (1%)	87%	0%	- Aluminium production
Cobalt	Extraction	Congo DR (59%) China (7%) Canada (5%)	Congo DR (68%) Finland (14%) French Guiana (5%)	86%	22%	- Batteries - Superalloys - Catalysts - Magnets
Lithium	Processing	Chile (44%) China (39%) Argentina (13%)	Chile (78%) United states (8%) Russia (4%)	100%	0%	- Batteries - Glass and ceramics - Steel and aluminium metallurgy
Natural Graphite	Extraction	China (69%) India (12%) Brazil (8%)	China (47%) Brazil (12%) Norway (8%) Romania (2%)	98%	3%	- Batteries - Refractories for steelmaking

Table 1: List of critical raw materials for LIBs

[1] Based on Domestic production and Import (Export excluded)
[2] IR = (Import-Export) / (Domestic production + (Import-Export)
[3] The End-of-life Recycling Input Rate (EoL-RIR) is the percentage of overall demand that can be satisfied throughsecondary raw materials. Data from: Study on the EU's list of Critical Raw Materials (2020) Final Report

Source: European Commission, 2020.

2.2 Environmental pollution

If used batteries are handled and disposed of in a manner that is inefficient or irresponsible, theymay contaminate the land, the water, and the air. This pollution might be caused by the release of toxic chemicals. Because of the high toxicity of the substance that makes up the battery, it not only poses a direct danger to the health of humans but also poses a direct threat to the health of animals that can be found at various trophic levels. This is because the battery is composed of substances that have a high level of toxicity. Even while leaching, disintegration, and deterioration of batteries have been proved to constitute pollution routes, it has also been shown that violent events such as fires and explosions are substantial contributors[16]. Figure 3 depicts the dangerous environmental implications of dumping spent LIBs in the environment. As a direct result, the reuse of outdated LIBs is unavoidable.

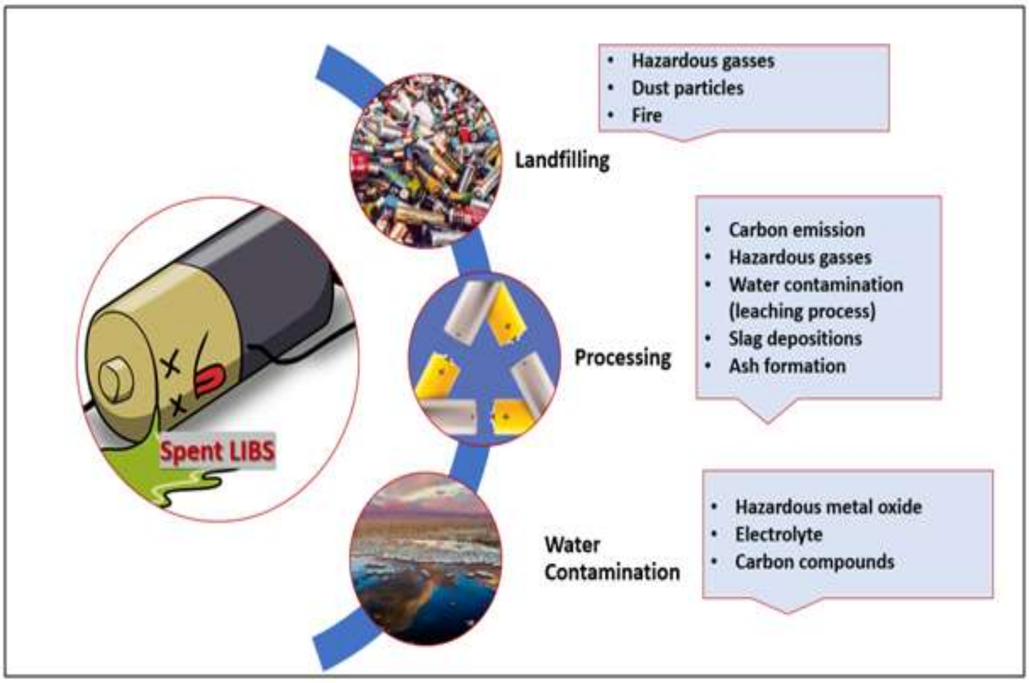


Fig.4 Hazardous effects due to LIBs disposal in the environment

2.3 Processes for LIBs recycling

The majority of LIBs that are recycled undergo a process known as "shredding," in which the battery is dismantled and shredded into ever-smaller fragments. This method accounts for the bulk of lithium-ion battery recycling. After being shredded into smaller bits, this so-called "black matter" undergoes further processing in order to recover important metals[16].

