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Review

Sustainable Development Goals and End-of-Life Electric Vehicle Battery: Literature Review

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Abstract: With a global urgency to decrease greenhouse gas emissions, there has been an increasing demand for electric vehicles on the roads to replace vehicles that use internal combustion. Subsequently, the demand and consumption of raw materials have increased, and thus, there has been an increasing number of retired lithium-ion batteries (LIBs) that contain valuable elements. This literature review paper looks at the following: lifecycle assessments (LCA) of EV batteries, the recycling of LIBs while analyzing what studies have been conducted to improve recycling processes, what recycling facilities have been established or are being planned, studies on the circular economy, the environmental benefits of recycling end-of-life (EOL) batteries, and how LIB recycling is aligned with the Sustainable Devel opment Goals, focusing in particular on Goal 13: Climate Action.

Keywords: sustainable development goals; recycling; circular economy; life cycle assessment; environmental benefits

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1. Introduction

The Sustainable Development Goals (SDGs) published in 2015 were an achievement for putting both developing and developed countries on the path of sustainable development (United Nations General Assembly, 2015) [1]. Through these goals, the world hopes to transform itself by ensuring human well-being, economic prosperity, and environmental protection, all by 2030. Many difficult issues that affect the globe are considered and worked upon through these SDGs, which consist of 17 goals and 169 targets. However, since these SDGs are linked implicitly, two conflicting goals may hinder the entire process and result in the world deviating from the path [2].

Due to this issue, it is necessary to investigate these interrelations and links between the goals so that we may find possible points of conflict and address them, and these points of concern can be found across [3] and within the SDGs) [4]. While this may seem to be a major problem, it can be noted that this is not the first time such dependencies that cause issues have appeared in global agendas. Plans such as the Millennium Development Goals (MDGs) [5], poverty alleviation [6] and climate change adaptation and mitigation response [7], have also faced and addressed similar issues. Below in Table 1, we have listed the seventeen goals highlighted in the SDG agenda.

Table 1. List of Goals in the SDG Agenda [8].

Goals		
Goal 1: No Poverty	Goal 2: Zero Hunger	Goal 3: Good Health and Well-being
Goal 4: Quality Education	Goal 5: Gender Equality	Goal 6: Clean Water and Sanitation
Goal 7: Affordable and Clean Energy	Goal 8: Decent Work and Economic Growth	Goal 9: Industry Innovation and Infrastructure

Table 1. *Cont.*

Goals		
Goal 10: Reduce Inequalities	Goal 11: Sustainable cities and communities	Goal 12: Responsible consumption and production
Goal 13: Climate Action	Goal 14: Life Below Water	Goal 15: Life on Land
Goal 16: Peace, Justice, and Strong Institutions	Goal 17: Partnerships for Goals	

Of these seventeen goals, our focus is primarily on Goal 13: Climate Action. We will investigate how recycling the LIBs of Electric Vehicles (EVs) around the world plays a role in the progress and success of this goal. To keep the global temperature increase below 2 °C, CO_2 emissions must be reduced "by around 25% by 2030 from 2010 levels, and reach net zero by around 2070" [9]. To keep the increase in temperature below 1.5 °C, which is the more optimized and preferred target, there must be a reduction of 45% by 2030 in global human-produced net CO_2 emissions compared to the 2010 levels, to reach a net zero near 2050 [9]. Unfortunately, instead of decreasing, emissions have, in fact, increased [10].

There have been several reviews of the current literature regarding LIB recycling, like [11], who focused on recycling and its environmental impact, and [12], who primarily studied recycling technologies and used a Weighted Product Method to choose the best LIB recycling processes. [13] prepared a review using two methodologies, namely ProKnow-C and Methodi Ordinatio, to develop a bibliographic portfolio that presents the latest and best literature regarding LIB recycling. They propose a database of a finite collection of articles and reports with relevant authors to push new research forward on this theme, which is a crucial endeavor. With respect to BEV range anxiety, [14], both address concerns and propose a solution involving Peer to Peer Car Charging (P2C2), which allows EVs to share charge while in motion. Through observations of simulations of this P2C2 solution, they found significant improvement in EV mobility. Furthermore, ref. [15], prepare a literature review of the current and potential charging infrastructures, addressing various strategies in their present use as well as future possibilities.

The purpose of this article is to provide a literature review on battery recycling by considering its evolution and impact on sustainable development. Academic and industrial readers will find it convenient to consider papers and models that we examined and investigated on lifecycle assessments of EV batteries, recycling processes, circular economies, and environmental benefits with an analysis of how the reduction of GHG emissions through battery recycling could enhance the attainment of Goal 13 (climate change) of the SDGs.

2. Research Methodology

This research study was conducted in two stages. Firstly, the key phrases "Recycling Lithium-Ion batteries" and "literature review" were used in the title, abstract, and keywords to undertake the search for articles. These keywords were used in the Google-scholar search engine and Scopus. Searches were performed for LIB recycling, then for the circular economy, and finally for the Sustainable Development Goals; all the articles were then analyzed for relevancy. Secondly, this process was repeated for the years 2020, 2021, and 2022 to make sure articles and reports were as recent as possible. A total of 357 articles were searched for and collected, and after a meticulous assessment of each, 164 were chosen to be analyzed and discussed in this review. To accurately investigate LIB recycling, recycling processes, the circular economy, and the Sustainable Development Goals, this is a valid number of articles, papers, and reports to examine. Table 2 below summarizes the research methodology and presents the remainder of this work where every row of the table denotes a future section of the manuscript. For example, row three or Section 3 relates to the Sustainable Development Goals (SDGs), Section 4 is about the Life Cycle Assessment, Section 5 covers recycling processes, Section 6 addresses the circular economy, and Section 7 presents environmental benefits, and then, finally, related discussions are reported.

Table 2. Number of Articles in each Section.

Section Number	No of Articles
1.0 Introduction	15
3.0 Sustainable Development Goals	15
4.0 Life Cycle Assessment	13
5.0 Recycling Processes 17 Pyrometallurgical 14 Hydrometallurgical 21 Special Recycling 8 Direct Recycling 12 Metallurgical and Mechanical 7	79
6.0 Circular Economy	27
7.0 Environmental Benefits	8
8.0 Discussions	6
Total	163

Figure 1 below reveals the number of papers reviewed per year from 1990 to 2023.

