NanoScience Technology, Volume 8 (2023), pp: 24-43

NanoScience Technology

Journal homepage: https://jnanoscitec.com

Current and future prospects of Li-ion batteries: A review

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Abstract

In contemporary society, Li-ion batteries have emerged as one of the primary energy storage options. Li-ion batteries' market share and specific applications have grown significantly over time and are still rising. Many outstanding scientists and engineers worked very hard on developing commercial Li-ion batteries in the 1990s, which led to their success. An aqueous or non-aqueous electrolyte, an anode, a cathode, and a membrane that separates the two while permitting ions through are the four essential components of all battery systems. While still underutilized in power supply systems, Li-ion batteries are the preferred solution for the developing electric car industry, particularly when combined with photovoltaics and wind power. As a technological advancement, Li-ion batteries provide enormous worldwide potential for sustainable energy production and significant carbon emission reductions. This review covers the working principles, anode, cathode, and electrolyte materials and the related mechanisms, aging and performance degradation, applications, manufacturing processes, market, recycling, and safety of Li-ion batteries.

Keywords: *Li-ion battery, Anode, Cathode, Electrolyte, Grid energy storage, Recycling*

© Article info: Accepted by: 3 March 2023, Published by: 17 March 2023.

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1. Introduction

Concerns about air pollution and the diminishing availability of fossil fuels in recent decades have prompted numerous studies to focus heavily on substituting alternative energy converters like solar panels and wind turbines for fossil fuels [1]. Efficient energy storage is seen as essential for the smooth transition to renewable energy sources, and electrochemical energy storage technologies have played an important role. They will continue to play a significant role in helping to realize this desirable objective. Gilbert N. Lewis, a professor of physical chemistry and the dean of the College of Chemistry at the University of California, Berkeley, began his work on lithium batteries in 1912. In the 1970s, the first primary lithium batteries hit the market. Before Sony Energytec's 1990 commercialization of the first rechargeable Li-ion battery, two more decades had passed. One of these Li-ion batteries in a handheld video camera exploded shortly after. Since then, it has become well-recognized that one of the main issues with lithium batteries is the safety concern related to the threat of thermal runaway and battery fire [2].

Nowadays, Li-ion batteries have been widely used in portable electronics, electric vehicles, and grid storage. These batteries are the leading technology for these uses due to their high energy density, good cycle ability, high operating voltage, and low self-discharge. As a result, efforts are being made to significantly boost energy density in order to extend the range of electric vehicles [3]. These batteries can contribute significantly to establishing a sustainable energy future in our contemporary society. By offering storage capacity and auxiliary services, Li-ion batteries, in conjunction with the electrical grid, could facilitate the integration of high shares of photovoltaic (PV) and wind energy in the power mix [4]. New energy vehicle advancements are now the go-to option for sustainable development. Li-ion batteries have been extensively employed in the domains of communication, aviation, automobiles, and other industrial sectors. They are the primary power source of new energy vehicles [5].

Consumer electronics have significantly increased demand for Li-ion batteries during the past ten years. 7.19 billion mobile phones, almost a billion laptops, and another billion tablets are in use now globally [6]. Due to their exceptional benefits over other battery technologies, Li-ion batteries have garnered much attention as grid support equipment [7–9]. Li-ion batteries have successfully been developed in recent years, and their performance has improved noticeably [10–12]. Li-ion batteries are an exceptionally flexible technology since the combination of electrochemically active and inactive components ultimately determines the cell's performance metrics and general features [13–17]. Most recent Li-ion battery research has been on various active electrode materials and appropriate electrolytes for high cut-off voltage applications [18]. On the other hand, numerous studies have been conducted regarding improving battery management systems, safety, and efficiency. The development and synthesis of high-performance materials have also significantly improved the performance of the cathode, anode, and electrolyte. Furthermore, machine learning methods have recently played a role in developing Li-ion batteries. Another critical aspect that has received more attention in recent years with the significant increase in the consumption of Li-ion batteries is their recycling, and various methods have been studied in this field.

