Aalto-yliopisto
Aalto-universitetet
Aalto University

Bachelor's Programme in Chemical Engineering

Recycling of Lithium Iron Phosphate (LFP) Batteries

Martin Kella

Bachelor's thesis 2025

Aalto-yliopisto
Aalto-universitetet
Aalto University

Author Martin Kella

Title of thesis Recycling of Lithium Iron Phosphate (LFP) Batteries

Programme Bachelor's Programme in Chemical Engineering

Major Chemical Engineering and Processes

Thesis supervisor D.Sc. Jari Aromaa

Thesis advisor(s) D.Sc. Mehrdad Hesampour, D.Sc. Jari Aromaa

Collaborative partner Kemira Oyj

Date 16.5.2025 **Number of pages** 38 **Language** English

Abstract

The use of lithium iron phosphate (LFP) batteries has increased considerably in electric vehicles, due to their safety, thermal stability, and cost-effectiveness of the battery. There is a paramount of importance to recycling as these batteries reach to the end of their service life. This bachelor's thesis is a literature review that investigates the recycling of LFP batteries, focusing specifically on the processes of pre-treatment, pyrometallurgy and hydrometallurgy. In addition, this thesis reviews the economic feasibility of the battery and the environmental issues that arise during recycling.

Pre-treatment processes such as discharging, dismantling, shredding, and material separation play a crucial role in ensuring safety, minimizing material loss, and facilitating the recovery of valuable metals. Pyrometallurgy offers a relatively simple and established method for recycling but is associated with the loss of lithium. In contrast, hydrometallurgy enables the efficient recovery of lithium and other metals through leaching, solvent extraction, precipitation, and ion exchange methods. Although these processes are often more complex and may involve hazardous chemicals, they typically produce fewer greenhouse gas emissions and allow more selective material recovery.

Economically, the recycling of LFP batteries is challenging due to the absence of high-value metals such as cobalt and nickel. Nevertheless, lithium and other components can make the process viable when appropriate methods and technologies are used. Environmental considerations are also critical. Pyrometallurgical processes tend to have a higher carbon and sulfur dioxide footprint, while hydrometallurgical processes generate chemical waste but can be more energy efficient.

Emerging technologies such as direct recycling, bioleaching, and microwave-assisted pyrolysis are also explored. These approaches show promise in enhancing cost-efficiency and reducing the environmental footprint. Direct recycling, for instance, aims to restore battery components to a virgin state with minimal energy and chemical input. While still in development, these innovations may improve the overall sustainability of battery recycling.

The findings of this literature review emphasize that efficient and environmentally conscious recycling of LFP batteries is essential for achieving circular economy goals and ensuring long-term sustainability in the battery industry. Further research and development are required to optimize current recycling methods and to advance new technologies for broader industrial implementation.

Keywords Lithium iron phosphate battery, battery recycling, pyrometallurgy, hydrometallurgy, pre-treatment processes

Aalto-yliopisto
Aalto-universitetet
Aalto University

Tekijä Martin Kella

Työn nimi Kirjallisuuskatsaus Litium-rautafosfaattiakkujen kierrätyksestä

Koulutusohjelma Kemian tekniikan kandidaattiohjelma

Pääaine Kemiantekniikka ja prosessit

Vastuuopettaja/valvoja TkT Jari Aromaa

Työn ohjaaja(t) TkT Mehrdad Hesampour, TkT Jari Aromaa

Yhteistyötaho Kemira Oyj

Päivämäärä 16.5.2025 **Sivumäärä** 38 **Kieli** Englanti

Tiivistelmä

Litium-rautafosfaattiakkujen (LFP, *lithium iron phosphate*) käyttö sähköautoissa on lisääntynyt huomattavasti akkujen turvallisuuden, tasapainon sekä kustannustehokkuuden ansiosta. Akkujen käyttöiän päättyessä niiden kierrätys nousee keskeiseksi kysymykseksi niin materiaalien uudelleenkäytön kuin ympäristönsuojelun kannalta. Tämä kandidaatintyö on kirjallisuuskatsaus, jossa tarkastellaan litium-rautafosfaattiakkujen kierrätystä erityisesti ensikäsittelyn, pyrometallurgian sekä hydrometallurgian näkökulmista. Lisäksi kirjallisuuskatsauksessa käydään läpi myös akun kierrätyksen taloudellista kannattavuutta, siihen liittyviä ympäristöongelmia sekä uusia, kehitteillä olevia kierrätysmenetelmiä.

Esikäsittelyprosessit, kuten purkaminen, materiaalien erottelu ja murskaus ovat keskeisiä kierrätyksen onnistumiselle. Esikäsittelyvaiheessa pyritään varmistamaan turvallisuus, minimoimaan materiaalihäviöt sekä helpottamaan arvometallien talteenottoa. Pyrometallurgia on laajasti käytetty menetelmä, joka tarjoaa nopean ja yksinkertaisen tavan kierrättää akkuja. Kuitenkin pyrometallurgian menetelmät johtavat usein arvokkaiden materiaalien, kuten litiumin menetykseen. Hydrometallurgia puolestaan mahdollistaa arvometallien, erityisesti litiumin tehokkaamman talteenoton. Hydrometallurgiset prosessit ovat yleisesti monimutkaisempia sekä voivat vaatia vaarallisten kemiallisten aineiden käyttöä.

LFP-akkujen kierrätys on taloudellisesti haastavaa, koska ne eivät sisällä arvokkaita metalleja, kuten kobolttia tai nikkeliä. Litiumin, koboltin ja nikkelin kaltaiset arvometallit tekevät akkuteollisuudessa kierrättämisestä kannattavaa. Tällä hetkellä kierrätyksen suurimmat kompastuskivet johtuvat kierrätyskustannuksista. Energian ja kemikaalien käyttö sekä jätevedenkäsittely kasvattavat kokonaiskuluja merkittävästi. Ympäristönäkökulmasta pyrometallurgiset prosessit aiheuttavat merkittäviä hiilidioksidi- ja rikkioksidipäästöjä korkean energiankulutuksen seurauksena, mikä kasvattaa niiden ilmastovaikutusta ja happamoitumisriskiä. Hydrometallurgia puolestaan kuluttaa vähemmän energiaa ja tuottaa vähemmän kasvihuonekaasupäästöjä, mutta aiheuttaa kemikaalipohjaisia ympäristöriskejä.

Suora kierrätys ja bioliuotus ovat esimerkkejä tulevaisuuden teknologioista, joiden kehityksellä voi olla merkittävä rooli kierrätysprosessien parantamisessa. Näiden uusien menetelmien odotetaan parantavan kierrätyksen kustannustehokkuutta ja pienentävän ympäristöjalanjälkeä. Erityisesti suora kierrätys voisi mahdollistaa akkumateriaalien palauttamisen käyttökelpoiseen tilaan vähäisemmällä kemikaalien käytöllä ja energiankulutuksella.

LFP-akkujen kierrätyksen tulokset korostavat sen merkitystä kiertotalouden ja kestävän kehityksen tavoitteiden saavuttamisessa. Tehokkaan ja ympäristöystävällisen kierrätyksen varmistamiseksi on tarpeen lisätä tutkimusta prosessien optimoinnista sekä uusien teknologioiden kehittämisestä ja käyttöönotosta. LFP-akkujen kierrätyksen edistäminen tukee siirtymistä kohti vähäpäästöistä ja resurssitehokasta yhteiskuntaa.

Avainsanat Litium-rautafosfaattiakku, akkukierrätys, pyrometallurgia, hydrometallurgia, esikäsittelyprosessit

Preface and acknowledgements

First and foremost, I would like to express my sincere gratitude supervisor D. Sc Jari Aromaa, and my thesis advisor D. Sc Mehrdad Hesampour for their invaluable guidance and continuous support throughout the thesis process. Jari's and Mehrdad's helpful feedback, encouraging discussions, and critical insight have greatly contributed to the quality and direction of this work.

I would also like to thank my family and friends for their encouragement and patience during the writing process. Their support has been essential to the successful completion of this thesis.

Otaniemi, 16 May 2025

Martin Kella

Table of contents

Preface and acknowledgements 5
1 Introduction 7
2 LFP Battery 8
2.1 Electrochemical Reactions 11
2.2 Anode Materials 12
2.3 Cathode Materials 12
3 Recycling Methods 14
3.1 Pre-treatment Processes 15
3.2 Pyrometallurgical Processes 17
3.3 Hydrometallurgical Processes 19
3.3.1 Leaching 19
3.3.2 Solvent extraction 20
3.3.3 Deep eutectic solvents 21
3.3.4 Ion exchange resins 22
3.3.5 Precipitation 23
4 Economic and Environmental Aspects 24
4.1 Economical aspect 24
4.2 Environmental challenges 25
5 Technological Advancements 29
5.1 Pyrometallurgy 29
5.2 Hydrometallurgy 30
5.3 Direct recycling 30
6 Conclusions 32
References 33

1 Introduction

Lithium-ion batteries are used in electric vehicles as their main power unit. As electric vehicles gain popularity, their demand and production are projected to skyrocket in the near future. For example, in 2022 there were 26 million electric cars on the road, and 2023, there were 40 million, increasing sales of cars by 14 million in one year. Alone in China, there are almost 22 million electric cars (International Energy Agency, 2024).

When increasingly more batteries come to the end of the product lifecycle, recycling becomes highly important. Materials and metals used in batteries are limited and scarce, and the world is moving closer to zero greenhouse gas emissions. Acknowledging that recycling has become increasingly complex is the key to improvement with products containing dozens or hundreds of different metals and materials. As society tries to curb climate change, factors such as energy consumption, waste generation, and resource recovery rates are worth investigating. Different cathode materials can be used in batteries, where lithium iron phosphate ($LiFePO_4$) or in short LFP being one of more popular cathode materials. Finding the best solution for more effective, economically, and environmentally friendly recycling of lithium iron phosphate batteries could help to be more sustainable in the future.

Other applications that use lithium iron phosphate batteries are energy storage systems, which plays a critical role in achieving sustainable development goals. LFP is low cost to produce due to not using nickel or cobalt and has a long lifecycle, which makes it an attractive solution. However, LFP has downsides concerning its low energy density due to a very low vibration density and compaction density (Wang et al., 2022).

This bachelor's thesis is a literature review, for which purpose is to explore more about the recycling processes of LFP batteries. Chapter 2 focuses on the materials used in LFP battery, while also analysing the performance of LFP batteries in terms of cycle life, thermal stability, and energy density. Chapter 3 reviews pre-treatment processes, pyrometallurgy and hydrometallurgy iron, copper, and aluminium. Chapter 4 investigates economic and environmental aspects of different recycling methods. Finally, chapter 5 explores possible upcoming technological advancements in recycling of LFP.

2 LFP Battery

Lithium iron phosphate is one of the several chemistries used in lithium-ion batteries. The demand and interest in lithium-ion batteries (LIB) are rapidly increasing among the different chemistries. The increase of electrical vehicles reflects their growing market share. As illustrated in Figure 1, LFP has the biggest demand and holds a significant position among global LIB chemistries. The battery market share of LFP is expected to more than double between 2025 and 2030 (Rostami et al., 2024).