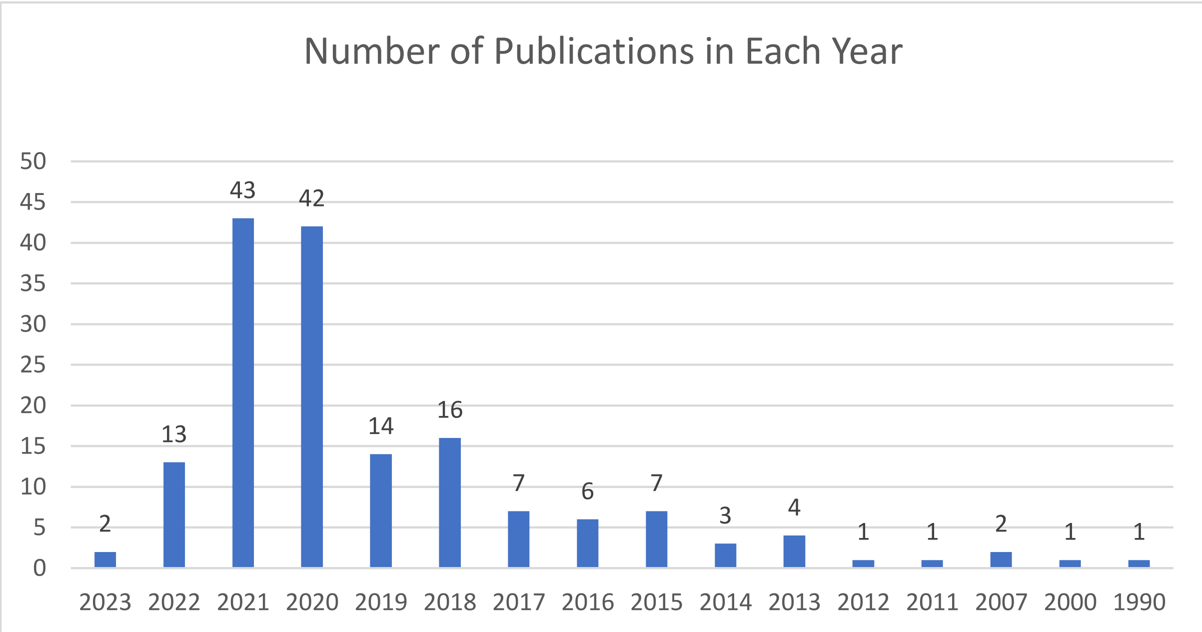

Figure 1. Number Per Year of Reviewed Publications.

3. Sustainable Development Goals (SDG)

In 2000, the Millennium Development Goals were agreed upon by the United Nations to guide global development. These goals were to be achieved by 2015 [16]. The Sustainable Development Goals (SDGs) were a collection of 17 topics and a total of 169 targets agreed upon by the United Nation General Assembly [1]. They were the succession of the Millennium Development Goals. While the former ran from 2000 to 2015, the latter focused on the years 2015 to 2030. However, the difference of the SDGs was to push a shift in the global development paradigm towards more economic, social, and environmental sustainability. With five cores (5P) of the people, planet, prosperity, peace, and partnership, the SDGs have jumpstarted many national actions, and provided many visions for the future. Table 3 summarizes the papers reviewed in this research work.

Table 3. Sustainable Development Goals by Author and Year.

Author	Year	Remarks
Bose and Khan	2022 [17]	The study examined how far the SDGs have progressed, as per testimony from companies across the globe; it also investigated how testimony regarding SDGs changes when considering national institutional factors.
Pereira et al.	2022 [18]	The editorial team investigated the effects of the Russian-Ukrainian conflict on the SDGs relating to Biophysical, Social, and Economic values, as well as how they affected national partnerships.
Business Line	2021 [19]	This article suggested that any sustainable development strategy to fight climate change (according to SDG 13: Climate Change) must be supported by a reduction in emissions from transportations; thus, adopting cleaner options.
Belmonte et al.	2021 [20]	This study focused on four areas highly relevant to sustainable development and finding a balance between ecological and economic systems with respect to development: the circular economy, degrowth, green growth, and research specifically addressing the SDGs.
Zwiers et al.	2020 [21]	This paper identified the required knowledge that allows for circular economical thinking and practices for sustainable development.
Hernandez et al.	2020 [22]	The study used an innovation systems approach to develop a roadmap for solar and wind energy to predict and improve the effects of a transition to a low carbon future in a manner ensuring that climate goals and the SDGs are mutually reinforced.
Tremblay et al.	2020 [23]	Considering people, planet, prosperity, peace, and partnership (5P), this paper presents the categorization of the Sustainable Development Goals and their objectives with the aim to offer a better perception of relationships for possible collaborations related the 5P categorization.
Feijoo et al.	2020 [24]	A systemic literature review featuring the Sustainable Development Goals and business schools is presented in this paper with emphasis on the role these schools can play to favor the implementation and adoption of these goals.
UNDP	2020 [25]	This report assessed the effect of various COVID-19 recovery situations on the SDGs, looking at the impact of the pandemic for the next 10 years (UNDP and the Pardee Center for International Futures at the University of Denver)
Vinuesa et al.	2020 [26]	This paper demonstrated that the use of consensus-based artificial intelligence can result in the completion of 134 targets of the SDGs but may slow progress of fifty-nine other targets.
Schroeder et al.	2019 [27]	This paper identified how relevant circular economical practices are for the progress of the SDGs.
Allen et al.	2018 [28]	This paper provided a literature review for national efforts and experiences for progression of the SDGs in twenty-six countries by thoroughly investigating how the countries are considering and progressing through the key stages of SDG implementation provided by the literature.
Stafford-Smith et al.	2017 [29]	This study determined that significant attention is required across the connections between each of the industry sectors, societal actors, and countries of ranging economic prosperity.

While there have been numerous setbacks from difficult circumstances, ranging from global to national in scale, we noticed a consistent drive for progress. Many countries wish to adopt frameworks and execute plans that touch multiple goals from the SGDs, such as the circular economy and stimulation of the electric vehicle market. The magnitude of progress fluctuates over the years, so the literature on our advancements toward sustainability will increase continuously.

4. Life Cycle Assessment

Ref. [30] claim that using EV batteries in stationary applications would be environmentally beneficial when considering their life cycle. These said batteries still have roughly 80% of the capacity they come with, which makes them good for reuse in applications with a lower energy demand [31]. Table 4 below presents the papers reviewed in this research work. Below that, in Figure 2, we present a Lifecycle assessment for LIBs.

Table 4. Life Cycle Assessment of LIBs by Author and Year.

Author	Year	Remarks
Koroma et al.	2022 [32]	This study conducted an LCA for three contexts considering future changes in EV charging, battery efficiency fade and refurbishment, and recycling by determining their significance on battery life cycles and performance.
Shafique and Luo	2022 [33]	This paper investigated the impacts on the environment caused by the production, transportation, and other EV phases; it found that China's EVs had the high est impact when compared to other EVs, considering the 2019 and 2025 electricity mix scenarios.
Yang et al.	2021 [34]	This study used an LCA to find the CO_2 emissions from vehicle production, use, and EOL.
Sun et al.	2020 [35]	This paper showed that, for a LIB's lifecycle, the highest energy demand and global warming potential come from its material preparation, wrought aluminum, and electrolytes.
Qiao et al.	2019 [36]	This paper showed that in 2015, the life cycle GHG emissions of an EV came out to be 41.0 t of CO_2-eq, which was 18% lower than ICE vehicles.
Bicer and Dincer	2018 [37]	The study conducted an in-depth comparison of ICE vehicles, hybrid electric vehicles, and EVs, with regards to environmental impact, by employing a process based LCA to analyze raw material extraction to vehicle disposal.
Burchart-Korol et al.	2018 [38]	This paper focused on EVs in Poland and the Czech Republic, conducting an LCA about electricity production for charging batteries; it considered systems from 2015 to projected systems in 2050 to be used to charge EVs.
Wu et al.	2018 [39]	This study conducted an LCA to quantify the GHG emissions from EVs and ICE vehicles across their lifecycles in 2010, 2014, and 2020 under various contexts; it found that there is potential for such GHGs to be reduced by adopting EVs as the main mode of transport, as their life cycle showed lower emissions than ICE vehicles.
Kim et al.	2016 [40]	This paper assessed the emissions across the life cycle of a particular battery in an EV, namely, the LIB in the Ford Focus. It considered energy materials' input and other data collected from the battery cell and pack supplier, and it concluded that the GHG emissions for these 24 kWh LIBs are 3.4 tons of CO_2-eq across its lifespan, which translates to 140 kg per kWh or 11 kg per kg of the battery.
Tagliaferri et al.	2016 [41]	This study conducted an LCA on a European LIB powered EV and compared it to an ICE vehicle; it showed that the GHG emissions for the former were half that of the latter during their use phases.