This paper investigates Li-ion batteries from various aspects, and the fundamental principles and recent developments have been described. In section 2, the basic principles of these batteries are explained, and their components and mechanism of operation are described. Also, the types of anodes, cathodes, and electrolytes investigated recently in various researches are mentioned. In addition, different types of Li-ion batteries have been noticed. Sections 3 and 4 describe Li-ion battery aging, performance degradation, and various applications. Section 5 presents the current process of producing Li-ion batteries. Sections 6 and 7 deal with the Li-ion battery market and artificial intelligence applications in their improvement, respectively. In section 8, the processes related to recycling Li-ion batteries are mentioned, and in section 9, the safety problems of these batteries and solutions are described.

2. Li-ion battery fundamentals

Li-ion batteries have been used commercially for more than thirty years. During this time, Li-ion batteries have been widely used in various industries [19]. A Li-ion battery contains a cathode, anode, electrolyte, and separator as its main components [20]. The movement of electrons through the external circuit and lithium ions through the electrolyte causes the charging and discharging of these batteries (Figure 1) [21].

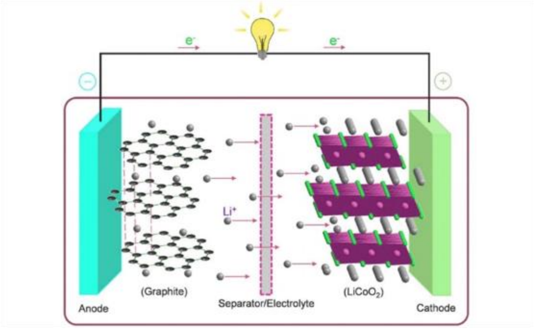

Figure 1. Illustration of a lithium-ion cell's fundamental parts [21].

2.1 main components of a Li-ion battery

2.1.1 Anode

2.1.1.1 Carbon-based anodes

A Li-ion battery's anode is usually made of graphite because carbon is cheap and widely available. In addition, the stability of graphite makes it a common material in commercial Li-ion batteries. The low thermal expansion of Li-ion batteries helps them to maintain their discharge/charge capacity even after long discharge/charge cycles. However, the capacity of graphite to accommodate lithium insertion is relatively low, and if this property is improved, Li-ion batteries will attract more attention [19]. Despite graphite's consistent and well-known performance, the growing range of applications for rechargeable batteries exposes the drawbacks of carbon-based anodes. The first and foremost challenge is the issue of lithium plating, which results from a potential thermodynamic shift at low temperatures brought on by the low working potential of graphite and overpotentials at high currents brought on by the increasingly fast charging rates that are currently necessary [1].

A graphene sheet has a carbon atom as its only layer of thickness. Graphene has good mechanical properties because of its hexagonal lattice structure. However, there are certain practical use restrictions for graphene. The enormous specific surface area between graphene sheets will lead to aggregation, and a reduction in the effective area will lower the capacity. Additionally, the movement of electrons and Li^+ in the sheets is limited, leading to poor performance of graphene as an anode material. Another carbon-based material that could be used as an anode is porous carbon nanostructure. The network structure is highly stable, has outstanding electrochemical performance, and prevents irreversible capacity loss. Higher capacity, better rate performance, and better cycle stability are all characteristics of Li-ion batteries that use hollow carbon spheres as the anode [22].

2.1.1.2 Alloying-type anodes

Compared to carbon-based anodes, alloying-type anodes often offer substantially greater specific capacities. Due to their largest gravimetric and volumetric capacities, electrochemical alloys of lithium and silicon have the most promise for practical applications [22]. The performance of Li-ion batteries created with Si/graphite has unique benefits over other methods, including low electrode swelling and good stability. Further, dependable electrolyte design can be established to produce lower electrode swelling, larger areal capacity, and lower cost of Si-based electrodes through enhanced structural design, more controllable graphite-blended, molecular design, or hybrid binder material synthesis. Despite the significant advancements, Si-based anodes still need to be developed. Poor electrical conductivity and wide volume variation are some of the problems of Si-based anodes. Si-based Li-ion batteries with high energy and power densities are anticipated to be produced soon [23], [24].