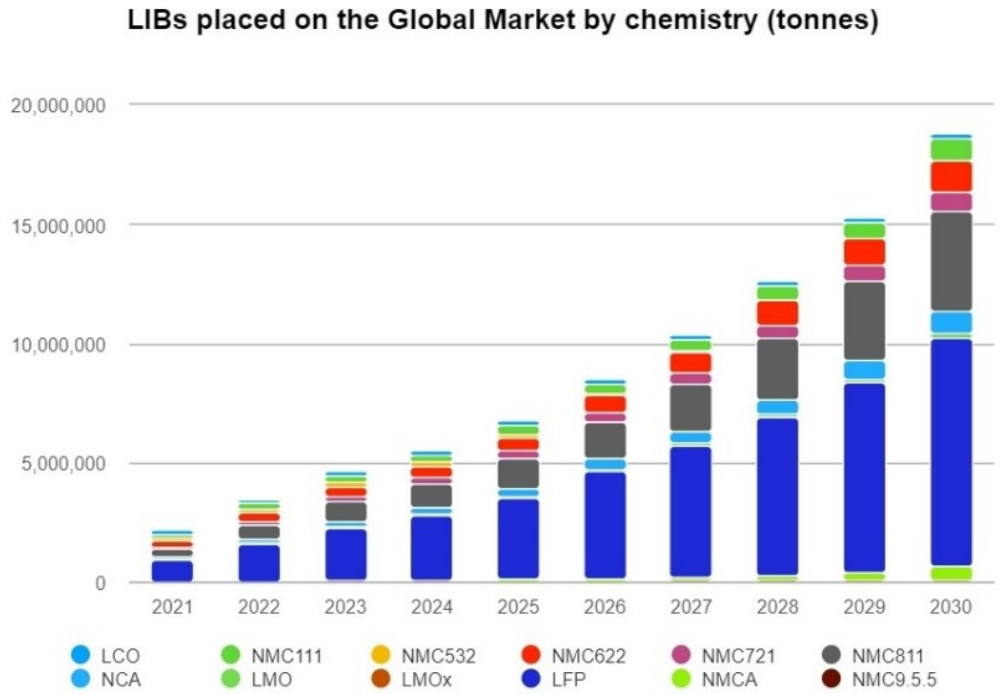

Figure 1. The rise of Lithium-ion batteries in tonnes with different chemistries (Rostami et al., 2024).

All lithium-ion batteries share the same structural composition, consisting of shell, cathode electrode, anode electrode, separator, and electrolyte. However, the differences between battery chemistries emerge mainly in the selection of cathode material. In Figure 2 the internal structure of an LFP battery is illustrated. The cathode is composed of lithium iron phosphate, which is coated with aluminium foil. Similarly, the anode consists of graphite and is coated with copper foil (M. Wang et al., 2022).

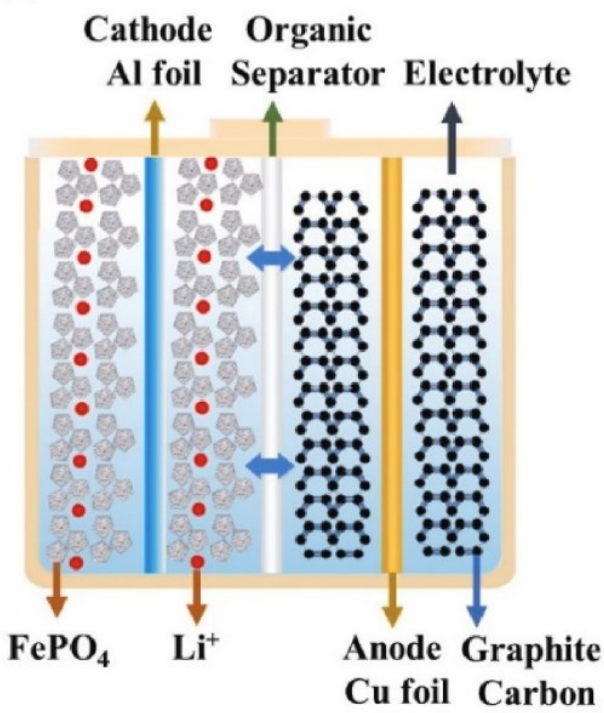

Figure 2. Internal structure of a LFP battery (M. Wang et al., 2022)

While working at the University of Texas in 1990s, research team led by A. K. Padhi under the supervision of John B. Goodenough, demonstrated that lithium ions could undergo reversible insertion and extraction from the olivine structure of LFP. This electrochemical reaction occurred at approximately of 3.5 V vs lithium metal reference electrode. The significance of Padhi's research helped the widespread adoption of LFP, with longer longevity and cost efficiency. Furthermore, making LFP a promising alternative to traditional transition metal oxides, such as $LiCoO_2$ used in a rechargeable lithium-ion batteries (Padhi et al., 1997). Today, lithium iron phosphate batteries are used extensively in electric vehicles.

LFP is a part of olivine-type phosphate belonging to the orthorhombic system. In Figure 3 phosphorus is in the centre of the tetrahedron, and lithium and iron are both surrounded by the six nearest oxygen atoms. A stable framework is composed of PO_4 tetrahedra, LiO_6 octahedra, and FeO_6. Between O, P and Fe atoms there are strong covalent bonds, which make the structure durable and stable. Low electronic conductivity (10^{-7}–10^{-9} S/cm) and slow lithium-ion diffusion (10^{-16}–10^{-14} cm²/s) can be explained by the separation of FeO_6 octahedra by PO_4 octahedra resulting in poor rate performance. Subsequently, poor rate performance can lead to capacity loss over extended cycles. (Ren et al., 2023)

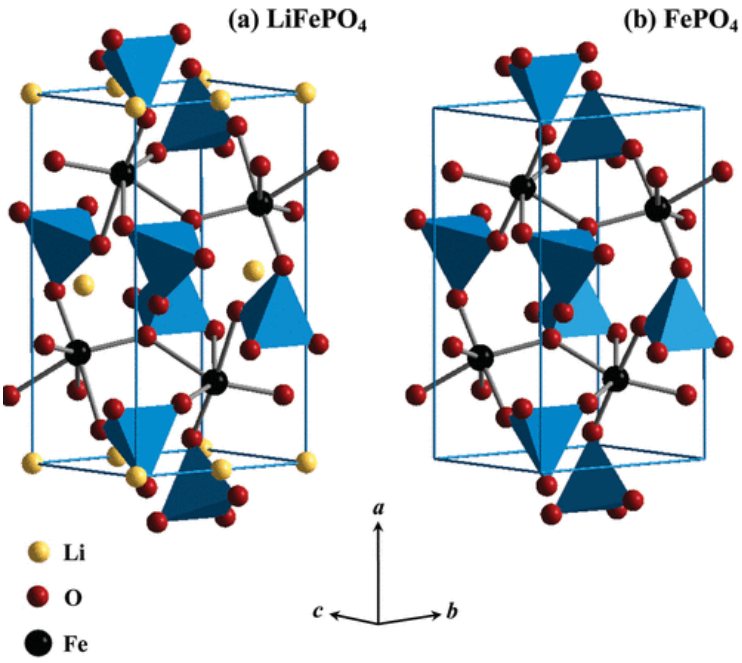

Figure 2. Crystal structure of $LiFePO_4$ and $FePO_4$ (Castro et al., 2010).

Despite the structural stability and electrochemistry of LFP battery, other key performance characteristics such as thermal resistance and safety behaviour are worth examining when discussing battery suitability for electric vehicles. Researchers constantly study and investigate battery behaviour under various stress conditions to determine most effective and efficient cathode materials.

Golubkow et al. (2014) conducted an experiment on "thermal-runaway experiments on consumer Li-ion batteries with metal-oxide and olivine-type cathodes", where the research team investigated the thermal and safety characteristics of three different types of commercially available 18650 consumer cells of lithium-ion batteries (Golubkow et al., 2014). Component amounts in the LFP battery may differ slightly from manufacturer to another. Yet, this Golubkow's experiment provides perspective on difference of composition between the batteries. In Figure 4 battery components of LCO/NMC, NMC and LFP batteries are listed. Typically, in lithium-ion batteries the cathode active material, housing, and anode active material contribute the most of battery's mass. When comparing LCO/NMC, LFP and NMC battery chemistries, LFP has by far the best safety and longest cycle life (~2000) compared to LCO/NMC or NMC batteries. Furthermore, the materials used in LFP are abundant and nontoxic to the environment. LFP batteries have low energy storage (theoretical specific capacity (~170 Ah/kg), low conductivity and inferior cold weather performance. In comparison LCO has 300 cycle life and

theoretical specific capacity of 274 Ah/kg. NMC has 800 cycle life and theoretical specific capacity of 270–285 Ah/kg. In 2020 LFP batteries accounted only 2% world market. On the other hand, in China 90% of new busses are equipped with LFP batteries. (Vasconcelos et al., 2023).

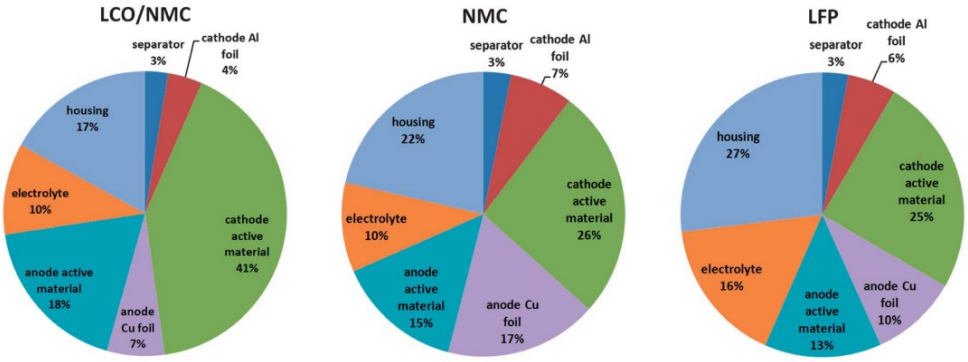

Figure 4. Main components of the three cell species based on mass split (m%) (Golubkow et al., 2014)

2.1 Electrochemical Reactions

In an LFP battery, the charge-discharge happens in two phases:$LiFePO_4$ and $FePO_4$. When charging $FePO_4$ is formed by gradually separating lithium ions from $LiFePO_4$. During discharging $LiFePO_4$ is formed by embedding lithium ions to $FePO_4$.