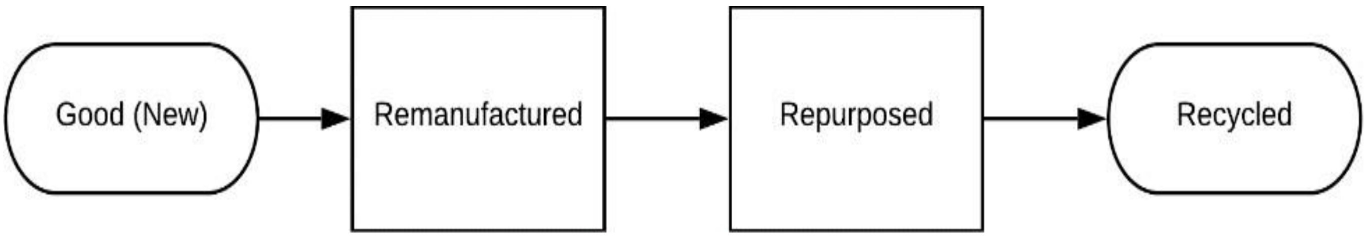

Figure 2. LIB's Lifecycle State [42].

5. Recycling Processes

Although recycling techniques are typically utilized in industry, there is still considerable work being done on an experimental and laboratory scales to improve recycling operations, profit, and energy efficiency [43]. Table 5 below lists the worldwide facilities for recycling LIBs as per [35,44–57]. The remainder of this section covers the LIB recycling steps and the various recycling processes.

5.1. Recycling Steps

The steps for the industrialized recycling for EV LIBs, as shown in Figure 3, usually consist of collection, sorting, handling, elimination, and distribution, which allow for significant material recovery [58].

Table 5. Lithium-Ion Battery Recycling Facilities Worldwide.

Company	Country	Process	Volume (tons/year)	Status
Recycling by using the Pyrometallurgical/Hydrometallurgical process				
Accurec	Germany	Pyro/hydro	4000	In Operation
Akkure	Finland	Pyro/hydro	4000	In Operation
Umicore Valeas	Belgium	Pyro/hydro	7000	In Operation
Brunnp Recycling Technologies	China	Pyro/hydro	10,000	In Operation
JX Nippon Mining	Japan	Pyro/hydro combo	5000	In Operation
Glencore	Switzerland	Pyro/hydro combo	3000	In Operation
Total			33,000	
Recycling by using the Pyrometallurgical process				
Inmetco	US	Pyrometallurgical	6000	In Operation
Quzhou Huayo	China	Pyrometallurgical	40,000	In Operation
Validi	France	Pyrometallurgical	20,000	In Operation
Sony/Sumitomo	Japan	Pyrometallurgical	150	In Operation
Inmetco	US	Pyrometallurgical	6000	In Operation
Quzhou Huayou	China	Pyrometallurgical	40,000	In Operation
Dowa Eco-System	Japan	Pyrometallurgical	6500	In Operation
Total			118,650	
Recycling by using the hydrometallurgical process				
Recupyl	France	Hydrometallurgical	110	In Operation
Redux	Germany, Austria	Hydrometallurgical	50,000	In Operation
Retriev (Toxco)	Canada	Hydrometallurgical	4500	In Operation
GEM	China	Hydrometallurgical	30,000	In Operation
Li-Cycle	US	Hydrometallurgical	5000	In Operation
Li-Cycle	Canada	Hydrometallurgical	5000	In Operation
Taisen	China	Hydrometallurgical	6000	In Operation
Li-Cycle	Gilbert, AZ, US	Hydrometallurgical	10,000	Planned
Li-Cycle	Tuscaloosa, AL, US	Hydrometallurgical	10,000	Planned
Fenix	UK	Hydrometallurgical	10,000	Planned
Total			130,610	
Recycling by using the preprocessing process				
Envirostream	Australia	Preprocessing	3000	In Operation
Guanghua Sci-Tech	China	Preprocessing	12,000	In Operation
Total			15,000	
ABT	US	Unknown	20,000	Planned
Northvolt	Norway	Unknown	8000	Planned
Fortum	Finland	Unknown	Unknown	Planned
Green Li-ion	Singapore	Unknown	Unknown	Planned
Gotion High-Tech	China	Unknown	Unknown	Planned
Tesla	China	Unknown	Unknown	Planned
Posco Hy Clean Metal	Korea	Unknown	12,000	Planned

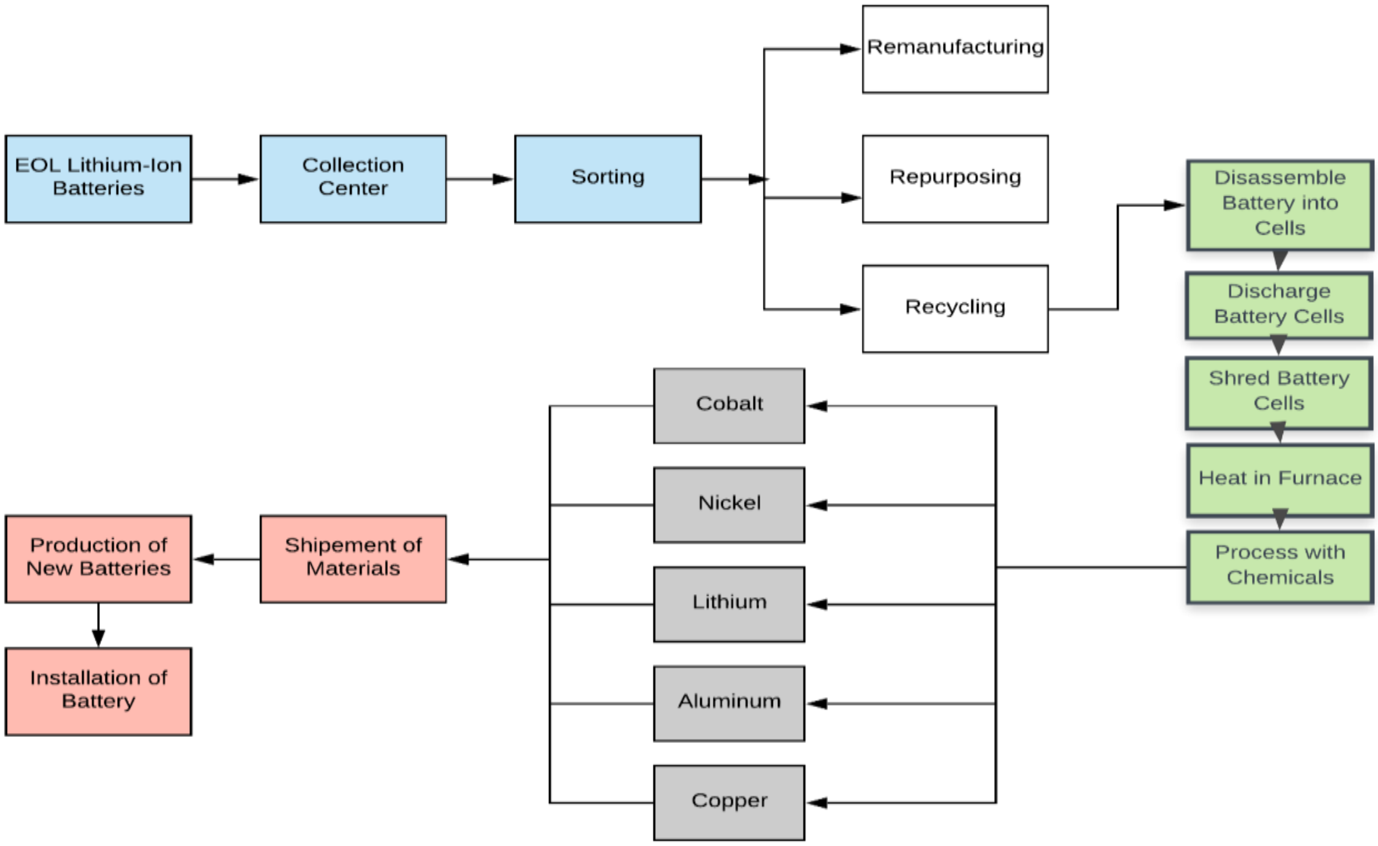

Figure 3. LIBs recycling [59].