Germanium (Ge) and Si have lots of similar properties. Germanium conductivity and lithium-ion diffusion rate are superior to silicon. Due to Germanium's isotropic volume expansion and homogeneous stress on the anode, the issue of electrode material cracking brought on by stress concentration is avoided. The same volume expansion issue that Si has also affected Ge. Ge has a relatively high price because it is a rare metal [25]. Ge nanoparticle performance can be slightly enhanced by carbon coating [26].

2.1.1.3 Transition metal oxides

Theoretically, the specific capacity of transition metal oxide (TMO) anodes is high, and they function exceptionally well during cycles. TMO anode materials provide better safety and specific capacity when compared to commercially available graphite anodes since they can prevent lithium dendrites [21]. TMO-based anodes are more affordable to produce than alloying-type materials. Nevertheless, the commercial application currently in use is still in its infancy, and a number of issues still need to be resolved, including poor conductivity causes by breakdown and voltage hysteresis between charge and discharge. [25]. Co, Fe, and Mn are some of the typical transition metals used in the conversion mechanism. For high-power batteries, titanium oxides, particularly lithium titanate ($Li_4Ti_5O_{12}$, LTO), could be an appropriate choice for Li-ion anode. LTO-based anodes have high substantial working potential. The 3D structure of LTO should result in outstanding rate performance. Nevertheless, it performs poorly at high rates because of its low intrinsic electronic conductivity and low Li^+ diffusion coefficient [27]. The discovery of electrolytes that remain stable at high voltages may increase the use of LTO-based batteries. In the near future, nano-structured carbons, which offer better thermal and electronic conductivity, will likely replace graphite as a conductive additive, which is required for LTO electrodes [1].

Iron oxides such as Fe_2O_3 and Fe_3O_4 can be used as anodic materials. To enhance the electrochemical performance, carbon-based materials or coatings are mixed with iron oxides [28]. Two Co oxides with high specific capacities are CoO and Co_3O. By altering the synthesis procedure and environmental factors, the size and shape of the Co-based oxide can be changed. The most popular techniques for synthesizing Co-based anode materials are hydrothermal methods [29]. Mn oxides such as MnO and Mn_3O_4 are other examples of TMOs that have attracted much attention because of their high capacity and low cost, even though they have disadvantages like other TMOs [30].

2.1.1.4 Metal organic frameworks

Metal organic frameworks (MOFs), which have a large specific surface area and variable pore sizes, have received much attention recently as anode materials for Li-ion batteries. Their porous structure allows for the entrance and extraction of lithium electrons and can adapt to the battery's volume change during charging and discharging. By choosing various organic ligands, the battery operating voltage can be changed based on the benefits of the self-assembly of organic ligands and metal ions. Increased lithium-ion storage sites and improved battery electrochemical performance can be achieved by altering organic ligands. Hence, a hollow framework that is appropriately orientated must be designed. Additionally, the structure must have high stability to prevent structural failure during the cycle. The MIL (Materials of Institute Lavoisier), MOF (Materials Organic Framework), ZIF (Zeolitic Imidazolate Framework), and PB (Prussian Blue) are common MOFs utilized for lithium battery negative electrode materials [25].

2.1.2 Cathode

2.1.2.1 Metal oxide cathode materials

Current commercial Li-ion batteries are named after the lithium-ion in the cathode, which is the primary determinant of battery performance. Usually, cathodes are composed of a complex lithium composite material, especially several lithium metal oxide materials, such as $LiCoO_2$, $LiMn_2O_4$, and $LiFePO_4$. With different cathodes, battery performance varies. Compared to metallic lithium, all of the above compounds exhibit high impedance due to low diffusion coefficients and ionic conductivity [19].