During the charging of LFP battery, lithium ions enter electrolyte under the action of an electric field force from the lithium iron phosphate crystal surface. Upon entering the electrolyte, lithium ions migrate to the crystal surface of graphite and finally embedding in the graphite lattice. While this is happening, electrons from the aluminium foil collector at the positive pole flow through the conductor. Electrons then move to the copper foil collector at the negative pole by passing through the external circuit. Electrical energy is generated as electrons flow through the external circuit (C. Wang et al., 2022). This process can be described with the following equation.

$$LiFePO_4 - xLi^+ - xe^- \rightarrow xFePO_4 + (1+x)LiFePO_4 \qquad (1)$$

When the LFP battery is discharged, the process is reversed. Lithium ions leave the graphite crystal and enter the electrolyte. Lithium ions move through separator before reaching crystal surface and re-embedding themselves into lithium iron phosphate lattice. Electrical energy is generated by the movement of electrons through the conductor to the copper foil at the

negative foil. Ions move through the electrical circuit and reach the anode of lithium iron phosphate, so that the charge at the anode reaches equilibrium and the conversion to lithium iron phosphate is completed. This conversation equation is shown below (C. Wang et al., 2022).

$$FePO_4 + xLi^+ + xe^- xLiFePO_4 + (1-x)FePO_4 \quad (2)$$

2.2 Anode Materials

The anode is a major component of lithium-ion batteries and plays a crucial role in the intercalation and deintercalation of lithium ions during charging and discharging cycles with the assistance of electrolyte. In general, graphite with coated copper foil has been used as an anode material for commercially available batteries. In the future the theoretical capacity of graphite (372 mAh/g) will not be sufficient for high-performance lithium-ion batteries. Other possible anode materials for lithium-ion batteries include alloy-based, silicon-based, and carbon-based materials. However, these are still under development and represent emerging technologies (Nzereogu et al., 2022).

One favourable characteristic of graphite is its low density (2.26 g cm^{-3}), which reduces the weight of the battery pack. In addition, graphite is non-toxic and cost-effective. Limitations of graphite include reduced lithium storage capacity performance at low temperature, with a practical capacity of 300-320 mAh/g compared to the theoretical limit of 372 mAh/g. Another drawback is the irreversible loss of lithium during the initial cycle. To mitigate this drawback, additional lithium is added to the anode, which increases the weight and cost of the battery (Yang, 2020; Bhushan, 2017).

2.3 Cathode Materials

The cathode material is also one of the most important components of lithium-ion batteries. The cathode determines several performance characteristics of lithium-ion batteries, including cycle life, energy density and voltage.

Various types of cathode materials for lithium-ion batteries have been developed and each offering a slightly different performance profile. Commercially used cathode materials include lithium cobalt oxide (LCO), lithium iron phosphate (LFP), lithium manganese oxide spinels (LMO), and lithium nickel oxides (LNO). LMO offers low cost and good electrochemical

performance. Both LCO and LNO have high structural stability. However, LCO contains toxic cobalt and LNO is difficult to produce (Mekonnen, Sundararajan and Sarwat, 2016).

LFP is known for its long cycle life, low cost, and high safety, but its low voltage (3.2 V) may restrict its use in high-performance lithium-ion applications. The safety of LFP batteries comes from the cathode lithiation process, which follows a two-phase mechanism. During charge and discharge the two-phased lithiation process supports the stable voltage of LFP. One way to increase the performance of cathode material is by applying carbon coating. LFP batteries with carbon coatings have shown improved capacity retention, discharge capacity and rate capability (Vasconcelos et al., 2023).

Typically, lithium-ion cathodes are composed of lithium metal oxides coated onto aluminium foil. To bond cathode active material and aluminium foil, polyvinylidene fluoride (PVDF) is usually used.

PVDF not only prevents the cathode material from detaching but also increases chemical resistance against electrolyte solvents. It also improves electronic conductivity by evenly dispersing carbon additives (Vasconcelos et al., 2023).

3 Recycling Methods

The popularity and rise of LFP batteries over the years have led to an increasing need for efficient recycling, especially in recovering valuable metals such as lithium, iron, copper, and aluminium. Various recycling methods exist. However, lack of nickel or cobalt in LFP batteries affects the choice of recycling strategies and makes recycling financially less attractive. The primary methods for efficiently recover materials from LFP batteries include pre-treatment processes, pyrometallurgy, hydrometallurgy and direct recycling. These recycling methods each have distinct advantages and limitations. The flowsheet in Figure 5 illustrates several pathways through which LFP batteries can be recycled. First, spent LFP batteries go through a pre-treatment phase. The appropriate route after pre-treatment depends on the desired outcome, considering factors such as material recovery efficiency, economic feasibility, and environmental impact.

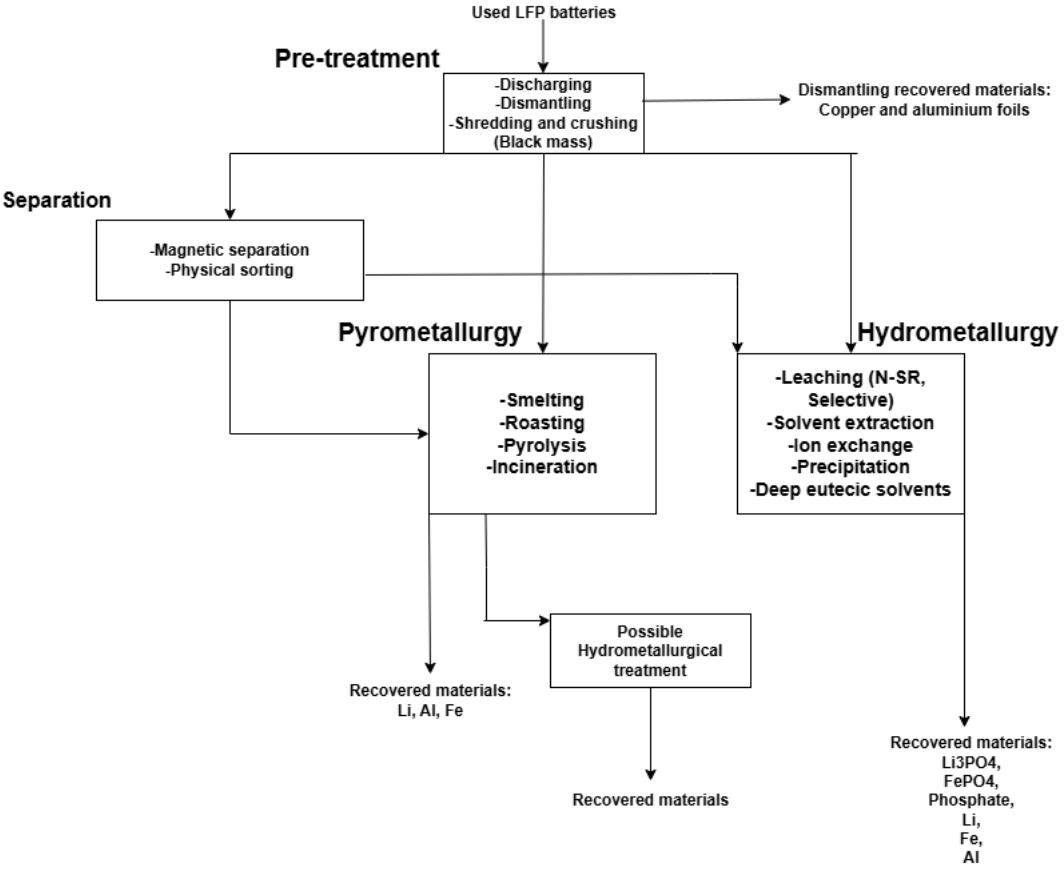

Figure 5. Several possible ways to recycle LFP batteries and recover valuable materials and metals.

The following sections evaluate these recycling methods in detail, starting with pre-treatment processes, followed by pyrometallurgy and hydrometallurgy.

3.1 Pre-treatment Processes

In battery recycling, pre-treatment is the first and most crucial step in the recycling of LFP batteries. Pre-treatment mainly consists of discharging, dismantling, shredding, grinding, and powder separation. The primary objectives of LFP battery pre-treatment are (1) ensuring operational safety, (2) extracting organic compounds, (3) crushing down components, and (4) separating different materials. Additionally, the pre-treatment process should aim to minimize the loss of valuable materials and mitigate environmental impact (Luo, 2025; Zhao, 2024).

To ensure workplace safety and minimize combustion or explosion risks, discharging is a vital step in the pre-treatment of lithium-ion batteries. Explosions during dismantling can result from short circuits. (Zhao et al., 2024). Currently, there are two common discharging methods: electrical and solution discharging. During electrical discharging the resistance is attached on external circuit. High voltage and large battery packs are suitable for electric discharging. Advantages of electric discharging include safety and controllability. However, high equipment cost, and battery complexity complicates using electric discharge. On the other hand, solution discharging is low cost and highly efficiency making it ideal for large-scale industrial applications. The battery is immerged in saltwater in solution discharging and solutes such as sodium chloride, manganese sulphate, and sodium sulphate are used. Nevertheless, the battery casing is corroded, and slag is produced, which increases the need for subsequent treatment (Luo et al., 2025).

The main purpose of dismantling is to separate and disassemble the larger battery elements. LFP battery can be dismantled into a cathode, an anode, and a separator. LFP cathode is coated with aluminium foil and the anode with copper foil. Battery electrolyte can be recovered in the dismantling process. Before getting into battery core, casing must be removed. There are manual and mechanical dismantling pathways. Manual dismantling is used to separate the cathode and the anode from the cell. Manual dismantling is labour-intensive and unsuitable for large-scale production. Mechanical dismantling on the other hand can be automated and more convenient yet not favourable through complicated follow-up separation process (Luo, 2025; Zhao, 2024).

After dismantling crushing is the next step. Valuable metals are usually bind into plastic or iron case. With the help of crushing the resulting product is black powder (also known as black mass), which will undergo a series of additional recycling processes to recover valuable materials (Al-Thyabat, 2013; Zhao, 2023). Yang et al. (2017) research team dismantled LFP battery from Brunp Recycling Co. Ltd. in China and showed that cathode black mass contained about 4 wt % of lithium, 31.25 wt % of iron, 15.88 wt % of phosphorus and 0.16wt% of aluminium. The amount of copper was not reported. (Yang et al., 2017).

After crushing the next step is to separate the valuable materials from the black mass. There are many separation techniques including magnetic separation, flotation, and physical sorting.

Magnetic separation is used to separate magnetically active materials from less magnetic or non-magnetic materials in the battery. Environmentally friendly, simple process and low cost make magnetic separation favourable separation technique. Hu et al. (2022) studied high-intensity magnetic separation process on spent LFP batteries. In this study researchers explored the effectiveness of this technique considering factors such as material composition, magnetic field strength and particle size (Hu et al., 2022). In Figure 6 recovery of different valuable materials are illustrated. Using weak magnetic separation, iron can be recovered. LFP black mass contains about 30% wt. of iron.

Hu's research focused on high intensity magnetic separation (HIMS) with the two typical HIMS separators being high-gradient magnetic separator (HGMS) and induced roll magnetic separator (IRMS). With the help of HGMS and electrode powder particle size being –0.21 mm and optimum magnetic field strength of 1.0T the concentrate grade was 74.54 % and the recovery of LFP cathode pieces were 96.6%. Compared to IRMS the concentrate grade was 93.3% and the LFP cathode pieces were 98.69% in optimum magnetic field strength of 0.8T, using electrode pieces as a feed material after shredding. In IRMS, the efficiency of separation was clearly improved by using larger electrode pieces to reduce the generation of superfine LFP particles, whereas the powder used in HGMS had the limitation factor. The use of IRMS had more potential for the industrial use. However, more studies need to be conducted to optimize HIMS (Hu et al., 2022).