5.2. Pyrometallurgical Process

Pyrometallurgy is a widely used process to recover various metals (precious metals and base metals) from electronic waste. This process encompasses smelting, incineration, and high-temperature roasting [60]. A single-shaft furnace is employed in the pyrometallurgical process where the batteries are brought apart and placed into the furnace by gradually increasing the temperature from 300–700 °C to 1200–1450 °C. Given this heat, the electrolyte is faded/evaporated, the plastic is pyrolyzed and the other materials are melted down [61,62]. The outcome of this process results in a mix of copper, cobalt, nickel, lithium, iron, and rare earth elements [61,63].

From the pyrometallurgical process, cobalt, copper, and "nickel alloys (metallic phase) or matte (Sulfidic phase)", aluminum, manganese, lithium "slag (oxidic phase)", and flying ash, are produced [64–66]. Another process, hydrometallurgy, is used to separate these mixed materials and recover the individual metals: cobalt, lithium, manganese, nickel, and graphite [65,66]. Table 6 summarizes the papers reviewed and related to the pyrometallurgical process.

Table 6. Pyrometallurgical Process by Author and Year.

Author	Year	Remarks
Makuza et al.	2021 [67]	With the aim to recycle EOL LIBs, this article presented an overview of possible pyrometallurgical methods. The article outlined various methods to salvage the active cathode materials.
Holzer et al.	2021 [68]	This paper investigated at an elevated temperature the behavior of the cathode materials to identify lithium cobalt oxide ($LiCoO_2$) and lithium iron phosphate ($LiFePO_4$) from LIB with a carbon addition.

Table 6. *Cont.*

Author	Year	Remarks
Hu et al.	2021 [69]	This paper provided information about the salvaging of Co, Ni, Mn, and Li through the use of a pilot-scale Electric Arc Furnace.
Assefi et al.	2020 [64]	This brief article review discussed the available pyrometallurgical methods for recycling rechargeable batteries including "Lithium-ion, Nickel-Cadmium and Nickel-Metal-Hydride batteries".
Sommerfeld et al.	2020 [70]	This paper addressed an appropriate design to enrich slag by lithium and blended cobalt, nickel, and copper alloy "as intermediate products in a laboratory electric arc furnace".
Arshad et al.	2020 [71]	This paper summarized the recent progress of recycling anode, cathode, and electrolyte materials of LIBs. Through laboratory experimentation and industrial study, the paper focuses on the recovery of anode and electrolyte.
Pinegar and Smith	2019 [72]	Metallurgic treatment of LIB modules and cells were addressed in this review with a focus on the excessive costs of managing organic and halogenic parts in the metallurgic process route.
Chen et al.	2018 [73]	In their research work to salvage valuable metals from the cathode active powder, the authors proposed a thermal treatment-ammoniacal leaching process.

5.3. Special Recycling Process

A mechanochemical recycling process, used for retired LIB cathode materials (C and $LiCoO_2$), and waste polyvinyl chloride (PVC) was examined by [74]. With a combination of grinding and leaching techniques, they found a viable recovery of raw materials, as well as a high potential for an environmental and economic impact. Table 7 presents a summary for the papers reviewed for such special recycling processes.

Table 7. Special Recycling Process by Author and Year.

Author	Year	Remarks
Chen et al.	2020 [75]	This research studied the pyrolysis characteristics of main biomass components (i.e., cellulose, lignin) in the presence of the EOL LIB cathodes enriched in transition-metals (e.g., Ni, Co). The battery cathode with a good thermostability could be used as a catalyst for biomass conversion.
Cognet et al.	2020 [76]	Inspired by an open-loop method that limits the amount of waste while manufacturing a high volume of valuable materials, this manuscript proposed such an approach for recycling LIBs.
Pindar et al.	2020 [77]	This report showed the effectiveness of metal extraction from the cathodes of EOL LIBs via microwave processes. The report presents a comparative study about microwave reduction of (pure and mixed) cathode materials.
Norgren et al.	2020 [78]	This article discussed and proposed improvements for recycling (design for recycling) principles based on a review of published industrial and academic best practices, alongside a consultation with experts in the field.
Sommerville et al.	2020 [79]	Separation methods employed in EV LIBs recycling are addressed in this review article with a focus on physical methods that are applied before starting chemical treatment and purification.
Silvestri et al.	2020 [80]	This paper discussed the first life cycle assessment (LCA) for nickel–metal hydride (NiMH) batteries, which considers production and recycling processes.
Mohr et al.	2020 [81]	This paper parametrized process models of optimized pyrometallurgical and hydrometallurgical recycling for LIBs, showing the possibilities for use beyond just LIB cell chemistries.

5.4. Direct Recycling Process

This process comprises physical and chemical steps, with battery separation completed at low energies and temperatures. Thus, ref. [82] determine that this would be more cost effective than leaching due to a lower material requirement. They also note that direct recycling is not widely used across the industry currently, and published processes from recycling companies are scarce [83]. Table 8 summarizes the papers reviewed regarding direct recycling processes.

Table 8. Direct Recycling Process by Author and Year.

Author	Year	Remarks
Anthony et al.	2022 [84]	This paper evaluated the process of thermal re-lithiation applied to end-of-life cathode materials.
Park et al.	2021 [85]	This paper demonstrated oxidation-reduction mediators could deliver lithium ions and electrons from a lithium source to the cathode to "relithiate" the EOL cathode materials, making them (after a post heat treatment) ready for new battery fabrication.
Li et al.	2021 [86]	This paper used the Taguchi Design of the Experiment method to study the efficiency of material recovery from cathodes of LIBs. Moreover, a regression model was presented to find the output and help with parameter selection.
Wu et al.	2021 [87]	A method considering aclosed-loop LIB cathode regeneration chain with high atomic utilization was introduced in this research work where energy consumption is minimized.
Folayan et al.	2021 [88]	This paper demonstrated a satisfactory separation of a "95% grade or higher of NMC111 in the froth product and 95% grade of LMO in the tailing product" when using separation methods with multiple phases.
Sloop et al.	2020 [89]	Considering a case study, this research work showed, in an industrial model, the cathode-healing™ method for recycling lithium-ion found in both consumer electronic and EV batteries.
Ross et al.	2020 [90]	A method using leftover LiOH·H2O to have a chemical reaction with fluorine can, prevent lithium elimination, and fix the cathode material. The paper also demonstrated that a thermal process can both eliminate the binder and add lithium to the cathode.
Xu et al.	2020 [91]	This paper reported "an efficient and environmentally friendly LIB material recovery method based on deflect-targeted healing, which" is a very different perspective for LIB recycling.
Garole et al.	2020 [92]	The paper summarized the strategies used to recover materials from EOL LIBs and spent catalysts.
Larouche et al.	2020 [82]	This review paper investigated various approaches/alternatives pyrometallurgy method, namely leaching or direct recycling methods.
Song et al.	2017 [93]	This paper proposed "a direct regeneration of cathode materials from spent $LiFePO_4$ batteries using a solid phase sintering method".