Due to its high specific capacity and high nominal voltage, lithium cobalt oxide ($LiCoO_2$) has been recommended as a promising alternative ever since the commercialization of Li-ion batteries began. A metal oxide, such as ZrO_2, can be coated on the surface of the $LiCoO_2$ particles to increase their specific capacity to 170 mAh/g. The findings demonstrate that $LiCoO_2$ coated with ZrO_2 may effectively prevent Cobalt dissolution and produce excellent electrochemical behavior in higher voltages (above 4.4V) [31]. Compared to $LiCoO_2$, $LiNiO_2$ is significantly less hazardous, has an exceptional achievable specific capacity of 240 mAh/g, and is significantly less expensive. Due to the preferred cation mixing of Li and Ni ions, it is relatively challenging to synthesize $LiNiO_2$. Poor performance is caused by the excess Ni ions that are residing in the lithium layers, which obstruct the Li^+ ability to move easily during cycling. Additionally, throughout cycling, the material goes through a number of structural changes [32].

Compared to cobalt and nickel oxides, manganese oxides are more affordable which makes them promising cathode materials [33]. The orthorhombic $LiMnO_2$ structural varieties of these batteries are well-known. There are some stability issues with the battery system at high temperatures. Due to its high capacity, consistent crystal structure, and low price, vanadium pentoxide (V_2O_5) is a good option. However, the actual use of V_2O_5 in Li-ion batteries is hampered by its low electronic conductivity, low Li^+ diffusion coefficient, poor rate capability, and poor cycle stability [31].

2.1.2.2 Spinel cathode materials

High voltage cathodes (4.5–5.0 V) have been proposed for more sophisticated Li-ion batteries as a feasible candidate. The main substances in this group include spinel $LiMn_{1.5}Ni_{0.5}O_4$, olivine $LiCoPO_4$, olivine $LiNiPO_4$, and inverse spinel $LiNiVO_4$. [34]. Due to its low cost, reversible, and rapid intercalation of Li^+, spinel $LiMn_2O_4$ is one of the most alluring cathode materials. Spinel $LiMn_2O_4$ is thought to behave electrochemically better at 4V than 3V. In general, $LiMn_2O_4$ experiences capacity fading due to phase transitions as well as the chemical instability of the spinel $LiMn_2O_4$ with the electrolyte, which causes the dissolution of Mn ions. This problem is most acute at temperatures of 55℃ [32]. The cathode materials of $LiMn_2O_4$ batteries can be improved by coating or doping aluminum or by cationic substitution with some transitional metals like Cr, Ti, Cu, Ni, Mg, and Fe [1]. The spinel $LiMn_2O_4$ is transformed into $LiNi_{0.5}Mn_{1.5}O_4$ by substituting 25% of the Mn ions for Ni ions, which is one of the most promising cathode materials for high-energy applications. In $LiNi_{0.5}Mn_{1.5}O_4$, the disorganized structure performs better than the regular spinel structure. Although compared to other materials, it has tremendous voltages beyond the electrolyte's stability range. It has an impact on the kinetics of Li-ion electrochemistry [32].

2.1.2.3 Polyanionic cathode materials

Over twenty years ago, lithium transition metal phosphates with an olivine structure were initially developed as cathode materials for Li-ion batteries. As a cathode material for Li-ion batteries, polyanionic olivine $LiMPO_4$ is particularly appealing. The relatively low electronic conductivity of this material presents a significant obstacle. Instead of only employing one or more conductive carbons as an electrode additive, the active material nanoparticles are surface coated with carbon to resolve this problem. Despite their reduced electronic conductivity, phosphate materials are frequently employed in high-power applications, such as hybrid electric vehicles, because the active material design has significantly improved [1].

$LiFePO_4$ has a limited application in the automotive sector due to its low energy density. Therefore, it is crucial to research and create additional olivine family members, such as $LiMnPO_4$, with a greater discharge voltage and energy density. $LiMnPO_4$ had more potential and a higher energy density than $LiFePO_4$. Nevertheless, $LiMnPO_4$'s weak kinetics and low ionic and electronic conductivity compromise its cyclic stability and rate capacity. The potential of the $LiCoPO_4$ and $LiNiPO_4$ materials is very high. Lithium extraction from $LiNiPO_4$ is challenging to achieve within the constant voltage range of the accessible electrolytes. Additionally, compared to $LiFePO_4$ and $LiMnPO_4$, both compounds displayed substantially poorer electronic conductivity. In the process of looking for alternative high-energy cathode materials, silicate was used to replace phosphate. Due to their better electrochemical performance, safety, accessibility of raw materials, and affordability, these cathode materials are intensely interesting. Compared to Li_2FeSiO_4, Li_2MnSiO_4 has a higher redox potential and specific capacity, making it a more intriguing material [32].