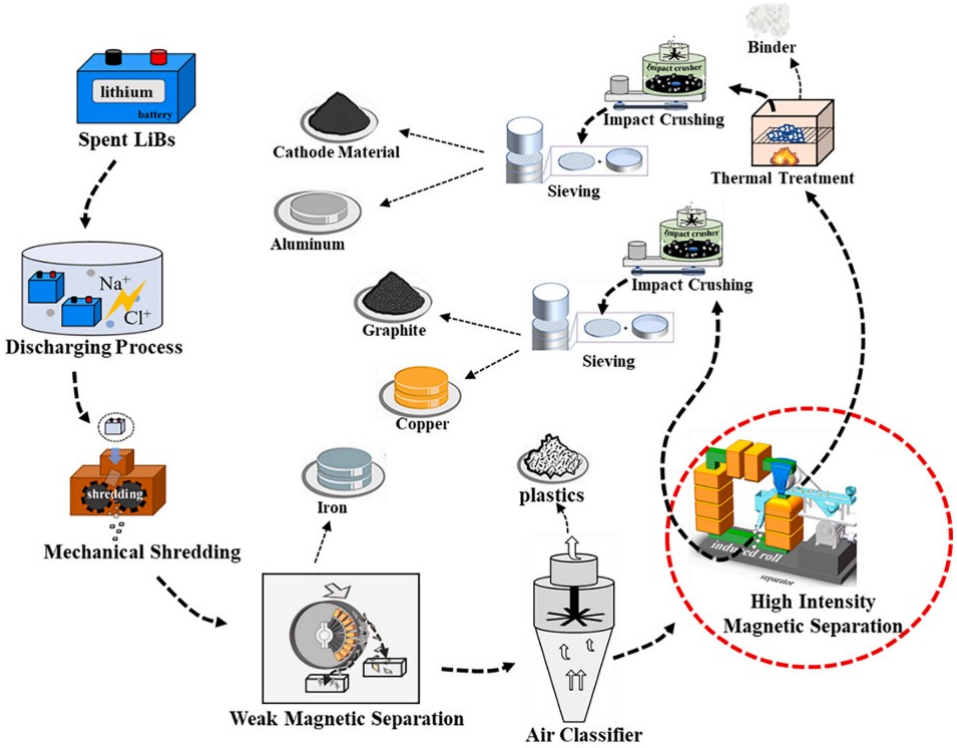

Figure 6 Potential recovery process of spent LIBs (Hu et al., 2022)

3.2 Pyrometallurgical Processes

This chapter focuses on pyrometallurgical recycling. The main objective is to investigate different pyrometallurgical process units to discover what valuable materials can be obtained. Also, it is essential to compare the recovery rate between different recycling process units. Pyrometallurgy uses high temperature to smelt the metal oxide and obtain valuable materials. Benefits of pyrometallurgy include shorter processing time, high efficiency, and less complex (Ouchi et al., 2023). Drawbacks to pyrometallurgy is the high cost as pyrometallurgy needs to operate at high smelting temperatures. Another significant challenge is the oxidation of battery components. There are two ways that oxidation of battery components could negatively affect the efficiency of pyrometallurgy. Firstly, large amounts of CO_2 are released into the atmosphere. Secondly, and more importantly, the loss of valuable materials such as lithium and aluminium are converted into oxides and removed as slag (Palaniyandy, Abhilash and Nalini, 2022). Additionally, a high amount of energy is used in pyrometallurgy recycling, which affect the cost of the recycling of LFP (Wang. M et., 2022).

In battery recycling, smelting is a pyrometallurgical process unit where LFP cathode material undergoes phase transition at high temperatures exceeding 1000 $°C$. Metal oxides are converted into metallic form using carbon or another reducing agent in the reduction smelting. Experiment done by Qu et al. (2023) on "Applicability of the reduction smelting recycling process to different types of spent lithium-ion batteries cathode materials" showed that reduction smelting can obtain LFP cathode material. However, approximately 20 % of Cu and Fe evaporated into the gas phase. Phosphorous volatilized into an alloy phase, while lithium melts as lithium chloride (LiCl), but can be recovered from dust collection systems. On top of some iron oxides are lost to slag as it is not reduced (Qu et al., 2023)

Roasting is another pyrometallurgical process, where reactions happen typically in the presence of air or oxygen and therefore is exothermic process. As other pyrometallurgy methods, roasting is also used in recycling of LCO and NCM batteries, because of Cobalt and Nickel. Roasting can be divided into three approaches: direct roasting, atmosphere roasting, and additive-assisted roasting. Direct roasting utilizes carbon or aluminium to reduce cathode materials. Under high temperatures, metal alloys are produced. In atmosphere roasting, vacuum or inert conditions are used to recover black powder. Lastly additive-assisted roasting adds inorganic salts or acids to improve recovery. For example, adding $CaCl_2$ and Na_2SO_4 to slag and roasting for one hour in 800 $°C$ can recover 90% lithium.

For LFP recycling, not all roasting methods are effective Direct roasting is not utilized commonly in recycling of LFP batteries. The atmosphere roasting can reduce the reaction temperature and lower use on energy in the process. In the other hand, roasting at excessively high temperatures destroys the crystal structure of FePO4 and lithium is evaporated (Yao et al., 2024).

Pyrolysis can be used as pre-treatment; however, it can be categorized as pyrometallurgical process unit. In pyrolysis, battery material is heated in an inert atmosphere or under vacuum conditions, where the organic compound is broken down into low molecular weight products. The purpose of breaking battery material in an oxygen-free environment is to prevent lithium from reacting with moisture or air. Also, by-products decomposition temperature lowers, and process efficiency notably improves. Since the active cathode can withstand pyrolysis temperatures, cathode does not decompose and requires additional recycling steps such as hydrometallurgical (Makuza et al., 2021).

Similarly, to pyrolysis, incineration can also be used as pre-treatment. In contrast to pyrolysis, incineration involves the presence of air or oxygen in the process (Palaniyandy, N., Abhilash, K.P. and Nalini, B, 2022). In incineration with the help of air or oxygen removal of carbon and binder materials

is possible, while the plastic fragments and the electrolyte are destroyed. By carefully controlling the temperature, the recovery of lithium and other valuable metals is possible (Saju et al., 2023).

3.3 Hydrometallurgical Processes

Hydrometallurgical recycling involves the use of aqueous solutions to extract valuables materials. For battery recycling, hydrometallurgy is used to dissolve cathode materials in acids or alkali solutions and subsequently separate the component metals through chemical precipitation or solvent extraction. China, in particular, applies hydrometallurgy commercially, offering a less energy-intensive and lower capital-cost hydrometallurgical recycling. The valuable materials that can be obtained through these methods are lithium, nickel, cobalt, and manganese. These valuable metals can be recycled into individual chemicals, chemical precursors, or new cathode materials. In the case of LFP, only lithium exists in cathode material. (Vasconcelos, 2023; Jung, 2021).

Unlike pyrometallurgy methods, which tend to use relatively high temperatures to extract valuable materials, hydrometallurgy recycling operates at relatively lower temperatures. Benefits to lower temperature operating are reduced energy consumption and lower environmental impact, although the environmental impact can still be significant.

3.3.1 Leaching

Leaching is a typical approach for LFP recycling, where valuable metals are dissolved from solid materials into a liquid solution using acids, bases, or organic solvents. For LFP recycling, there are two main types of leaching: non-selective recovery leaching and selective recovery leaching. The main difference is that non-selective recovery (N-SR) is a type of hydrometallurgical recovery process where components of the cathode (Li, Fe and PO_4) are leached out together instead of targeting specific metals. To recover lithium and iron, the olivine structure of LFP is broken down using strong leaching agents, such as H_2SO_4, HNO_3 and H_3PO_4. Non-selective recovery leaching requires various process steps and vast amounts of wastewaters are produced (Kumar et al., 2022).

In comparison, selective recovery targets a specific element, for example lithium from the leaching solution, while the rest of the cathode is recovered as leaching residue. Selective recovery has been seen as more eco-friendly approach to non-selective recovery as it uses weaker leaching agents and generates less wastewater. Other advantages of selective recovery are lower cost, simpler process and LFP battery crystal structure, which does not have to be broken down (Kumar, 2022; Vasconcelos, 2023).

For selective leaching of LFP battery the most common agent is sulfuric acid and process patented by Recypyl based in France can recover lithium using sulfuric acid. LFP black mass is leached in H_2SO_4 with the added steel shots to help recover copper trough cementation. After leaching process continues with precipitation using H_2O_2 or O_2 to oxidize iron. Lithium is recovered by using H_3PO_4 and adjusting pH, leading to precipitation of lithium phosphate. However, iron and phosphate are lost as waste. (Larouche et al., 2020).

Over the past few years, much research has been conducted on the selective recovery of LFP battery. In Mahandra et al. (2021) experiment, the team used formic acid (HCOOH) as a leaching agent, hydrogen peroxide (50 wt% H_2O_2) as an oxidant to oxidize Fe^{2+} to Fe^{3+}, sodium hydroxide (NaOH) as separation chemical and pH adjustment for iron precipitation. Tri sodium phosphate ($Na_3PO_412H_2O$) was used to recover lithium from the leach solution. In this study after pre-treatment selective leaching was done by optimizing pulp density, acid concentration, reaction time and temperature. The recovery rate of 99.5% for lithium phosphate was achieved by using 10% (v/v) of 50 wt% H_2O_2 concentrate. Additionally, the pulp density of 10%, molar ratio of HCOOH/Li 3.32, and leaching for 30 minutes at 30 $°C$ were concluded as optimal conditions. Further recycling must be done as $FePO_4$ was left as solid residue (Mahandra and Ghahreman, 2021).

In addition, single acid treatment for recovery of LFP metals is possible. In single acid treatment oxalic acid ($H_2C_2O_4$) form chelate with Fe^{3+}. This chelate helps to break down the LFP structure and simultaneously phosphoric acid (H_3PO_4) releases lithium ions from the olivine crystal structure. Up to 97% of lithium can be recovered through single acid treatment (Naseri and Mousavi, 2024).

3.3.2 Solvent extraction

Solvent extraction is a method to recover valuable ions such as lithium, iron, and aluminium from the aqueous solution. Solvent extraction looks like an appealing hydrometallurgical approach to recover valuable metals from LFP battery. The review done by Vasconcelos et al. (2023) examined several solvents. Their review mentioned that solvents like di-(2-ethylhexyl) phosphoric acid (D2EHPA), tributyl phosphate (TBP) and malonamides are used to recover valuable metals from the solution.

For example, using D2EHPA and TBP it is possible to recover 50% of Li^+. In this process D2EHPA is diluted in cyclohexane or TPB and carried out in batch and continuous. D2EHPA can also be used to extract Al^{3+}. Sulfonated kerosine and D2EHPA were used in the counter-current extraction, achieving 96.3% of Al^{3+} recovery and minimal iron loss. From hydrochloric acid solutions extracting Fe^{3+} with the help of malonamides with phenyl and methyl groups is possible. Environmental challenges and opposing risk to the health of the operator are the biggest concern while using solvent extraction method (Vasconcelos et al., 2023).