The three most important categories of processing are called pyrometallurgy, hydrometallurgy, and direct recycling (physical processes). The components of a process may be put together in a number of different ways, depending on a wide range of parameters, such as the amount and quality of the raw materials that are utilized, in addition to the value of the products that are recovered.

High temperatures are used in pyrometallurgy to help in the processes of oxidation and reduction. Through the use of these procedures, metals like cobalt and nickel may be converted from oxide to metal, and the mixed metal alloy that results can subsequently be used to create new products. Cathode material may be made from metals that have been separated after the process (via hydrometallurgy).Other components, such as aluminium, the anode, and the electrolyte, are subjected to oxidation in the smelter, which results in the production of the vast majority of the process's energy. In most cases, the aluminium oxide and lithium oxide that are present in the slag are not recovered. In the process of hydrometallurgy, acids are used to dissolve metal ions from a solid. This results in a solution that has a variety of distinct ionic species in its composition. After being recovered using a process such as precipitation or extraction with the aid of a solvent, they may then be reacted with other recovered components to generate new cathode material. The use of membrane separation is one of the other approaches that has been proposed. Using gravity separation, direct recycling separates the black substance into its constituent parts (active material powder from cell shredding). The cathode material may be recovered with relatively minimum treatment due to these techniques, which recover separated components without generating any chemical changes. Table 2 gives a comparison of different LIBs recycling techniques.

Table 2:A comparison of the most common battery-recovery recycling processes (Adopted from Battery recycling opportunity and challenges in India, Materials today: Proceeding)