2.1.3 Electrolyte

Li-ion batteries are distributed into liquid electrolytes and semi-solid and solid-state electrolytes. Liquid electrolytes are generally composed of lithium salts (e.g., $LiBF_4$, $LiPF_6$, and LiN) in organic carbonates (e.g., ethylene carbonate, propylene carbonate, ethyl methyl carbonate, dimethyl carbonate, and their mixture). Generally, semi-solid and solid-state electrolytes are formed from lithium salts as conducting salts and high molecular weight polymer matrices [19]. Garnet, LISICON, NASICON, sulfide, and polyethylene oxide are a few examples of solid electrolytes that have been researched. The use of the high-voltage cathodes discussed above will be possible, and novel liquid or solid electrolytes with required properties may also provide improved safety [5].

2.1.3.1 Aqueous electrolytes

Aqueous liquid electrolytes have significant stability restrictions with the electrodes in contrast to other liquid electrolytes, which hampered their progress. Although, aqueous electrolytes have garnered increased attention recently due to growing interest in highly safe electrolytes and high rate-capable, affordable, and environmentally friendly battery systems. On the other hand, aqueous liquid electrolytes are substantially more affordable because they are water-based and have incredibly high ionic conductivity [35]. High-concentration aqueous electrolytes made of water and salt have recently attracted much attention [36].

2.1.3.2 Organic liquid electrolytes

Electronic devices, power storage systems, and portable electronic devices all use Li-ion batteries with organic electrolytes [37]. Due to their intriguing properties, such as better ionic conductivity than solid electrolytes and regular contact with various electrodes, organic liquid electrolytes have been extensive research in recent years. Several physical criteria, particularly the safety and stability of the thermal and electrochemical processes, remain a problem. By changing the existing electrolyte systems, recent advancements in organic liquid electrolytes are looking to solve these problems. More intriguingly, due to their remarkable oxidation resistance, highly concentrated organic liquid electrolytes have recently been the subject of extensive research [35].

2.1.3.3 Ionic liquid electrolytes

Ionic liquids, also known as room temperature molten salts, are becoming more and more popular as potential electrolyte materials for Li-ion batteries because of their exceptional characteristics of suitable ionic conductivity at room temperature, high thermal stability, and greater safety compared to organic solvent electrolytes. Traditional organic solvent-based electrolytes are modified by adding a small amount of ionic liquids or by dissolving a lithium salt in an ionic liquid to create typical ionic liquids-based electrolytes for Li-ion batteries. Semisolid electrolytes for Li-ion batteries that are based on ionic liquids are made up of a parent polymer matrix, ionic liquids, and Li salts, which are also known as ionic liquid gels [38].

2.1.3.4 Solid-state electrolytes

Solid polymer electrolytes (SPEs) have recently been seen as one of the most promising alternatives for high performance. This is explained by their affordability, lightweight, and exceptional capacity to accept the volume variations of the electrodes throughout the charging and discharging operations, enabling flexible battery designs in any desired configurations and reducing the negative impacts. Therefore, solid electrolytes are emerging as the favored choice due to the rising requirement for high safety and flexibility in sophisticated energy storage systems. However, compared to other forms of electrolytes, the reported ionic conductivity of SPEs is substantially lower, indicating that the most challenging and pressing issue for solid polymer electrolytes is enhancing ionic conductivity [35,39].

2.2 Working principles

Two electrodes are connected to an external electrical source During charge process. As a result, electrons enter at the cathode, and leave the anode. At the same time, lithium ions internally move in a similar direction through the electrolyte from the cathode to the anode. Accordingly, external electrical energy is stored electrochemically in the battery as chemical energy in anode and cathode materials with different chemical potentials. In the discharge process, electrons move from the anode to the cathode, and lithium ions move from the anode to the cathode through the electrolyte [40,41].