3.3.3 Deep eutectic solvents

Deep eutectic solvents, or DESs for short, are a greener and more sustainable approach to metal recovery. According to Chen et al. (2024), about 70 papers focus on LIB recovery using DESs, but only one focuses specifically on LFP (Chen et al., 2024).

To synthesize DES, Wang et al. (2023) combined choline chloride (ChCl) and oxalic acid ($H_2C_2O_4$) with the molar ratio of 1:1. A homogeneous and colourless liquid was obtained after heating the mixture to 80°C . LFP powder was added into DES in varying solid-to-liquid ratio. The reaction between the LFP powder and DES was carried out at temperatures between 80-120 °C , while stirred at 800 rpm. Chen's team found the optimal conditions to be 106 °C for 110 minutes with a solid-to-liquid ratio of 0.02. Under these conditions, 95.3 % of lithium and 85.2 % of iron were leached from the LFP powder. To recover lithium and iron, precipitation was used. This DES recovery method was considered environmentally sustainable, as it avoided high temperatures and strong acids (Wang et al., 2023).

3.3.4 Ion exchange resins

Valuable lithium can be recovered through ion-exchange resins. In this method Li^+ ions are exchanged with H^+ in a counter flowing solution, typically a brine. Essentially, the solution flows through the LFP battery, and target ions are exchanged with preloaded resins (Kumar et al., 2022). For example, a study conducted by Zhang, Liu, and Qu (2023) explored the concept of recycling LFP battery using the ion-exchange technique. Zhang and his colleagues investigated ion exchange using strong and weak acid cation exchange resins. Performance of oxalic acid, citric acid and sulfuric acid were evaluated for lithium recovery from LFP. The highest lithium (99.3%) and iron (98.6%) leaching efficiencies were achieved with a 50 g/l solid-to-liquid ratio, at 80 $°C$ for one hour using sulfuric acid. Citric acid also achieved high recovery of lithium (90%) and iron (91.2%) under the same conditions. Oxalic acid showed favourable lithium recovery (95%), but only <5% of iron was recovered. Rod-like ferrous oxalate was formed in the residues. In the end (Zhang, Liu, and Qu, 2023).

The waste electrode materiel was also repurposed as fertilizer using a Li-K reaction. The product containing potassium and phosphorus could be sold for profit. K350 resins were used to exchange Li^+ and K^+ ions. The efficiency depends on the correct pH level and resin dosage. In Zhang's study, the correct resin amount was 1.4 g of resin per mg of Li to achieve above 90% Li-K efficiency, and preferred pH level was 3. However, 42% of the iron ions were precipitated. Figure 7 illustrates a possible flowchart using ion exchange (Zhang, Liu, and Qu, 2023).

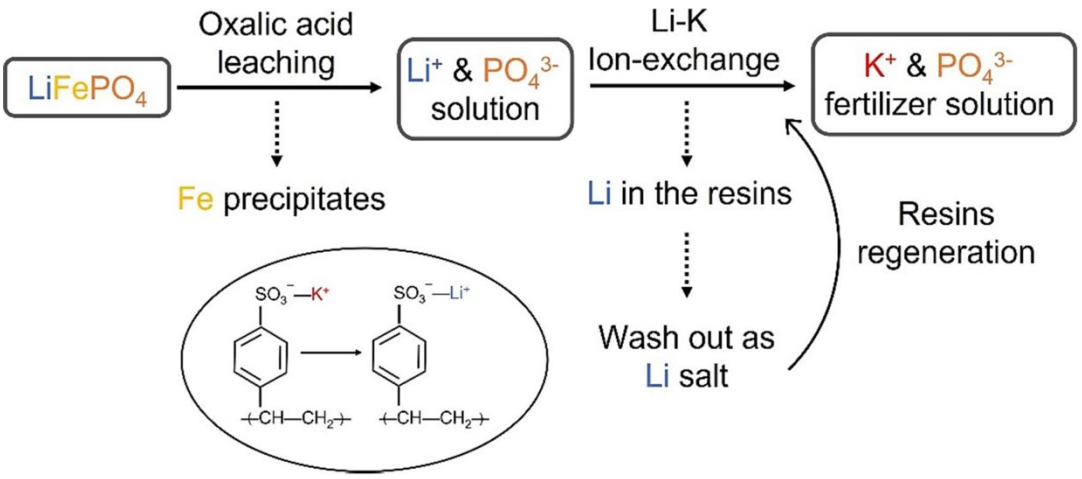

Figure 7. Proposed flowchart of recycling process using ion-exchange (Zhang, Liu, and Qu, 2023).

Main advantage of ion exchange is that recovered lithium from LFPs can be repurposed to single or multi-element fertilizer through potassium-lithium-ion exchange reaction (Zhang, Liu, and Qu, 2023).

3.3.5 Precipitation

Precipitation is a fundamental step in the hydrometallurgical process of LFP batteries. Recovery of lithium, iron, and phosphate from the leach solution is possible by adjusting the pH levels carefully and using various chemical reagents. The ability to selectively precipitate these elements underscores the importance of precipitation in optimizing the overall recycling process, resulting in improved resource management, and reduced environmental impact (Larouche et al., 2020).

Mahandra and Ghahreman (2021) recovered 99.5 % of lithium phosphate using formic acid and sodium phosphate in sequential precipitation steps. Mahandra and Ghahreman study did not focus solely on precipitation. However, precipitation was a crucial final step. Their work included a selective leaching and precipitation-based process to recover lithium phosphate from LFP batteries (Mahandra and Ghahreman, 2021).

4 Economic and Environmental Aspects

In this chapter, the thesis investigates the cost of recycling of LFP batteries. The cost of recycling is then compared to the possible profits from the recycled valuable materials, as well the potential environmental challenges posed by the recycling processes.

4.1 Economical aspect

To encourage the recycling LFP batteries, it must be economically feasible. The lack of nickel or cobalt significantly decreases the recycling value of LFP batteries. Nonetheless, LFP contains valuable materials, such as lithium, iron, aluminium, and phosphorus. By far, aluminium has the lowest weight percent of valuable material (0.16 wt. %), as it is used as foil in cathode. Lithium is next with about 4 wt % of battery containing lithium. However, lithium is by far the most valuable material to recover in the recycling process. Iron with weight percent of 31.25 and phosphorus 15.88 are less financially beneficial materials. As of April of 2025, the price of lithium carbonate was approximately 72 000 CNY/T. This unit is Chinese Yuan per metric ton and equivalents approximately 12 200 USD/T with exchange rate of 1 CNY to 0.14 USD (Trading economic, 2025; Forbes, 2025).

Additionally, the cost of recycling processes or process unit is a critical factor for recycling feasibility. The use of chemicals, electricity, and materials significantly contributes to the overall cost. Wastewater disposal is especially important to consider in hydrometallurgical processes. Many companies use a combination of pre-treatment, pyrometallurgy, and hydrometallurgy as their recycling process.

In Ma et al. (2018) paper, the team stated that variable costs (VC) and fixed costs (FC) are included in spent battery recycling. Many different factors contribute to variable and fixed costs. Through different literature reviews and reports Ma's team calculated recycling costs for LFP and NCM. The total cost of spent LFP recycling was 7176 CNY/T, which is approximately 1200 USD/T. Revenue was 10570 CNY/T, with profits of 3394 CNY/T (~ 570 USD/T), making the recycling process profitable (Ma et al., 2018). It is worth noting that Ma et al. (2018) used a lithium price of 860 000 CNY/T in 2018. As of April of 2025, the price of lithium has decreased (Trading economic, 2025).

Another economic assessment done by Tian et al. (2024), composed an assessment to economic and environmental impact to recycling of LFP

cathodes in China. The team studied the major recycling processes used in China. Figure 8 illustrates the cost, income, and profit associated with five different recycling processes. Two of the processes are hydrometallurgical and three are processes used in laboratory scale. Laboratory scale processes focus on sulfide roasting, acid-free extraction, and targeted healing. Process A is an acid-leach distillation process, in process B difference is in the precipitation step, though both use acid-leaching. In this assessment Tian et al. (2024) gathered the cost of different materials, chemicals, and energy. Furthermore, material and energy balances were calculated. Figure 8 demonstrates that acid-leach distillation process (Process A) was the most profitable, whereas acid-leach precipitation (Process B) was the least profitable, even though the process costs were similar. The highest process cost was observed for the targeted healing process (Process E) (Tian et al., 2024).

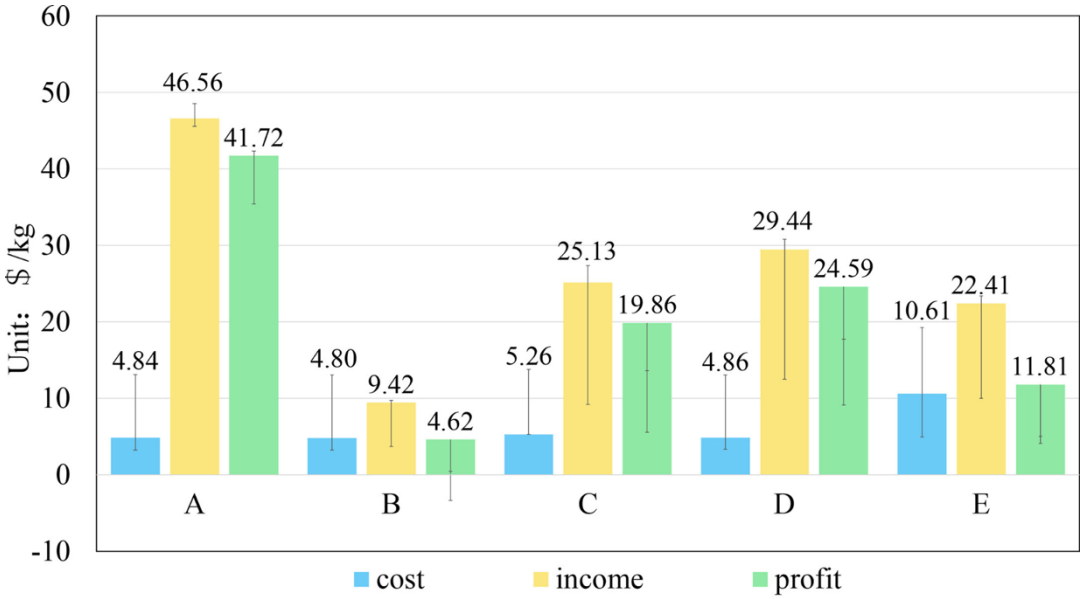

Figure 8. Cost, income, and profit comparison of five LFP recycling processes. Process A and B are hydrometallurgical: A is an acid-leach distillation process, and B is an acid-leach precipitation process. C, D and E are laboratory scale methods: Process C involves high-temperature sulfide roasting and sintering, Process D uses acid-free extraction with ball milling and vacuum separation and Process E is the targeted healing method (Tian et al., 2024)

4.2 Environmental challenges

Economic feasibility is important when recycling LFP batteries. Equally important is environmental aspects. Factors such as chemicals usage, energy consumption, and wastewater generation are important to consider when

analysing their effects on the environment and factory workers. Recycling and reusing are crucial as the valuable materials are scarce, and recycling can reduce pressure on mining operations to produce more metals. During environmental assessment, processes such as pyrometallurgy and hydrometallurgy are evaluated based on previously discussed factors.