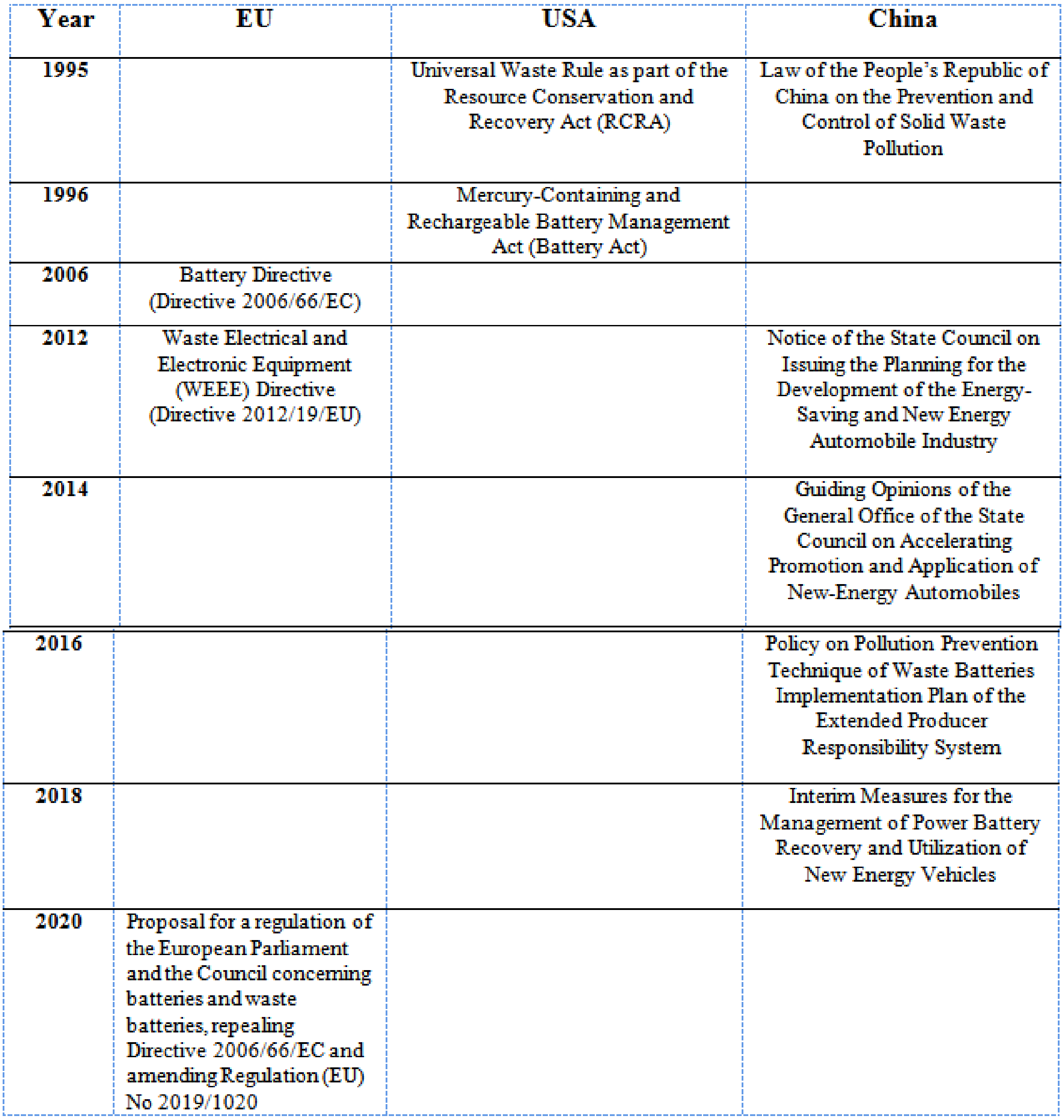
Recycling Method	Pros	Cons	Recovered material	Example
Mechanical process	Applicable to any battery chemistry and configuration. Lower energy consumption. Enhance the leaching efficiency of valuable metal	Must be combined with other methods (mainly hydrometallurgy) to recover most materials	Li_2CO_3	Taxco process
Hydrometallurgy	Applicable to any battery chemistry and configuration	Only economical for batteries containing Co and Ni	Copper, Aluminum, cobalt, Li2CO3. Anode is destroyed	Shenzhen Green Eco-manufacturer (China)
Pyrometallurgy (smelting)	Applicable to any battery chemistry and configuration	Only economical for batteries. containing Co and Ni, Gas clean-up is required to avoid the release of toxic substances	Cobalt, nickel, copper, and some iron Anode is destroyed	Umicore (Belgium); JX Nippon Mining and Metals (Japan)
Direct Recycling	Applicable to any battery chemistry and configuration	Recovered material may not perform as well as virgin material, mixing cathode materials could reduce the value of the recycled product	Almost all components (except separators)	On To Tech (USA)

III. RECYCLING CHALLENGES:

3.1 Recycling Regulations:

When it comes to exercising control over the recycling of any kind of waste material, legislation is a very significant factor. Government authorities may make a significant contribution to the development of an efficient circular economy by regulating disposal responsibilities and safety standards, establishing objectives for collection rates and recycling efficiencies, and setting targets for recycling efficiency rates.Extended producer responsibility (EPR), is a principle that places the duty of managing end-of-life (EOL) goods squarely on the shoulders of the manufacturing company. This is an essential idea in this context. In general, one differentiates between duties that involve one's body and those that involve one's finances. The term "physical responsibility" refers to the duty of ensuring that waste products are properly treated, which may include the collection, transportation, sorting, reuse, recycling, and disposal of garbage.

In most cases, these responsibilities may be handed off to a third party. The financial responsibility pertains to the funding of the actions that were stated above, and it enables producers to internalize the costs of waste treatment and include them in the prices that they charge. Different nations have different requirements for how used or obsolete batteries should be disposed of. The law of three of the world's main battery markets, namely China, the United States, and the European Union, is shown in Table 3.