2.3 Characteristics of Li-ion batteries

Coin, cylindrical, prismatic, and pouch are the most prevalent types of commercial Li-ion batteries in use today [19]. Graphite anode has a have theoretical capacity of 372 mAh/g and lithium metal oxide cathode materials, such as $LiCoO_2$, $LiFePO_4$, and $LiMn_2O_4$, currently used in commercially accessible Li-ion batteries, have theoretical capacities of less than 200 mAh/g. Li-ion batteries display a 75–200 Wh/kg specific energy. Numerous alternatives to graphite that have greater specific capacities are being investigated in order to increase the specific energy of Li-ion batteries further. Additionally, Li-ion batteries' cycle life is exceptionally alluring and can reach 10,000 cycles [19,42]. Additionally, the life of Li-ion batteries is significantly impacted by the storage temperature. To enhance the actual application of Li-ion batteries, more work is needed to investigate the self-discharging mechanism and develop cutting-edge electrodes and electrolytes [19].

Li-ion batteries will inevitably fail early if they are put under conditions that were not intended for them. Mainly, mishaps and safety concerns are frequently caused by the interactions of charged positive and negative electrodes with electrolytes at high temperatures. The phenomenon that Li-ion batteries start to lose capacity when cycled at temperatures higher than 60 °C is explained by the fact that all of these substances start reacting with the electrolyte at a modest rate at about 80 °C. Thus, before they can be approved for use, Li-ion batteries must undergo a variety of safety tests. The safety test must comprise mechanical, environmental, and electrical testing (such as short circuits and abnormal discharge and charging), which assist in establishing performance limits and guaranteeing the operational safety of Li-ion batteries [19].

3. Li-ion battery aging and performance degradation

The performance of Li-ion batteries can be significantly impacted by aging and inappropriate operation. Battery leakage, insulation degradation, and partial short circuit issues are all difficulties that can result in catastrophic accidents when the battery performance deteriorates to a certain degree. Investigations have revealed a connection between these accidents and Li-ion battery aging. Therefore, it is crucial to research the state of health (SOH) of Li-ion batteries to prevent catastrophic accidents.

Currently, some people evaluate battery performance and aging, using the battery's remaining useful life (RUL). As a result, SOH and RUL are closely related and may be used to describe battery performance [43,44].

3.1 Li-ion battery aging

The main factor influencing changes in battery health and life is Li-ion battery aging. External environmental and internal factors are the major causes of battery aging. External environmental factors include the battery's physical location as well as its working conditions, including temperature, charge and discharge rates, depth of discharge, and charging cut-off voltage. Three influencing processes are primarily referred to as internal factors: conductivity loss, loss of active material, and loss of lithium inventory. The development of an SEI layer, the growth of lithium dendrites, and battery self-discharge are all factors in the loss of lithium inventory. The aging mechanism that results in the battery's current collector breaking and decomposing and the battery adhesive peeling off and deteriorating is primarily what is meant by conductivity loss [43].

3.2 State of health (SOH) and remaining useful life (RUL)

State of health (SOH) measures a battery's dynamic state in relation to its starting condition. This initial state is typically regarded as 100%. Because of irreversible internal chemical and physical processes often referred to as battery aging, the SOH will decrease over time and with use. The battery's SOC, which estimates the proportion of energy it now holds compared to its most recent fully charged condition, is a crucial indicator of the battery's immediate status. The SOC can give the user a rough estimate of how long the battery will survive before it completely discharges [44].

Remaining useful life (RUL) denotes the time frame from the time of the observation to the anticipated end of life. When a battery characterization parameter crosses the threshold for replacement, that point is referred to as the estimated end of life [43].

The most crucial Li-ion battery characteristics to consider when assessing the battery's current health state are SOH and RUL. The steady functioning of electric vehicles is confirmed by the reliable and precise methodologies used to estimate SOH and RUL for Li-ion batteries. However, the charge-discharge cycles, temperature variations, and Li-ion batteries aging affect how well they work. As a result, a suitable and reliable SOH and RUL algorithm is required to solve current issues and enhance performance [45].