Additionally, life cycle assessments are typically conducted to evaluate the environmental impact of the entire battery life cycle, including that of LFP batteries. A life cycle assessment includes the extraction of materials and metals from mines, battery manufacturing, battery usage, recycling, and potential disposal. However, this thesis focuses only on environmental aspects of LFP battery recycling (Mallick, 2020).

Pyrometallurgy is a mature and established process, known for its high energy usage, as it requires elevated temperatures to smelt and roast LFP batteries. Pyrometallurgical processes produce gases, which pollute and harm the environment (Luo et al., 2025). CO_2 is produced during pyrometallurgical recycling, and the carbon footprint is one key measure used to investigate the pollution of the process. According to Chen et al. (2023) pyrometallurgy produces more carbon emissions than hydrometallurgy and direct recycling (Chen et al., 2023). Evaluation concluded by Li et al. (2024) showed that pyrometallurgical process produces 8.36 kg eq of CO_2 emissions, which are significantly higher than hydrometallurgy and direct recycling (ranging from 2.36 to 6.41 kg CO_2 eq). However, energy consumption in pyrometallurgy was lower than in hydrometallurgy or direct recycling. Contribution of electricity consumption was 58.4%. When looking at sulfur dioxide emissions, pyrometallurgy showed once again highest emissions (0.054 kg SO_2 eq), which contribute to terrestrial acidification. Lastly, human toxicity and fossil resource depletion were also highest in pyrometallurgy compared to hydrometallurgy or direct recycling (Li et al., 2024).

Hydrometallurgy is often carried out through the leaching process. A life cycle assessment by Liu et al. (2023) investigated the environmental impact of recycling three different cathodes: LFP, NMC, and LCO. In this assessment, Liu's team used several different leaching methods to investigate a closed-loop life cycle assessment. LFP had two different recycling routes illustrated in Figure 9. Option 5 involved separating $FePO_4$ directly from the leach solution, recovering Li_2CO_3 through precipitation, and recombining them (in a 1.05:1 molar ratio of Li_2CO_3 and $FePO_4$) followed by heat treatment to resynthesize LFP. Option 6 on the other hand simplified the process by adjusting the molar ratio of Li:Fe:P to 3:1:1 after leaching and directly resynthesizing LFP via a hydrothermal method. Option 5 showed lower environmental

impact than option 6. The lower environmental impact was due to the use of lithium additives.

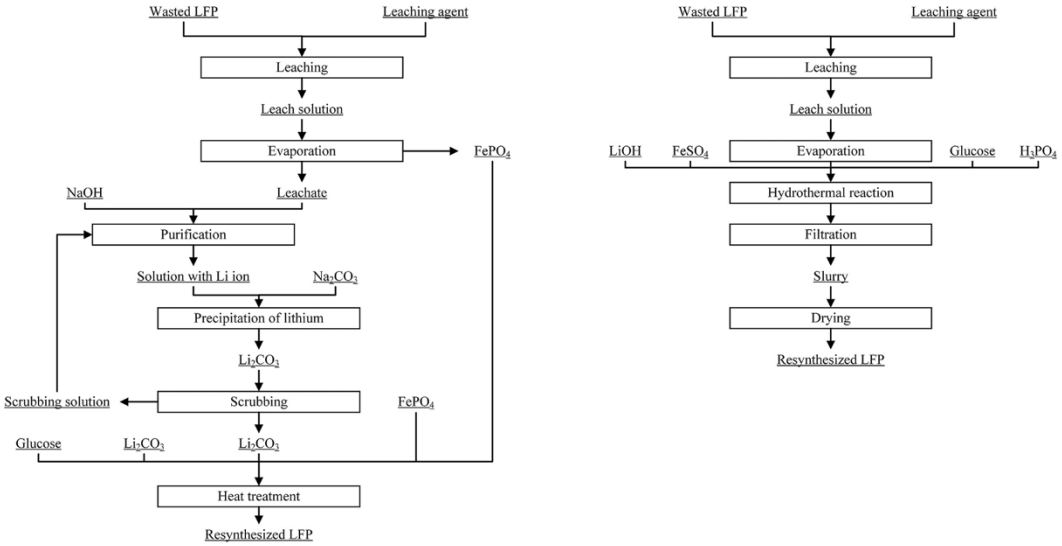

Figure 9. Recycling processes for $LiFePO_4$ (LFP): (a) Option 5 – involves separation, purification, and precipitation steps to recover Li_2CO_3 and $FePO_4$ for resynthesis; (b) Option 6 – a simplified method using direct leaching and hydrothermal treatment to resynthesize LFP (Liu et al., 2023).

The overall average environmental impact for LFP was 4.02 Pts/kg (points per kilogram), compared to 18.69 Pts/kg for NMC and 9.86 Pts/kg for LCO. Pts/kg is an eco-indicator that represent environmental impact points per unit mass. It differs from a typical life cycle assessment by simplifying LCA evaluation process. (Huang, 2022; Liu, 2023). LFP had the lowest environmental impact among the tested cathodes. The chemicals used in LFP leaching had a significant impact on the score. Using 3M sodium persulfate accumulated the score of 1.57 Pts/kg, while the highest impact came from 1.25M acetic acid, reaching over 8 Pts/kg. In Liu et al. (2023) assessment recycling process option 4 described NMC recycling process where NMC was regenerated by using coprecipitation and followed by solid-state sintering and had a similar environmental impact to LFP recycling, at 1.57 Pts/kg. While the average environmental impact of NMC recycling was 18.69 Pts/kg. Figure 10 presents a closed-loop comparison between LCO, LFP, and NMC. Even though hydrometallurgy consumes more electricity than pyrometallurgy, the choice of leaching agent has a major impact on the environment. (Li, 2024; Liu, 2023).

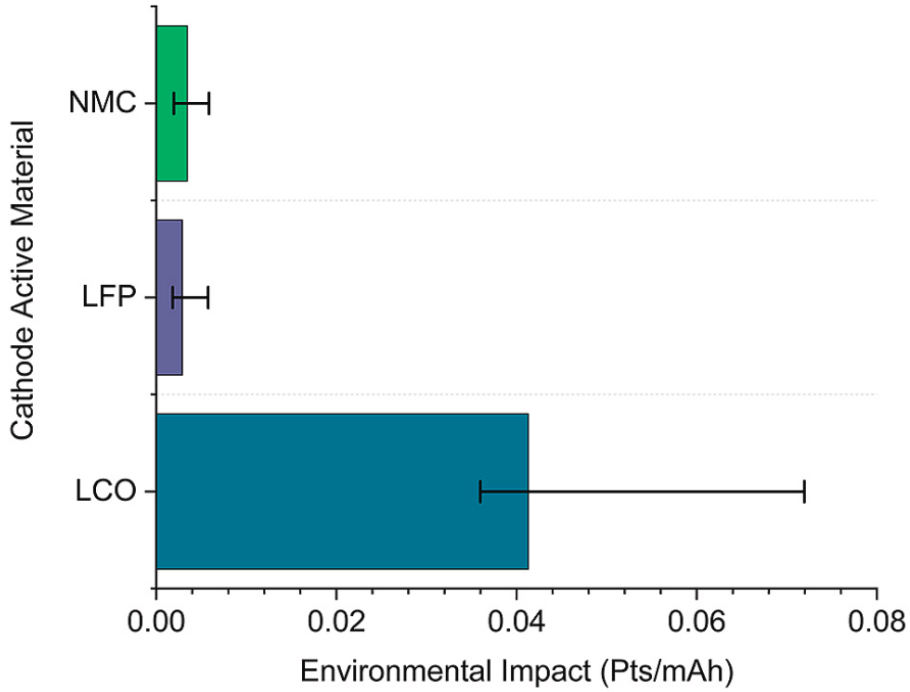

Figure 10. Close-loop LCA of NMC, LFP and LCO cathodes (Liu et al., 2023).

When looking other hydrometallurgical processes, solvent extraction is effective recycling process. Solvent extraction opposes serious environmental concerns as it uses toxic solvents. Some solvents could dissolve into the aqueous solution and contaminating water. Chemical D2HEPA used in solvent extraction is known for being toxic and corrosive chemical and has health risks on human. TBA, another chemical used in solvent extraction has shown damage to DNA and being neurotoxic. Additionally, TBA opposes risk to humans and ecosystems. Residues of TBA has been found in birds and fish (Vasconcelos et al., 2023).

Laws and regulations are excellent options for enhanced environmentally friendly recycling. Currently in China there are laws and regulations that support battery manufacture, collection, and recycling in nation scale. For example, Municipal Solid Waste disposal regulations is placed. Also, China is granting different subsidies for recycling of batteries and place gate fees as used batteries cannot be disposed to landfills. These laws, regulations and subsidies greatly increase environmental friendliness (Makuza et al., 2021).

5 Technological Advancements

This chapter explores the possible technological advancements in the field of LFP battery recycling. Researchers are continuously developing solutions to make the recycling of LFP more economical and environmentally friendly.

Advancements in both pyrometallurgy and hydrometallurgy methods enhance material recovery rates and help to reduce environmental impact with alternative chemical use. Additionally, this chapter explores possibility of direct recycling approaches, which aim to restore battery with minimal processing.

5.1 Pyrometallurgy

Microwave-assisted pyrolysis or in short (MAP) is a technology where electrode materials are rapidly heated and decomposed using microwave radiation. This technique lowers the environmental footprint and recovers precious metals. Compared to conventional pyrolysis, MAP utilizes microwave energy to directly interact with certain materials. These certain materials have high dielectric lost factory such as carbon based and metal compounds. Directly interacting with the materials increases the heating rates, more control over the process and energy consumption is reduced (He et al., 2024).

In the case of LFP batteries He at al. (2024) experiments verified that LFP and graphite have a medium to high microwave absorption coefficient. This coefficient ($\tan \delta\varepsilon > 0.02$) at 2.45 GHz allows LFP decomposition and efficient heating during pyrolysis. The experiment was carried out microwave-assisted pyrolysis reactor, where microwave generator was operated at 2.45 GHz, argon was used to maintain an oxygen free environment and liquid products were collected via cold traps. LFP process was carried out in ~300-500 $°C$ compared to ~800 $°C$ in typical pyrolysis. Also, high H_2 and CO production was observed, helping the technique to be more environmentally friendly. On top of that, the role of biomass (cellulose, hemicellulose, lignin, and peanut shells) played a crucial role. Roles of biomass were: 1) LFP decomposition were improved. 2) biomass acted as a reducing agent. 3) Biomass broken down into a gas containing high amount of H_2 and CO. Moreover, LFP can be partially oxidized to Fe (III) compound, which leads to loss of valuable material. Future research still needs to be done to MAP in order to have industrial capabilities (He et al., 2024).

5.2 Hydrometallurgy

Currently in hydrometallurgy recycling, the usage of excess oxidants or acid affect poorly on environment and sustainable recycling. Therefore, moving closer to environmentally friendly battery recycling has gained a lot of attention.