Year	EU	USA	China
1995		Universal Waste Rule as part of the Resource Conservation and Recovery Act (RCRA)	Law of the People's Republic of China on the Prevention and Control of Solid Waste Pollution
1996		Mercury-Containing and Rechargeable Battery Management Act (Battery Act)	
2006	Battery Directive (Directive 2006/66/EC)		
2012	Waste Electrical and Electronic Equipment (WEEE) Directive (Directive 2012/19/EU)		Notice of the State Council on Issuing the Planning for the Development of the Energy-Saving and New Energy Automobile Industry
2014			Guiding Opinions of the General Office of the State Council on Accelerating Promotion and Application of New-Energy Automobiles
2016			Policy on Pollution Prevention Technique of Waste Batteries Implementation Plan of the Extended Producer Responsibility System
2018			Interim Measures for the Management of Power Battery Recovery and Utilization of New Energy Vehicles
2020	Proposal for a regulation of the European Parliament and the Council concerning batteries and waste batteries, repealing Directive 2006/66/EC and amending Regulation (EU) No 2019/1020		

Table 3: Selection of the most important federal policies regarding the recycling (adopted from Adv. Energy Mater. 2022, 12, 2102917).

3.3 Challenges in LIBs recycling industries

The recent precipitous reduction in the price of cobalt raises issues regarding whether or not recycling LIBs or reusing them is a sensible financial option when compared to the production of new batteries using new materials. It would be difficult for recycled cobalt to compete in the market if the price of cobalt were to decrease. As a consequence, manufacturers would choose to use mined materials over recovered materials, putting recycling businesses out of business. As an additional long-term financial concern for companies contemplating a move into the electric-vehicle market in the coming years is the possibility that new battery technologies, such as Li-air batteries or vehicles propelled by hydrogen fuel cells, will gain a significant foothold, it is likely that the demand for recycling LIBs will decline. For businesses that recycle LIBs, this would be a bad development[17].

Another challenge is the battery's construction, which makes recycling much more difficult. LIBs are small, sophisticated devices that come in a range of sizes and forms and cannot be dismantled. A cathode, anode, separator, and electrolyte are all found in each cell. According to Liang An, an expert in battery recycling at Hong Kong Polytechnic University, “The fact that LIBs contain a large array of ever-evolving components and materials is one of the primary factors that contribute to the difficulty of recycling these batteries.” It is possible that recyclers will need to filter and sort batteries according to their composition in order to meet the expectations of consumers who are acquiring recycled materials. This will make the process more difficult and will lead to an increase in pricing.The large battery packs required to power electric vehicles may have thousands of individual cells organized into modules[18].The packs also include sensors, safety devices, and circuitry that regulates battery performance; these components further complicate the disassembly and recycling process and incur extra expenses.

3.4Research and development in LIBs

The fundamental purpose of research and development for LIBs has been to simultaneously enhance their performance and reduce their costs. Increasing chemical and thermal stability, modifying particle size, producing coatings to decrease the decomposition of active components, and altering electrolyte solutions are among the most essential study fields. Reducing the size of active materials and enhancing the mechanical characteristics of conductivity are also two of the most important research fields. Adjusting battery chemistry, modifying particle size, and creating coatings to decrease the breakdown of active materials are other essential study fields.

Lithium metal (lithium metal anodes), solid-state batteries that employ solid inorganic or polymer electrolytes, and lithium-sulfur with high-capacity sulfur-containing cathodes are only some of the types of batteries now being explored. In the coming decade, regardless of the direction in which battery technology goes, the chemistry of batteries is expected to have a substantial impact. Battery chemistry changes are a potential that the supply chain must be aware of. The price of battery metamodel and the demand for it might both be significantly affected by these adjustments. The creation of cathodes with less or no cobalt is one such example. There has been an emphasis on generating nickel-rich, cobalt-free cathodes in the development of Lithium Nickel-Cobalt - Manganese Oxide (NMC) andLithium-Nickel Cobalt Aluminium Oxide (NCA) cathodes, which are the major cathodes in-vehicle LIBs. In automobile LIBs, the direct cathodes are NMC and NCA[20].