5.5. Hydrometallurgical Process

Leaching and purification used in the hydrometallurgical method have been found effective in recovering precious metals from electronic waste [94].

There have been many changes and additions to hydrometallurgical processes and techniques to recycle active materials of cathodes made of different chemistries of LIBs such as Lithium Cobalt Dioxide (LCO), Lithium Manganese Dioxide (LMO), Lithium Nickel Manganese Cobalt Oxide, (NMC), Lithium Nickel Cobalt Aluminum Oxide (NCA), and Lithium Iron Phosphate (LFP) [95], to salvage valuable metals, specifically cobalt, nickel, manganese, and lithium [96,97]. Any hydrometallurgical technique involves physical and chemical steps through liquid processing, thus resulting in a high material recovery [98–100]. The key benefits of hydrometallurgical processes are the decreased energy requirement under lower temperatures, the significant recovery of lithium in the carbonate form, the leaching of metals for use in new LIBs cathodes, and s efficiency on a variety of battery chemistries [101]. Table 9 presents a summary of the papers reviewed for hydrometallurgical processes.

Table 9. Hydrometallurgical Process by Author and Year.

Author	Year	Remarks
Vieceli et al.	2021 [102]	This paper assessed the consequences of incineration on the leaching yield of metals. Leaching efficiency of metals from EV LIBs (Mn, Ni, Co, and Li), was optimized at lower incineration temperatures of 400–500 °C and extended leaching times. This manner could be linked to the partial carbothermic reduction of the metals.
He et al.	2021 [98]	They summarized current technologies used in the recovery of electrode materials derived from EOL LIBs. In addition, an alternative recycling flowchart of EOL LIBs was proposed.
Kader et al.	2021 [103]	This paper discussed combined pre-treatment and hydrometallurgical processes as prospective mechanisms with a focus on the recovery value and benefits regarding the economy and environment.
Asadi et al.	2021 [104]	This paper investigated the main aspects of spent LIBs' recycling (environmental and economic) and determined the effectiveness of hydrometallurgical processes to retrieve valuable metals.
Djoudi et al.	2021 [99]	This study focused on the recovery of cobalt from LIB leachate in hydroxide form. At 25 °C, the thermodynamic simulations confirmed the possibility of recovering 99.8% of cobalt (II) hydroxide.
Verma et al.	2021 [105]	To recover and separate Li and Co from $LiCoO_2$, this paper developed a closed-loop process based on oxalate.
Cerrillo-Gonzalez et al.	2020 [100]	To process the battery waste, this research work identified a method coined combined hydrometallurgical-electro dialytic.
Chitre et al.	2020 [106]	This paper focused on improvements to the hydrometallurgical processes used to extract materials from LIBs by sorting the batteries and using alternative water-soluble binders. The paper recommended a holistic design approach for LIBs that enables end-of-life recyclability.
Anwani et al.	2020 [107]	This study focused on obtaining a purity of 90.13% of lithium cobalt oxide, thus, determining that battery fabrication is possible.
Zhou et al.	2020 [108]	This paper reviewed the most recent developments of the technologies to recover materials from EOL LIBs. They also described the challenges and future economic and application prospects.
Wang et al.	2020 [109]	This paper summarized the most up to date technologies to recycle $LiNixCoyMnzO_2$ and $LiFePO_4$-based LIBs regarding pre-treatment, hydrometallurgical recycling, and direct regeneration of the cathode materials.
Cerrillo-Gonzalez et al.	2020 [110]	This paper presented experimental results for the hydrometallurgical treatment of $LiCoO_2$ cathodes recovered from LIBs. A physicochemical model is shown to improve the knowledge of the leaching process and identify its limitations.
Chan et al.	2020 [111]	This study focused on the development and optimization of efficient hydrometallurgical processes to recycle EV LIBs, using systematic experimental and theoretical approaches based on the design of experiment methodology.
Lv et al.	2018 [56]	This work focused on hydrometallurgical processes and a summary of current LIB recycling and recycling processes are provided.
Takacova et al.	2016 [112]	This paper analyzed how the extraction of cobalt and lithium affects the internal structure of the active mass composed primarily of $LiCoO_2$. In addition, the paper shows that the cobalt extraction depends on the extraction of lithium from the $LiCoO_2$ structure.
Chen et al.	2015 [96]	This study considered a hydrometallurgical method to recapture high values of nickel, manganese, cobalt, and lithium from waste cathode materials, using a leaching solution of sulfuric acid.
Joulié, et al.	2014 [113]	This study presented a metals recovery process based on hydrometallurgy. The emphasis is on the cathode materials of spent LIBs, where the efficiency rate of salvaging valuable metals reached 100% for cobalt and 99.99% for nickel.

Table 9. *Cont.*

Author	Year	Remarks
Meshram et al.	2014 [114]	This paper considered a pre-treatment process of EOL LIBs. Leaching solutions consisting of various acids were applied to the cathode materials. Next, a separation process of lithium and other metals from the leach solutions followed.
Sun and Qiu	2011 [115]	To salvage cobalt and lithium from spent LIBs, this research work proposed a novel approach consisting of vacuum pyrolysis and a hydrometallurgical method.

5.6. Metallurgical and Mechanical Processes

EOL LIBs can also be treated via mechanical techniques. First, they are broken down into incredibly fine pieces and are then categorized by their physical properties. From here, typical outputs are aluminum/copper, non-ferrous metals, and ferrous metals, which can be treated with other metallurgical processes, and a material called black mass, which can be treated through pyrometallurgy or hydrometallurgy. If the latter is performed, organic components must be removed via thermal processes [65,116]. "Employing pyrometallurgical method, cobalt, copper, and nickel alloys (metallic phase) or matte (sulfidic phase), aluminum, manganese, and lithium slag (oxidic phase), and flying ash are produced" [64,65,67]. "These elements can be further processed by hydrometallurgical methods to recuperate the individual metals". In hydrometallurgy, cobalt, lithium, manganese, nickel, and graphite can be recovered [65,117]. Table 10 summarizes the reviewed papers on metallurgical and mechanical processes.

Table 10. Metallurgical and Mechanical Processes by Author and Year.

Author	Year	Remarks
Munir et al.	2020 [118]	The application of bio-producible/degradable ascorbic acid for the leaching of $LiNixCoyMnzO_2$ (LNCM) cathode batteries was investigated while performing parametric variations. This study showed that using a biodegradable reagent instead of hazardous materials would be effective for sustainable metallurgy.
Brückner et al.	2020 [65]	This review article investigated the progress achieved in the metallurgical treatment of lithium-ion battery modules and cells.
Porvali et al.	2019 [119]	LIB waste by mechanical and hydrometallurgical techniques in a hydrochloric acid solution.
Yun et al.	2018 [120]	This review article summarized the two foremost and fundamental aspects of recycling battery-packs' mechanical methods, and chemical salvaging (metallurgical) methods. Accordingly, it is necessary to have a process/method that can be semi-automatic to fully automatic to warrant the quicker, more accurate dismantling of battery packs, and identify and detect residual energy in battery packs, as well as recuperate valuable materials from batteries.
Li et al.	2018 [121]	To explain the kinetics of the leaching process, the authors proposed a novel formulation inspired from the shrinking-core model. Considering the leaching of Li, Co, Ni, and Mn, the initial energy per metal was found to be 66.86, 86.57, 49.46, and 45.23 kJ mol−1, respectively. Their findings confirm that the leaching process is a controlled chemical reaction.
Xiao et al.	2017 [122]	"This study suggested an integrated method to oversee bulk spent lithium manganese ($LiMn_2O_4$) batteries to locally recycle high value-added products" without any additional materials.