According to their definition, there is a close relationship between SOH and RUL since both concepts may be defined using the aging parameter. As a result, from this perspective, the SOH and the RUL may be calculated using the same techniques [43]. Various techniques, including conventional methodologies, model-based approaches, and clever algorithms, are used to assess the battery's SOH and RUL. Nevertheless, the approach's robustness is lacking due to model uncertainty. However, the calculation involved in the approaches is complicated and requires a lot of training data [45].

4. Application of Li-ion batteries

4.1 Electric vehicles

Electric vehicles will largely replace gasoline-powered vehicles in the near future. The primary element of an Electric vehicle is its rechargeable battery, which demands exceptional performance. The Li-ion battery has been used extensively in consumer electronics because it has a high energy and power density, a long service life, and is environmentally friendly compared to other regularly used rechargeable batteries including Ni-Cd, Ni-MH, and Lead-acid batteries. To create a battery pack, many batteries must be arranged in parallel and serial for use in high-power applications like electric vehicles and energy storage devices. Cost, stability, consistency, and safety issues are brought forth by this. Li-ion batteries' range of uses is constrained by these issues [46].

The charge rate, temperature, and voltage range all have an impact on how safely and reliably Li-ion batteries can be used. If these limits are exceeded, battery performance may quickly deteriorate and may potentially cause safety issues. Additionally, it is crucial to assess the Li-ion battery capacity and project the Electric vehicle's remaining useful life over the battery's service life to guarantee the reliable operation of Li-ion batteries. Further, cell sorting techniques are essential to ensure cells' dependability and security [46].

The external environment and internal elements that affect Li-ion batteries cause battery aging and performance degradation, which should be taken into account while assessing their SOH. In battery electric vehicles, accurate SOH prediction helps prolong battery life and promote safe operation. There are several SOH prediction algorithms available right now, but the majority of them are used in simulated settings because they are difficult to use in actual industrial production [43].

4.2 Portable electronic devices

Since the Sony Corporation initially commercialized the Li-ion battery in 1991, Li-ion batteries have become the most widely used rechargeable batteries today, ushering in a new era for portable electronic devices. They have posed a significant threat to other battery types since their introduction, which can be attributed to several benefits, including high specific energy (typically twice that of standard Ni-Cd batteries), low self-discharge rate, high voltage (three times that of typical Ni-based battery), maintenance-free, lightweight, good safety and cycling performance. Due to their excellent characteristics, Li-ion batteries are the most excellent energy storage choice for portable electronic devices, such as mobile phones, laptops, and digital cameras [41,47].

There are still some issues with Li-ion batteries. For example, compared to other rechargeable batteries, the more significant production costs increase prices. Li-ion batteries also need extra protective circuits to restrict voltages and currents during operation. Furthermore, Li-ion batteries would degrade if kept at temperatures above 30°C for a lengthy period. Li-ion battery issues are being actively researched and worked on by battery scientists and engineers, especially for using portable electronic devices [41].

4.3 Grid storage

The grid energy storage system is crucial to maintaining a balance between power generation and consumption during the electrical energy transformation. Due to rapid response, modular design, and adaptable installation, batteries have much promise for usage in grid energy storage systems. Typically, battery technologies are needed to meet complicated and extensive distribution applications to the power grid when batteries are used as part of a grid energy storage system. Hence, it is essential to consider the criteria for grid energy storage, including capacity, energy efficiency, lifetime, and power and energy densities [19].

Because of its outstanding advantages, including relatively high specific energy (up to 200 Wh/kg), high energy efficiency (more than 95%), and extended cycle life (3,000 cycles at profound depletion of 80%), Li-ion batteries have drawn much attention as supporting devices in the grid storage. A high-value market for Li-ion batteries is shown by the fact that 77% of the electrical power storage devices in the USA that are now used to maintain the grid depend on them. Furthermore, Li-ion batteries will be an excellent option for integrating with solar and wind power in grid energy storage systems because of their high energy density [19]. Peak trimming and load leveling are required to store the electricity generated and provide electricity at peak load. Storage systems can keep the consistency of the voltage and frequency of the electrical supply when there is a mismatch between power generation and use. Li-ion batteries have a lot of potential for use because of their high energy density and round-trip efficiency [19].