According to Aviceene Energy, the chemistry of NMC cathodes shifts from having a high cobalt concentration to having a lower cobalt content and a higher quality nickel content (NMC 622 and NMC 811). Tesla automobiles are made using NCA chemistry, which is also heading toward higher nickel percentages (and lesser cobalt content). Contrary to NMC and NCA, lithium manganese oxide (LMO) and lithium iron phosphate (LFP) do not include any cobalt, hence the majority of research and development efforts are directed at improving the performance of these materials. Graphite is still the most common anode material in most LIBs, however, silicon has recently been provided as a more affordable substitute in certain LIBs.The reason behind this is Silicon has a larger energy capacity and may be found in relatively large amounts in the planet’s crust.

3.5Recycling costs

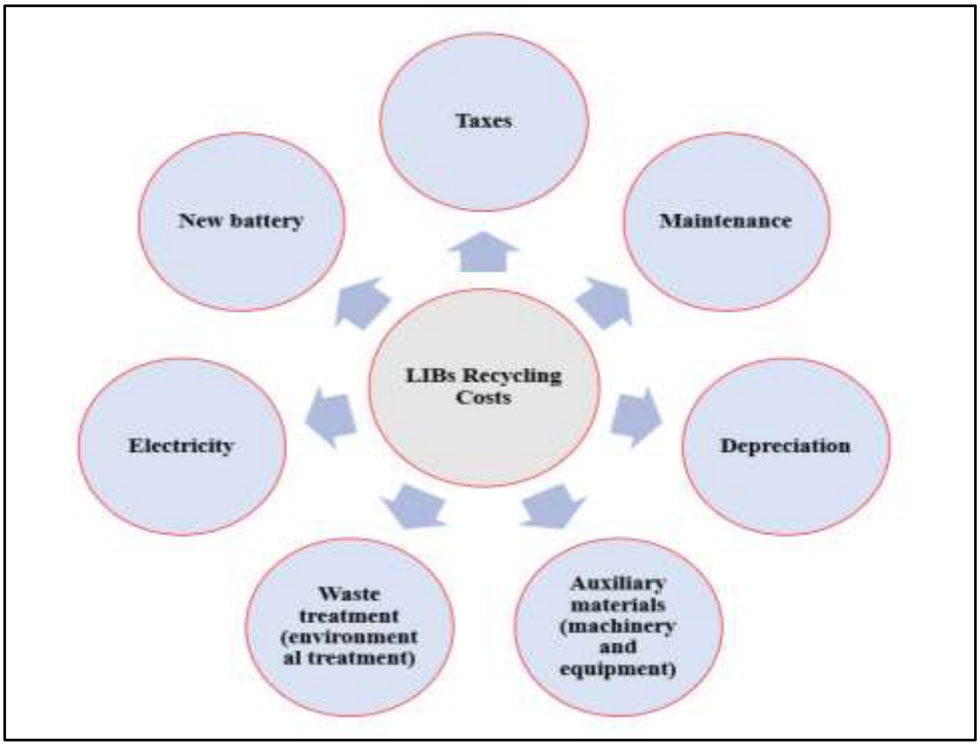


Fig.5LIBs recycling costs can be divided into the above eight factors

The value of recycling might potentially be calculated by bringing together all of the different anapestic depicted in Figure 5.Recycling costs and the weighting given to each component in the overall cost of recycling might vary depending on where the recycling facility is located, so bear this in mind. This is a key component of the total recycling price tag.In addition, according to the plant survey the existing cost of recycling lithium batteries, is now at Approx. US$26 per kWh, there is also a recycling tax of US$10 per kWh that must be paid[20-21].