6. Circular Economy

According to several authors [115,123,124], the notion of a circular economy was first proposed by [125] and it has been increasing in popularity since the 1970s. [126] The report by Pearce and Turner investigated economic systems, especially their linearity and open-endedness by looking at how natural resources are used in production and consumption as inputs, as well as how they end up as waste as output. Figure 4 shows how a circular economy would connect its processes, namely, material input, design, production, consumption, and recycling. When considering recycling as a product's end-of-life, it allows us to close the loop by using the materials from the output as new materials for input [127].

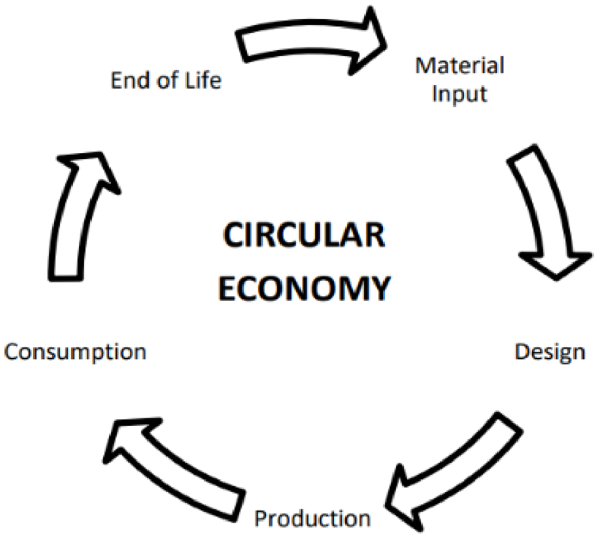

Figure 4. The Circular Economy [127].

Ref. [128] published a Canadian report with respect to reverse logistics whose purpose was to find the best places to establish battery dismantling recycling facilities, as well as calculate the economic and environmental impacts of such infrastructure. Their results indicated that the average costs of recycled raw materials are 1.29 CAD per kg of spent battery pack, and carbon intensity is 0.7 kg CO_2-eq per kg of spent battery pack. As per the Paris Agreement targets [129], a main driver for their completion is establishing a circular supply chain for electric vehicle batteries. Valuable materials such as cobalt, nickel, copper, lithium, and aluminum can be recovered via LIB recycling, as shown in Figure 5.

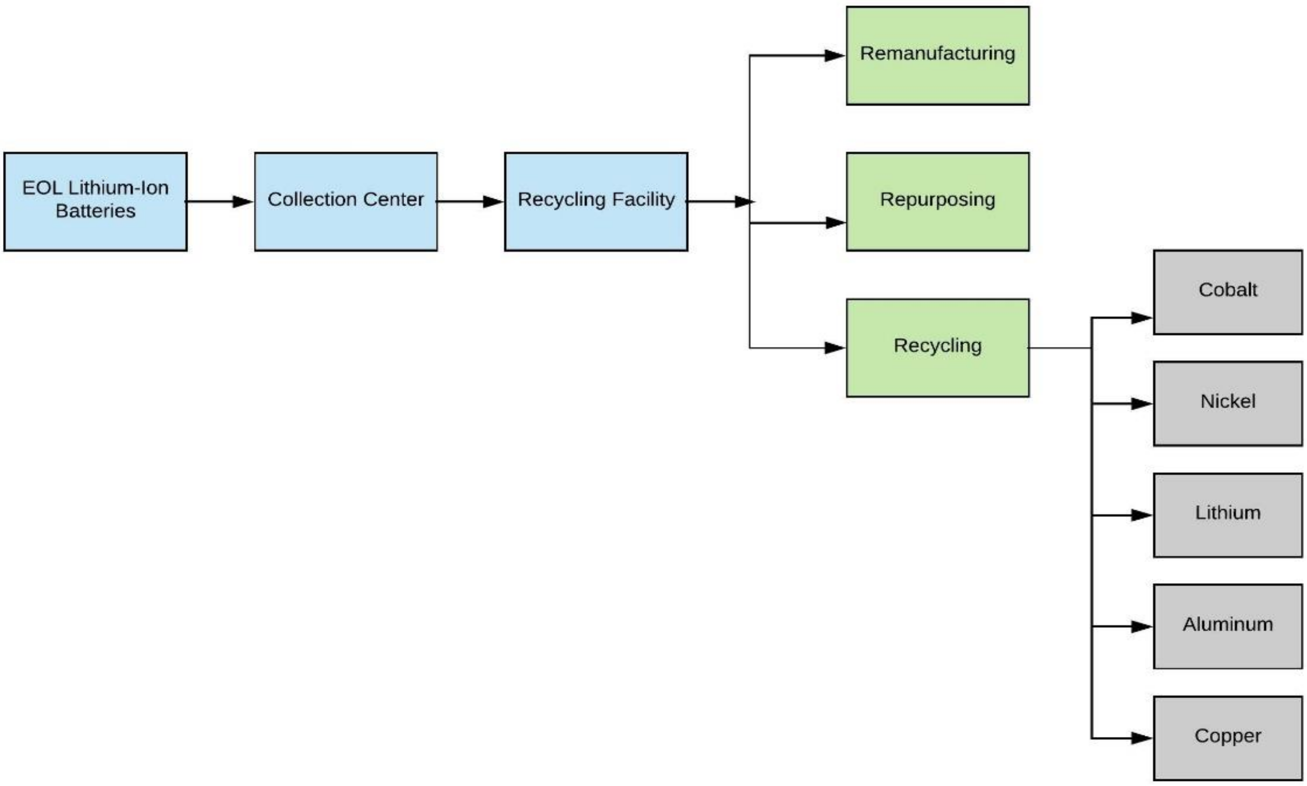

Figure 5. Assets Recovery [**127**].

Table 11 summarizes the research work pertaining to the circular economy.

Table 11. Circular Economy by Author and Year.