Conventional hydrometallurgy approaches often rely on the usage of excess amount oxidants and acids. This has negative affect on environment. Electrochemical approach is an innovation that replaces oxidants with electrical energy, which can lead to a more sustainable lithium recovery from LFP batteries. Mediated electrochemical leaching is a process that requires redox mediators (RMs), such as ferricyanide/ferrocyanide $[Fe(CN)_6]^{-3}$/ $[Fe(CN)_6]^{-4}$and these RMs shuttles between the electrode and the LFP material. These mediators are activated at the anode and oxidize the spent LFP particles. Strength to mediated electrochemical leaching is the regenerative behaviour of RMs leading only need of catalytic quantities. During this process hydrogen gas is produced as by-product due the cathodic reaction often involving proton reduction. With this method, requirement of chemical usage is greatly reduced while offering better energy efficiency (Beek, Yilmaz and Devin, 2025).

Moving closer to environmentally friendly battery recycling has gained a lot of attention. Initially, bioleaching was used to extract metals from ores. However, bioleaching is still far from industrial scale as low adaptability and rigorous leaching conditions oppose problems. Currently bioleaching studies have been done largely to LCO and LNCM batteries (Kumar et al., 2022). Eco-friendly recycling could come one step closer with the help of bioleaching. Essentially bioleaching is leaching where leaching agents are organic such as acetic acid, citric acid, malic acid, oxalic acid, and tartaric acid. For LFP recycling fruit waste, algae or fungi must be used. In the bioleaching process microbes, bacteria, and fungi (Roy, Cao, and Madhavi, 2021: Kumar, 2022)

5.3 Direct recycling

As industries do not prefer wet conditions, such as in hydrometallurgy and given that the formation of HF gas is troublesome. Other recycling methods are needed. End-of-life or spent LFPs can be regenerated to prolong LFP life cycle. The aim is to regenerate the battery to its unused performance state.

In ideal situation whole battery could be regenerated. However, mostly cathode is as it has the most economical value. Direct recycling is one method that batteries can be regenerated. Even though direct recycling is still at research state, many methods is researched, including solid-state-, electrochemical- and solution-based regeneration (Barbosa, Duda, S. and Petranikova, M, 2025). Benefits to direct recycling is that it is claimed to be less costly due not needing to dissolve active material. However, full regeneration to virgin state requires up to same number of steps as leaching and might not offer economical advantage. Currently direct recycling cannot restore the performance to initial state (Larouche et al., 2020).

Solid-state thermal regeneration is one of the most researched regeneration methods. In solid-state thermal regeneration the precise amount of lithium salt is mixed with LFP and heated in reductive conditions and high temperatures for sintering or calcination. Advantages to solid state thermal regeneration include that this method consumes less chemicals and uses less steps. Nonetheless, this method also produces poisonous gases, which enter the exhaust stream and different LFP batteries containing slightly different composition, the precise amount of added lithium can be seen as a difficult task (Barbosa, Duda, S. and Petranikova, M, 2025).

Electrochemical regeneration is a type of direct regeneration. One method involves using spent LFP as the working cathode, platinum plate or mesh as an anode and Ag/AgCl as a reference electrode. For lithium source and electrolyte Li_2SO_4 solution was used. Lithium diffused into LFP without passing any current and reactivating the composition. However, reactivation was not fully complete. LFP battery was sintered after lithium diffusion until stable potential state was achieved. The performance of regenerated LFP was 135.2 mAh/g at 1C (1C = 170 mAh/g) and after 500 cycles capacity was still 95.3%. Theoretical capacity of new LFP battery is 170 mAh/g (Xu, 2023; Wu, 2024).

In hydrothermal regeneration is conducted by replenishing missing Li in LFP with rich lithium solution, where reaction is done in elevated temperatures and pressures. To successfully regenerate LFP Fe^{3+} is redacted to Fe^{2+} by using citric acid–LiOH and ethyl alcohol–CH_3COOLi. For example, Xu et al. (2020) repair of degraded LFP by using citric acid to lower activation energy and iron ions could move back to initial position and helping the movement of lithium ions, which can be recycled to reduce to lower recovery costs. After 100 cycles, 93.7% of the initial capacity was maintained. (Xu, 2020; Wu, 2024).

6 Conclusions

As the demand for electric vehicles continues to rise annually, it is crucial to achieve sustainability goals for battery demand. This thesis explored and investigated the current state of lithium iron phosphate (LFP) battery recycling, revealing a number of key technical, economic, and environmental insights. LFP batteries are increasingly used due to their safety, long cycle life, and cost-effectiveness. Their recycling remains underdeveloped compared to other lithium-ion battery chemistries. A major challenge identified is the low economic value of recovered materials due to the absence of high-value metals such as cobalt and nickel in LFP chemistry. This reduces the financial incentive for commercial recycling efforts. Despite this, environmental regulations and sustainability goals make LFP battery recycling increasingly important in the long term.

Among the recycling methods reviewed, pyrometallurgy remains a simple and mature process. However, it presents significant drawbacks, including loss of valuable metals such as lithium in the slag. High volume of CH_2 gases is produced in the process, which negatively affect sustainability goals. Hydrometallurgical processes, in contrast, are the most developed and commonly researched. Hydrometallurgy enables the usage aqueous solution to recover valuable metals. When optimized with appropriate chemical agents and process conditions, the recovery of lithium and iron is satisfactory while being environmentally friendly and cost effective. Although the overall profitability remains limited.

Direct recycling is a particularly promising method, as it aims to recover and regenerate cathode materials with minimal chemical conversion. However, this method remains in research phase and faces several challenges, such as the need for efficient sorting and pre-processing of spent cells, and the precise amount of added lithium is quite challenging effort.

In industrial scale, a combination of pre-treatment, pyrometallurgical and hydrometallurgical processes is typically employed to maximize material recovery. In the future, LFP recycling comes even more crucial. For that reason, more experiments and studies must be conducted to optimize these methods. Environmental footprint and sustainability of battery recycling can be improved by integrating current technology with future advancements. Furthermore, policy measures, including extended producer responsibility and recycling mandates, could play a significant role in fostering a circular economy for lithium-ion batteries. Future technologies such as direct recycling, microwave-assisted pyrolysis, and electrochemical leaching offer promising pathways to improve efficiency and minimize environmental harm.

References

Al-Thyabat, S., Nakamura, T., Shibata, E. and Iizuka, A. (2013). Adaptation of minerals processing operations for lithium-ion (LiBs) and nickel metal hydride (NiMH) batteries recycling: Critical review. Minerals Engineering. [online] Vol 45. pp.4–17. Available: DOI 10.1016/j.mineng.2012.12.005.

Barbosa, Duda, S. and Petranikova, M. (2025). Recycling of Lithium Iron Phosphate (LiFePO4) Batteries from the End Product Quality Perspective. Batteries. Vol 11:1. Available: DOI 10.3390/batteries11010033.

Beek, V., Yilmaz, E. and Devin (2025). Sustainable Hydrometallurgical LFP Battery Recycling: Electrochemical Approaches. ChemSusChem. [online] Article No:202402699. Available: DOI 10.1002/cssc.202402699.

Bhushan, B. (2017). Springer Handbook of Nanotechnology. [online] Springer Nature. p. 230. ISBN 978-3-6625-4357-3.

Castro, L., Dedryvère, R., El Khalifi, M., Lippens, P.-E. ., Bréger, J., Tessier, C. and Gonbeau, D. (2010). The Spin-Polarized Electronic Structure of LiFePO4 and FePO4 Evidenced by in-Lab XPS. The Journal of Physical Chemistry C. Vol 114:41. pp. 17995–18000. Available: DOI 10.1021/jp106631v.

Chen, Q., Lai, X., Hou, Y., Gu, H., Lu, L., Liu, X., Ren, D., Guo, Y. and Zheng, Y. (2023). Investigating the environmental impacts of different direct material recycling and battery remanufacturing technologies on two types of retired lithium-ion batteries from electric vehicles in China. Separation and Purification Technology, [online] Vol 308. Article no; 122966. Available: DOI 10.1016/j.seppur.2022.122966.

Chen, Y., Zhang, F., Yang, C., Ju, X., Zhang, Z., Liu, Z. and Yang, M. (2024). Efficient and Selective Dissolution of Li from Lithium-Ion Battery LiFePO4 Cathode by Natural Deep Eutectic Solvents. Energy Fuels, [online] Vol 38:6. pp.5391–5396. Available: DOI 10.1021/acs.energyfuels.4c00080.

Forbes (2025). CNY To USD: Convert Chinese Yuan to United States Dollar. [online] Forbes Advisor. [Accessed 13.4.2025]. Available at: https://www.forbes.com/advisor/money-transfer/currency-converter/cny-usd/

Golubkow, A. W. et al. (2014), thermal-runaway experiments on consumer Li-ion batteries with metal-oxide and olivin-type cathodes. RSC Adv. Vol 4:7. pp. 3633-3642. Available: DOI 10.1039/c3ra45748f

He, M., Wang, T., Weng, T., Dong, Y., Zhao, J. and Ma, W. (2024). Microwave-assisted pyrolysis of biomass and electrode materials from spent lithium-ion batteries: Characteristics and product compositions. Industrial Crops & Products Vol 222. Article no; 119899. Available: DOI 10.1016/j.indcrop.2024.119899.

Hu, Z., Liu, J., Gan, T., Lu, D., Wang, Y. and Zheng, X. (2022). High-intensity magnetic separation for recovery of LiFePO4 and graphite from spent lithium-ion batteries. Separation and Purification Technology, [online] Vol 297. Article no: 121486. Available: DOI 10.1016/j.seppur.2022.121486.

Huang, W., Liu, Y., Zheng, D., Chen, X., Yang, M., Li, Y. and Li, X. (2022). Exergy-environment assessment for energy system: Distinguish the internal and total exergy loss, and modify the contribution of utility. Energy Conversion and Management, [online] Vol 251. Article no; 114975. Available: DOI 10.1016/j.enconman.2021.114975.

International Energy Agency (IEA), 2024. Global EV Outlook 2024: Moving towards increased affordability. Paris; International Energy Agency. [Accessed 26.2.2025] Available at: https://www.iea.org/reports/global-ev-outlook-2024

Jung, J.C., Sui, P. and Zhang, J. (2021). A review of recycling spent lithium-ion battery cathode materials using hydrometallurgical treatments. *Journal of Energy Storage*, [online] Vol 35. Article no: 102217. Available: DOI 10.1016/j.est.2020.102217.

Kumar, J., Neiber, R.R., Park, J., Soomro, A., Greene, G.W., Mazari, A., Seo, Y., Lee, H., Shon, M., Chang, W. and Cho, Y. (2022). Recent progress in sustainable recycling of LiFePO4 type lithium-ion batteries: Strategies for highly selective lithium recovery. Chemical Engineering Journal, [online] Vol 431. Article no: 133993. Available: DOI 10.1016/j.cej.2021.133993.

Larouche, F., Tedjar, F., Amouzegar, K., Houlachi, G., Bouchard, P., Demopoulos, G. P., & Zaghib, K. (2020). Progress and Status of Hydrometallurgical and Direct Recycling of Li-Ion Batteries and Beyond. Materials. Vol 13:3. pp. 801. Available: DOI 10.3390/ma13030801

Li, H., Wang, X., Zhang, W., Li, P., Wang, X., Zhang, X., Wu, B., Gao, W., Wen, J., Huang, G. and Xu, S. (2024). Multi-perspective evaluation on spent

lithium iron phosphate recycling process: For next-generation technology option. Journal of Environmental Management, [online] Vol 367. Article no; 121983. Available: DOI 10.1016/j.jenvman.2024.121983.