IV. RECYCLING GROWTH:

In order to properly collect LIBs from electric cars, the first step is to develop efficient techniques for collecting retired ELVs. ELVs have been recycled for the recovery of critical components and resources for many years. Until 2015, 95 % of the EU's ELVs had been recycled, mostly for the purpose of recovering important metals. In the modern-day, almost every car in the United States is recycled. Approximately 86% of the vehicle is recovered or used to generate electricity throughout the recycling process[22]. Currently, the European Union's current waste reduction rules have set important goals for ELV recycling. According to the End-of-Life Vehicle Directive of the European Union, vehicle manufacturers are responsible for collecting and recycling End-of-Life Vehicles (ELVs). Prior to 2015, the maximum amount of an ELV that may be discarded in a landfill was 5 percent of its total weight. In that year, the EU produced more than eight million tons of ELVs; 80 to 100 percent of the materials collected by collection trucks were recycled or repurposed. Despite this, not every vehicle that is removed off the road is sent to recycling and recovery facilities via the standard procedures. Not all nations have attained the Directive's recycling goals[23].2007 research commissioned by the European Parliament revealed that numerous nations failed to achieve the EU's ELV collection and recycling standards. The export of ELVs to countries with less severe disposal legislation, the hiring of unlicensed operators who solely remove economically useful components, and the "garaging" or abandonment of ELVs by their owners were challenges faced throughout the collection process. Compliance was hindered not just by bureaucratic restrictions, but also by automakers' refusal to pay the expenses of take-back schemes. Japan passed the End-of-Life Vehicle Recycling Law on January 1, 2005, after it was approved in 2002 and went into force on that day. The regulation is comparable to that of

Europe, with the exception that car owners must pay a recycling fee after their vehicle has reached the end of its useful life. On September 18, 2000, this fee was mandated by Directive 2000/53/EC of the European Parliament and the Council on end-of-life vehicles (EPC)[24, 25].

The recycling of lead-acid batteries cannot be compared to the recycling of LIBs that have reached the end of their useful life. After the electrolyte solution has been drained and additional chemical processing has been performed, recycled lead may be used to make new batteries due to its high purity. Because recovered lead can be reprocessed into new batteries, recycling lead-acid batteries have a positive return on investment. When compared to U.S. recycling efforts, Europe and Asia are light years ahead of where we are right now. A large portion of this may be attributed to the European Environmental Agency's stringent environmental regulations (particularly Directive 2006/66/EU on waste batteries and accumulators and Directive 2000/53/EC on end-of-life of life vehicles) China's recycling efforts are bolstered by the economic value of recovered materials, which puts the country at the forefront of the global recycling race[26].

In 2016, the ability of the world's economies to recycle spent batteries increased to around 94,000 tones. These estimated capacities take into account the use of all electrochemical storage batteries, with the exception of lead-acid batteries. In comparison, China by alone is responsible for around 33 percent of these sites, which means that European countries only account for roughly 5 percent of this capacity. The current recycling facilities around the world can be seen Table 4.

Table 4: Current recycling facilities around the world (adopted from Energy and environmental science journal)

Company name	**Location**	**Process[a]**	**Capacity (tons of battery per year)**
Accurec Recycling	Germany	P, M	4000
Akkuser	Finland	M	1000
Aubermacher Redux	Germany	M	1000
Bangpu Ni\\& Co High Tech	China	H	3600
Batrec	Switzerland, Wimmis	P	200
Dowa Eco-system Co. Ltd	Japan	P, H	1000
Duesenfeld	Germany	M	3000
Envirostream	Australia	P	3000
Euro Dieuze	France	M, H	6000
GEM	China	H	100 000
Glencore	USA,Canada, Norway	P	7000 (Norway)
High Power International	China	P, H	10 000
Huayou Cobalt	China	H	60 000
HunanBrunp Recycling Tech	China	H	30 000
Immetco	USA	P	6000
Jiangxi Ganfeng Lithium	China	H	5000
JX Nippon Mining & Metals Corp	Japan, Tsuraga	P, H	600
KOBAR	South Korea	H	1000
LiCycle	Canada	H	2500
Nickelhutte Aue	Germany	P, H	1000
Nippon Recycle Center Corp	Japan	P	2000
Recupyl	France/Singapore	H	110/1200
SNAM	France	P, M, H	1500
SungEel Hitech	South Korea	H	8000
Sungeel Hi-tech	Hungary	M, H in South Korea	3000

Taisen Recycling	China & South Korea	H	6000
Tele Recycle	China	H	2000
TES (Recupyl)	France	M, H in Singapore	1000
Umicore	Belgium	P, H	7000
Ute Vilomara	Spain	H	> 53.32

[a] P - Pyrometallurgy, H - hydrometallurgy, M - Physical separation

V. RECYCLING REVENUE:

Making money out of the trash produced by LIBs is a possibility. The components and metals that go into making LIBs are not exactly simple to come by, but it's important that everyone have access to them anyway. Issues concerning the availability of sufficient natural resources to manufacture more LIBs surfaced initially in relation to lithium. However, cobalt deposits have become a more pressing issue in recent years. Some nations are advocating that older battery that includes a significant amount of cobalt be recycled as soon as possible in order to ensure that there is an adequate supply of this metal[27].Table 5 displays the most recent price information available from the market for the key components of LIBs.