Author	Year	Remarks
Trang and Li	2023 [130]	This paper presented the literature review of a reverse supply chain for end-of-life vehicles.
Shafique et al.	2021 [131]	This paper calculated that by efficient recycling methods, by 2030 there would be around 5–7 kilotons of recovered lithium, 35–60 kilotons of recovered nickel in China alone, as well as 2.3–2.6 kilotons of recovered lithium and 16–26 kilotons of nickel recovered in the US.
Meegoda et al.	2022 [132]	This paper suggested improvements to EOL LIB management in the US, considering current and emerging recycling technologies, current collection, transportation, reuse applications, and regulatory policies in place.
Shafique and Luo	2022 [33]	This paper presented a life cycle analysis of electric vehicles across ten countries using present and future electricity mix scenarios.
Akram and Abdul-Kader	2021 [133]	This paper provided information about hydrogen production and the worldwide entities that are adopting green hydrogen. Moreover, the authors evaluated the benefits of fuel cell EVs on the environment in the case of using hydrogen generated by considering the surplus renewable energy in Canada.
Fujita et al.	2021 [134]	The authors presented guidelines on the 3R of LIBs and methods to decrease the usage of valuable materials and the number of EOL LIBs, by salvaging and "remanufacturing used parts and designing new batteries considering the concepts of 3R".
Szałatkiewicz et al.	2013 [60]	The authors addressed various recycling methods that are currently available in the world (with particular attention, in Canada), by focusing on the Canadian job market for disposing spent LIBs.
Baars et al.	2021 [135]	This paper described strategies to limit the extraction of raw materials, such as cobalt reserves.
Kotak et al.	2021 [136]	This paper investigated the reuse and recycling of LIBs, with a focus on the discussion of whether to reuse the batteries or recycle them after their first use.
Curtis et al.	2021 [137]	This report analyzes "drivers, barriers, and enablers to circular economy for LIBs used in United States mobile and stationary applications".
Akram and Abdul-Kader	2021 [138]	This research work examined the effects of recycling spent LIBs on the environment and the economy: reduced emissions through recycling and values of recoverable materials from the LIBs.
Kouhizadeh et al.	2021 [139]	This paper analyzes the implementation of a circular economy, technology such as a blockchain may be helpful. One of the biggest issues in initiating a circular economy is the absence of collaboration between manufacturers and end-of-life product managers. Blockchain technology can improve collaboration while decreasing supply chain barriers.
Albertsen et al.	2021 [140]	This report mentions circular business model canvases, like repair, refurbishing, repurposing, and recycling strategies.
Akram and Abdul-Kader	2021 [42]	This paper calculated that an LIB could work for 12.5 years in an EV. It becomes available for recycling 22.5 years after its use in an Electric Vehicles and in a stationary application.
Fan et al.	2020 [141]	This paper analyzed the EV battery market competition, with a focus on the economy, environment, and policy. They then propose a 4H method to recycle batteries to optimize efficiency, safety, economic return, and environmental benefits.
Ahuja et al.	2020 [142]	This paper described the current issues to a sustainable value chain for LIBs, while making the case that interventions at the legislative and judicial level are required to steer the market in this direction.
Sehnem et al.	2019 [143]	This paper focused on a major factor required for the successful adoption of a circular economy using focal companies selected from both emerging and mature economies, namely Brazil and Scotland, respectively.
Giampietro	2019 [144]	This paper clarified the term circular bioeconomy, clearing misunderstandings around its definitions and interpretations.
Oriekhova	2019 [145]	This paper presented the primary factors of a circular economy: the possibility of a Fourth Industrial Revolution, circular value chains based on recycled waste, leadership within a circular economy, and cooperation.
Kirchherr et al.	2018 [146]	This paper focused on barriers for companies and legislators possible in a circular economy, such as hesitancy within staff and missing consumer awareness and/or interest.
Korhonen et al.	2018 [147]	This paper focused on contributing to the scientific research on the circular economy.
Geisendorf and Pietrulla	2017 [148]	This paper proposed a revised definition of the "circular economy" after assessing and comparing the related concepts tied most closely to it.

7. Environmental Benefits

There are immense costs, energy, and environmental deficits (GHG emissions) to producing items with raw extracted resources. As such, there are equally significant benefits for remanufacturing, repurposing, and recycling, as they cut down on all three of the aforementioned metrics [43,149]. All the tasks that occur when a LIB is to be remanufactured, repurposed, or recycled (via reverse logistics) are shown below in Figure 6, a process flow chart.

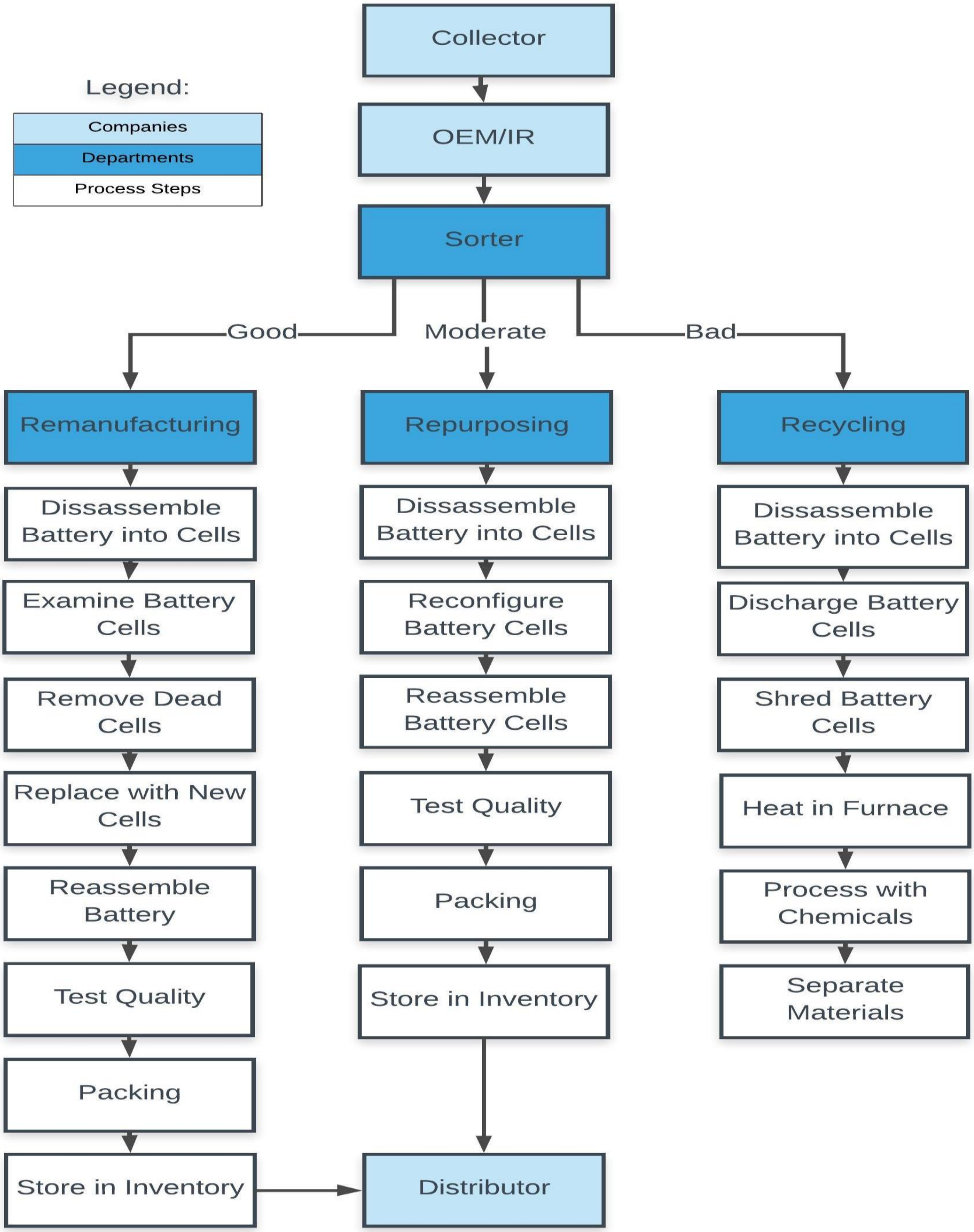

Figure 6. RL Process Flow of End-of-Life LIB [138].

Table 12 summarizes the papers reviewed that talk about environmental benefits.

Table 12. Environmental Benefits by Author and Year.