Liu, Z., Sederholm, J.G., Lan, K., Cho, E.J., Dipto, M.J., Gurumukhi, Y., Rabbi, Kazi Fazle, Hatzell, M.C., Perry, N.H., Miljkovic, N., Braun, P.V., Wang, P. and Li, Y. (2023). Life cycle assessment of hydrometallurgical recycling for cathode active materials. Journal of Power Sources. [online] Vol 580. Article no; 233345. Available: DOI 10.1016/j.jpowsour.2023.233345.

Luo, B., Xu, B., Yan, Q., Zhou, Y., Dong, Z., Huang, X. and Zhao, Z. (2025). Advances and challenges in recycling spent LiFePO4 batteries. Separation and Purification Technology, [online] vol 362:2. Article no: 131780. Available: DOI 10.1016/j.seppur.2025.131780.

Ma, X., Ma, Y., Zhou, J. and Xiong, S. (2018). The Recycling of Spent Power Battery: Economic Benefits and Policy Suggestions. IOP Conference Series: Earth and Environmental Science, [online] 159(1), Article no: 012017. Available: DOI 10.1088/17551315/159/1/012017.

Ma, Z., Shao, G., Fan, Y., Wang, G., Song, J. and Liu, T. (2014). Tunable Morphology Synthesis of LiFePO4 Nanoparticles as Cathode Materials for Lithium Ion Batteries. ACS Appl. Mater. Interfaces, [online] Vol 6:12. pp.9236–9244. Available: DOI 10.1021/am501373h.

Mahandra, H. and Ghahreman, A. (2021). A sustainable process for selective recovery of lithium as lithium phosphate from spent LiFePO4 batteries. Resources, Conservation and Recycling, [online] Vol 175. Article no: 105883. Available: DOI 10.1016/j.resconrec.2021.105883.

Makuza, B., Tian, Q., Guo, X., Chattopadhyay, K. and Yu, D. (2021). Pyrometallurgical options for recycling spent lithium-ion batteries: A comprehensive review. Journal of Power Sources, [online] Vol 491. Article no: 229622. Available: DOI 10.1016/j.jpowsour.2021.229622.

Mallick, P.K. (2021). Materials, Design, and Manufacturing for Lightweight Vehicles. Cambridge, United Kingdom: Woodhead Publishing. (2nd Edition). pp 384-389. ISBN 978-0-12-818712-8

Mekonnen, Y., Sundararajan, A. and Sarwat, A.I. (2016). A review of cathode and anode materials for lithium-ion batteries. SoutheastCon. pp.1–6. Available: DOI 10.1109/SECON.2016.7506639.

Naseri, T. and Mousavi, S.M. (2024). Treatment of spent lithium iron phosphate (LFP) batteries. Current Opinion in Green and Sustainable Chemistry. [online] Vol 47. Article No: 100906. Available: DOI 10.1016/j.cogsc.2024.100906.

Nzereogu, P.U., Omah, A.D., Ezema, F.I., Iwuoha, E.I. and Nwanya, A.C. (2022). Anode materials for lithium-ion batteries: A review. Applied Surface Science Advances, [online] Vol 9. Article no: 100233. Available: DOI 10.1016/j.apsadv.2022.100233.

Ouchi, T., Forsberg, K., Azimi, G., Alam, S., Neelameggham, N.R., Kim, H., Alafara Abdullahi Baba, Peng, H. and Athanasios Karamalidis (2023). Rare Metal Technology 2023. Springer Nature. pp.247–257. ISBN 978-3-0312-2761-5

Padhi, A. K. Nanjundaswamy, K. S. Goodenough, J. B. (1997). Phospho-olivines as Positive-Electrode Materials for Rechargeable Lithium Batteries. Austin, Texas: Journal of The Electrochemical Society. Vol 144:4. pp. 1188-1194. Available: DOI 10.1149/1.1837571

Palaniyandy, N., Abhilash, K.P. and Nalini, B. (2022). Solid State Batteries: Design, Challenges and Market Demands. Springer Nature, pp.262–271. ISBN 978-3-031-12469-3

Qu, G., Yang, J., Wang, H., Ran, Y., Li, B. and Wei, Y. (2023). Applicability of the reduction smelting recycling process to different types of spent lithium-ion batteries cathode materials. Waste Management, [online] Vol 166. pp.222–232. Available: DOI 10.1016/j.wasman.2023.05.009.

Ren, J., Zhu, H., Fang, Y., Li, W., Lan, S., Wei, S., Yin, Z., Tang, Y., Ren, Y. and Liu, Q. (2023). Typical cathode materials for lithium-ion and sodium-ion batteries: From structural design to performance optimization. Carbon Neutralization. Vol 2:3. pp.339–377. Available: DOI 10.1002/cnl2.62.

Rostami, H., Valio, J., Tynjälä, P., Lassi, U. and Suominen, P. (2024). Life Cycle of LiFePO4 Batteries: Production, Recycling, and Market Trends. ChemPhysChem. [online] Vol 25:24. Article No: 202400459. Available: DOI 10.1002/cphc.202400459.

Roy, J.J., Cao, B. and Madhavi, S. (2021). A review on the recycling of spent lithium-ion batteries (LIBs) by the bioleaching approach. Chemosphere, [online] Vol 282. Article No: 130944. Available: DOI 10.1016/j.chemosphere.2021.130944.

Saju, D., Ebenezer, J., Chandran, N. and Chandrasekaran, N. (2023). Recycling of Lithium Iron Phosphate Cathode Materials from Spent Lithium-Ion Batteries: A Mini-Review. Ind. Eng. Chem. Res., [online] Vol 62:30. pp.11768–11783. Available: DOI 10.1021/acs.iecr.3c01208.

Tian, X., Ma, Q., Xie, J., Xia, Z. and Liu, Y. (2024). Environmental impact and economic assessment of recycling lithium iron phosphate battery cathodes: Comparison of major processes in China. Resources, Conservation and Recycling, [online] Vol 203. Article no: 107449. Available: DOI 10.1016/j.resconrec.2024.107449.

Trading Economics (2025). Lithium. [online] Trading Economics. [Accessed 13.4.2025]. Available at: https://tradingeconomics.com/commodity/lithium

Vasconcelos, D. da S., Tenório, J.A.S., Botelho Junior, A.B. and Espinosa, D.C.R. (2023). Circular Recycling Strategies for LFP Batteries: A Review Focusing on Hydrometallurgy Sustainable Processing. Metals. Vol 13:3. p.543. Available: DOI 10.3390/met13030543.

Wang, C., Yang, H., Yang, C., Liu, Y., Bai, L. & Yang, S. (2023). A novel recycling process of LiFePO4 cathodes for spent lithium-ion batteries by deep eutectic solvents. The Journal of Material Cycles and Waste Management. Vol 25:4. pp. 2077-2086. Available: DOI 10.1007/s10163-023-01654-3

Wang, M. et al. (2022). Recycling of lithium iron phosphate batteries: Status, technologies, challenges, and prospects. Renewable and Sustainable Energy Reviews. Vol 163. Article no: 112515. Available: DOI 10.1016/j.rser.2022.112515

Wang, S. Liu, K. Wang, Y. (2022). AI for Status Monitoring of Utility Scale Batteries. London, United Kingdom: The Institution of Engineering and Technology. pp. 37-42. ISBN 978-1-83953-738-7

Wu, X., Liu, Y., Wang, J., Tan, Y., Liang, Z. and Zhou, G. (2024). Toward Circular Energy: Exploring Direct Regeneration for Lithium-Ion Battery Sustainability. Adv. Mater., [online] Vol 36:32. Article no; 2403818. Available: DOI 10.1002/adma.202403818.

Xu, P., Dai, Q., Gao, H., Liu, H., Zhang, M., Li, M., Chen, Y., An, K., Meng, Y.S., Liu, P., Li, Y., Spangenberger, J.S., Gaines, L., Lu, J. and Chen, Z. (2020). Efficient Direct Recycling of Lithium-Ion Battery Cathodes by

Targeted Healing. Joule, [online] Vol 4:12. pp.2609–2626. Available: DOI 10.1016/j.joule.2020.10.008.

Xu, P., Darren, Jiao, B., Gao, H., Yu, X. and Chen, Z. (2023). A Materials Perspective on Direct Recycling of Lithium-Ion Batteries: Principles, Challenges and Opportunities. Adv. Funct. Mater., [online] Vol 33:14. Article no; 2213168. Available: DOI 10.1002/adfm.202213168.

Yao, H., Zhang, Y., Yang, G., Fu, L., Li, Y., Zhou, L., Geng, S., Xiang, Y. and Wei, S.Z. (2024). Recycling of Spent Lithium Iron Phosphate Cathodes: Challenges and Progress. ACS Appl. Mater. Interfaces, [online] Vol 16:49. pp.67087–67105. Available: DOI 10.1021/acsami.4c09359.

Yang, N., Zhao, G. and Foord, J.S. (2020). Nanocarbon Electrochemistry. [online] John Wiley & Sons. pp. 85-89. ISBN 978-1-5231-3733-6.

Yang, Y., Zheng, X., Cao, H., Zhao, C., Lin, X., Ning, P., Zhang, Y., Jin, W. and Sun, Z. (2017). A Closed-Loop Process for Selective Metal Recovery from Spent Lithium Iron Phosphate Batteries through Mechanochemical Activation. ACS Sustainable Chem. Eng., [online] Vol 5:11. pp.9972–9980. Available: DOI 10.1021/acssuschemeng.7b01914.

Zhang, X., Liu, Z. and Qu, D. (2023). Proof-of-Concept study of ion-exchange method for the recycling of LiFePO4 cathode. Waste Management, [online] Vol 157, pp.1–7. Available: DOI 10.1016/j.wasman.2022.12.003.

Zhao, T., Mahandra, H., Marthi, R., Ji, X., Zhao, W., Chae, S., Traversy, M., Li, W., Yu, F., Li, L., Choi, Y., Ghahreman, A., Zhao, Z., Zhang, C., Kang, Y., Lei, Y. and Song, Y. (2024). An overview on the life cycle of lithium iron phosphate: synthesis, modification, application, and recycling. Chemical Engineering Journal, [online] Vol 485. Article no: 149923. Available: DOI 10.1016/j.cej.2024.149923.

Zhao, T., Marthi, R., Mahandra, H., Chae, S., Traversy, M., Sadri, F., Choi, Y. and Ghahreman, A. (2023). Direct selective leaching of lithium from industrialgrade black mass of waste lithium-ion batteries containing LiFePO4 cathodes. Waste Management, [online] Vol 171. pp.134–142. Available: DOI 10.1016/j.wasman.2023.08.030.

During this bachelor's thesis, AI tools (such as ChatGPT and DeepSeek) were utilized to check grammar and improve sentence structure. All information, interpretations, and references were verified manually by the author.