Table 5: Current market prices of the key components of LIBs (Local market survey)

Material	**Price (USD/Ton)**
Copper	9700
Nickel	20,150
Lithium	31,000
Cobalt	61,550
Iron	91,50
Aluminium	2658
Manganese	5,46

When you In order to be ready to launch LIBs recycling business the success of this endeavor will be contingent on a variety of factors, including the manner in which the company runs. The following costs are considered part of the typical initial investment required to launch a new company[28,29]:

- Facility or the premises will cost – Rs. 75000 or $1000/month
- Drop-off per unit will cost – 80,000 to 1 Lcs. or $1000 – $1500
- Equipment will include the cost – 5Lcs. to 7 Lcs. or $6500 – $7000
- Every staff costs at least 400-500 INR or $6/ Hr. So, it would take $1000 –$1500 a week.
- Then there are utilities that you can take $1000 extra for.

Therefore, in order to keep the firm running well, it requires anywhere between 100,000 and 150,000 dollars every single month. Additionally, there are options available to you that will allow you to reduce the expenses to some degree. The next step is to seek assistance from the government in order to aid you with this welfare cause. This is possible since the government already has several programs in place. You can be eligible for subsidies from the government, and you might also have access to cheaper loans via their assistance. Therefore, before you begin the business of recycling LIBs, you should make sure that you investigate the grants that are available from the state.

Although the battery business is enormous, the recycling sector is very little, and only lead-acid batteries can be recycled economically. With the correct supply chain, nickel-based batteries can earn a profit, but Li-ion and the overwhelming majority of other chemistries create too little precious metal to make recycling a profitable business without government support. Current batteries are more costly because of the time and effort required to prepare, purify, and process them on a micro and nano scale than they are because of the raw materials they use. When it comes to new products, batteries may be an excellent source of recyclable materials.

VI. CIRCULAR SUSTAINABLE ECONOMY

An energy-efficient multi-material recovery with recovery rates of at least 95% will be the focus of the next investigation. This recovery method should be flexible enough to accommodate changes in input streams and current output needs. As a result, the requirements for future recycling methods will be as follows: they will either need to be very flexible or they will need to be focused on certain types of batteries, which will need to be sorted successfully.Furthermore, the process routes that must be constructed should be specialized in relation to the many components that must be purified, such as the electrolyte, electrode components, and active materials. In order to do this, a variety of mechanical, thermal, and chemical process phases must be used and interconnected. These methodologies must also take into account new chemical discoveries and battery materials (e.g., solid-state batteries[30,31]).

In the long run, they should replace the energy-intensive techniques that are now being used for traditional LIBs. Because of this, future recycling procedures will have a substantially less impact on the environment and will use significantly less energy.To create a circular economy for any material, it is essential to have few components, a lower cost for the secondary process (recycling) than the original process (raw material extraction), a straightforward purification flowchart, valuable components, and a collection and separation mechanism. These conditions must be met in order to develop a circular economy for any commodity[32]. It is especially useful when the item has a significant environmental impact if it is not recycled. This tends to force recycling, which is a win-win scenario for all parties concerned. In terms of the many components that need to be handled, such as the components of the electrodes, and the active materials. In order to accomplish this goal, it is necessary to employ and link various combinations of mechanical, thermal, and chemical process stages. These methods also need to be devised taking into consideration new chemical developments and battery materials (e.g., solid-state batteries).