Author	Year	Remarks
Asokan et al.	2023 [150]	This paper found the emissions generated from three different recycling processes, and it concluded that the net CO_2-eq emissions of the pyrometallurgical treatment for lead acid batteries, hydrometallurgical treatment for LIBs, and pyrometallurgical for LIBs was 29.4, 31.7, and 43.3 kg per kWh, respectively.
Akram and Abdul-Kader	2021 [143]	This paper investigated "the environmental and economic effects of recycling end of-life (EOL) LIBs entering the future market by finding the emissions mitigated through recycling and the values of materials recoverable from LIBs".
Rajaeifar et al.	2021 [151]	The study analyzed three pyrometallurgical technologies and determined that adopting a process known as direct current plasma smelting, coupled with a pre-treatment phase, could reduce emissions by five-fold when compared to our current processes.
Mrozik et al.	2021 [152]	This paper discussed the diverse ways an EOL LIB can cause pollution, such as disposal and careless processing, and it provided evidence for how such practices can pollute the soil, water, and air.
Mohr et al.	2020 [82]	This paper pointed out a potential concern for our current recycling processes, namely, that achieving the highest material recovery from a battery may not be the most environmentally beneficial; it mentioned that for there to be both, we would need to adapt our processes for various cell chemistries.
Xiong et al.	2020 [153]	This paper evaluated the environmental benefit while remanufacturing lithium-nickel-manganese-cobalt oxide battery cells, and it determined that there is an 8.55% decrease in energy consumption and a 6.62% decrease in GHG emissions; it also considered the economic benefits, concluding that battery remanufacturing allows for cost savings of $1.87 per kg of cells produced.
Qiao et al.	2019 [36]	This study viewed "the economic and environmental benefits of EV recycling in China." It found "that the gross income per recycled EV is about $473.90, and energy consumption and greenhouse gas emissions were reduced by about 25.6 GJ and 4.1 t CO_2eq, respectively. Also, the environmental benefits per technology cost are about 241.3 MJ per dollar and 36.3 kg CO_2eq per dollar".
Tang et al.	2019 [154]	This paper investigated the impacts of recycling retired EV batteries at social, economic, and environmental levels while considering a Stackelberg game theoretical model using reward–penalty mechanisms.
Rahman et al.	2017 [155]	This paper investigated the quantity of active materials that can be recovered through a hydrometallurgical process; its results showed that 41% of cathode material and 48.8% of its price, as well as 8.5% of anode materials and 23.4% of its price, can be recovered; furthermore, they found that a figure of 52.85% of GHG emissions from battery material extraction, manufacturing, transportation, etc., can be controlled through recycling batteries.
Dunn et al.	2015 [156]	This research work proposed answers to three questions in the current discussion of the environmental impacts of LIBs whether there is a higher energy demand for material production versus battery assembly. The paper discussed the differences of facilities and how they impact the environment, for whether it is worthwhile to recycle batteries, it said that while energy consumption is high for assembling batteries from recycled materials, other environmental motivators take precedence. Finally, they found that EVs do, in fact, emit less GHGs when compared to ICE vehicles, which can be further improved via battery recycling.

8. Discussion

In the industry, two processes are extensively employed: pyrometallurgy and hydrometallurgy, which when correctly used together are incredibly efficient at recycling materials, particularly black mass, which can reach almost 100%. Specifically, through pyrometallurgy, cobalt, copper, and nickel are retrieved, and through hydrometallurgy, lithium, manganese, and further cobalt and nickel can be retrieved [65,157].

Various studies take into consideration the flow of materials from recyclable batteries and economic value chains across years. In Catalonia, Spain, under strict climate change laws, an increase of twenty-five times the number of batteries in 2030, and an increase of seventy-two times in 2040 are expected. An increase of up to 80% of cobalt, nickel, and copper, and 60% of lithium are projected in potential supply from secondary materials received from EOL batteries. As such, it is highly encouraging to put optimal management strategies in place as soon as possible to keep material recovery as efficient as possible [158]. A study in Brazil by [159], addressed how in 2030, the number of new electric vehicles in the market could exceed 1.8 million, which results in a demand of 8700, 15,000, 46,000, 15,000 and 92,000 tons of lithium, cobalt, nickel, manganese, and graphite, respectively. In addition, the number of EOL batteries would exceed 340,000 but the amount of raw material truly recovered is heavily dependent on the strategy employed to manage the input and output of batteries to/from recycling facilities. Thus, we consider the flow of materials through the phases of an EV battery, and a substance flow analysis done by [160] does so. They first determined that by 2040, 72–78 million electric vehicles would be present in Europe, whereas the number of batteries in their second use would number 3–11 million. In the same year 2040, the recycling waste flow would increase to around three million batteries with the total capacity being 125 GWh. Regarding the future, the authors concluded that the waste stream could substitute 10–300% of the demand for raw materials for electric vehicles.

The recovery of materials present in electric vehicle batteries offers a great benefit for countries wishing to partake in environmental goals. As mentioned earlier in Table 1, goal thirteen of the Sustainable Development Goals (Climate Action) discusses the reduction of emissions of CO_2 and other greenhouse gases. We can see that through battery recycling, environmental detriments associated with extracting raw materials and their transportation can be significantly reduced. It is shown in a study analyzing hydrometallurgical processes, a net saving of 1 kg of CO_2-eq per kg of EOL battery can be achieved [161]. Furthermore, even if we set a lower bound that says 30% of EOL batteries are to be recycled, a study by [162], showed that in China alone, 4.3 million tons of CO_2 emissions can be reduced by 2030. Additional research is still required to select the most efficient pyrometallurgical processes to optimally decrease CO_2 emissions [151].

The economic benefits achievable from battery recycling are also incredibly high. A study by [104], considered 500,000 tons of recyclable batteries from 2019, and determined that through correct recycling procedures, 15,000, 35,000, 45,000, 60,000, 75,000, and 90,000 tons of aluminum, phosphorus, copper, cobalt, lithium, and iron could be recovered, respectively.

9. Future Work

We now discuss various areas currently requiring additional study. A Life Cycle Assessment model for EOL batteries can be done with consideration to electric vehicle markets at the local (national) and global scales. Some developing countries have fewer opportunities for recycling management, so optimal route selection has yet to be researched. Battery storage systems constructed from cells from EOL LIBs are a growing concept, and they should be analyzed further to determine maximal economic benefits. Currently, it is not cost-effective for electric vehicle manufacturers to put recycling procedures in place, so an assessment of the level of government subsidies and assistance packages is still necessary. The applications and effects of blockchain technologies on EOL batteries' waste streams have yet to be discussed. Finally, new business models with consideration to reverse logistics may result in more efficient material returns to manufacturers, so in-depth research can be done.

10. Conclusions

With many countries striving for improvements in environmental policies, the demand for electric vehicles over internal combustion engine vehicles has been increasing. It follows, nonetheless, that the demand for electric vehicle batteries and their raw materials has seen an upwards trend. With many batteries reaching their end-of-life, it is equally imperative for environmental policies to recycle them to recover their valuable materials for reuse. We investigate the current most widely used recycling processes globally, as discussed in Section 8. Furthermore, an analysis of these various recycling processes of current recycling facilities worldwide was conducted, and the total annual recycling amounts for each process were calculated. After studying the various articles in the current literature, we found that there exist significant economic and environmental benefits of recycling batteries as opposed to discarding them at their EOL. Although various literature reviews have been published with respect to battery recycling, our review differs by focusing on the Sustainable Development Goals, specifically, Goal 13: Climate Action.

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