Recycling costs might be reduced by up to 70% if electrode components are separated without being shredded, as the study's results suggest. According to a UK-US collaboration report, the majority of problems with recycling LIBs might be resolved by using reversible adhesives and binders, thorough labeling, easier solid-bulk topologies, easy-to-open structures. The experts also proposed methods for implementing such criteria. They proposed, for example, that increased manufacturer accountability and the necessity to recycle end-of-life devices may force engineers to adopt a design-for-recycling strategy. They should be able to replace the energy-intensive techniques now used for ordinary LIBs in the long run. As a consequence, future recycling processes will have a far smaller environmental impact and use much less energy.We can also enhance the In-Situ electrochemical performance of battery material during recovery by using different chemical techniques as follows.

a) Increased efficiency by investigating novel leaching agents and benchmarking the operational parameters to facilitate maximum recovery of valuable metals to make the recycling of LIB economical and viable.

b) In situ one-pot production of metal nanoparticles during recycling to improve electrochemical performance for fabrication of high-performance cathode material.

c) Furthermore, recovery of anode material and in situ conversion into graphene nanocomposites as value-added by-product remains our other goal. The research will thus enhance the circular economy of LIB production.

It will lower the cost of producing new LIBs, but it will also make recycling more profitable and practicable as depicted in Fig.6. As a result, all stakeholders will benefit, and LIBs will avoid waste and landfills, minimizing the risk of soil and water contamination.

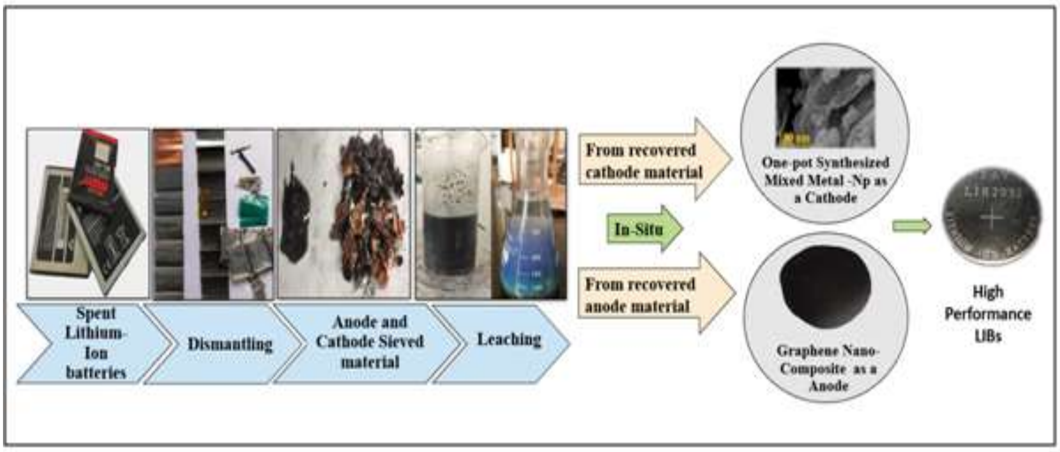


Fig.6 Fabrication of high-performance LIBs using spent LIBsrecoveredmaterial

VII. CONCLUSION:

The recycling of LIBs is a relatively new industry that will likely see a major upheaval when the technique itself is modified to solve the several issues outlined in this article. In the early phases, hydrometallurgy and pyrometallurgy are the best procedures for the recovery of metals of interest. But owing to the complexchemistries involved in LIBs and the problems associated with traceability other alternatives to hydrometallurgy require exploration on a broader scale than that of a laboratory. Enhancing the electrochemical performance of recycled materials for added value and economic advantages is another strategy.With current raw material prices and battery composition, all recycling technologies have been demonstrated to be economically feasible at high quantities. However, in order to fully achieve the economic benefits of recycling, the reverse supply chain for ELVs and LIBs must be optimized.

In order to make recycling practicable in the meantime, subsidies should be generated by taxing each sold pack. In addition to recovering metals for reuse, the objective is to prevent dangerous batteries from entering landfills. The ultimate objective is to combine environmental benefit with profit-making, and inventive new recycling techniques may make this possible. To attain this objective, LIB recycling research must be expanded. The private sector should spend heavily in the study and development of LIBs, which might result in progressively enhanced products with major direct effects on society. Sections of academia might contribute by developing novel ideas and concepts that could be commercialized in the coming decades. In the future, battery recycling and sustainable batteries should get the importance and consideration they merit.

Conflict of Interest

The authors declare no conflict of interest.

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