4.4 Implantable medical devices

Recently, medical applications using Li-ion batteries that can be recharged while still within the body have also been developed. Although the device's particular performance needs differ, several generic criteria are similar, Such as High levels of safety, reliability, volumetric energy density, prolonged service life, and state of discharge indication. Biomedical implanted devices and their use in treating human diseases have become possible due to the successful development and use of various types of batteries, especially Li-ion batteries [48,49].

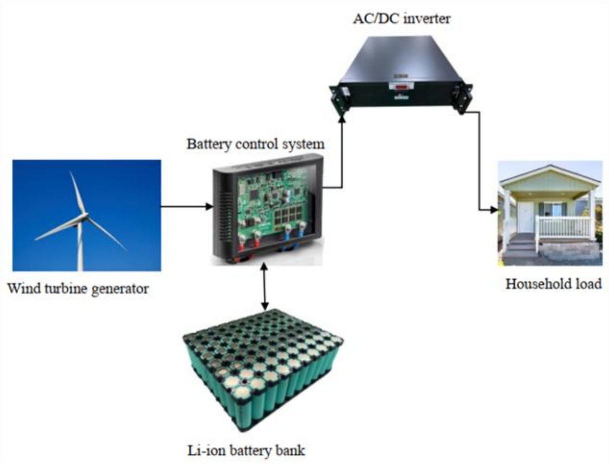

Figure 2. Schematic of wind power system with Li-ion battery bank [52].

When a Li-ion battery is utilized as the power source in an implantable medical device, it is crucial to monitor the battery's capacity deterioration and gauge its RUL over time. This can advise the patient and his or her healthcare professional as to whether and when a device replacement could be necessary. Neurological stimulators, spinal stimulators, cardiac stimulators like pacemakers and defibrillators, and diagnostic devices like cardiac monitors are a few examples of implantable medical devices that a Li-ion battery may power. [48].

4.5 Renewable energy systems

Batteries are crucial to the operation of renewable energy systems because they serve as the principal energy storage medium. Li-ion batteries hold particular promise due to their outstanding performance and steadily declining cost [50]. On the other hand, the supply of energy from renewable sources is frequently subject to changes because of things like a lack of wind or sunlight. As a result, it is essential to manage the power fluctuation of a power system that incorporates numerous renewable energy sources, like solar and wind [51,52].

One of the primary renewable energy sources is wind power generation. Wind energy generation suffers significantly from intermittency because it is so hugely affected by the season and geographic location. Furthermore, it is common to have a discrepancy between peak power output and consumption. An efficient method is to use Li-ion batteries to store extra wind turbine energy to offer electrical energy when the consumption of electricity peaks [19,52]. Figure 2

shows a schematic of using a Li-ion battery bank to store extra generated from a wind power system.

The integrated Li-ion packs can help solar photovoltaic (PV) power plants by conserving electrical energy and regulating output power. One of the critical issues is non-production solar photovoltaic throughout the night and when sunlight is obstructed. The combination of batteries creates an ideal operating system that can handle both steady-state power requirements and high-

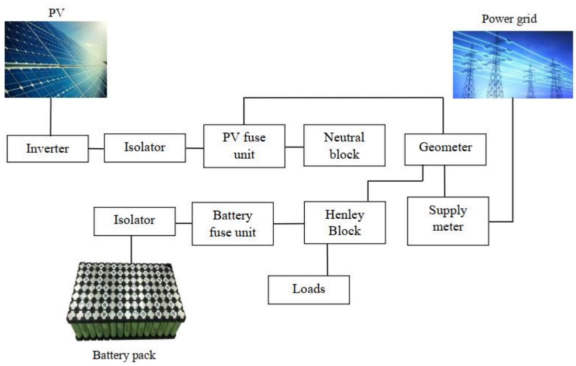

Figure 3. System diagram for a residential building with PV and static storage [71].

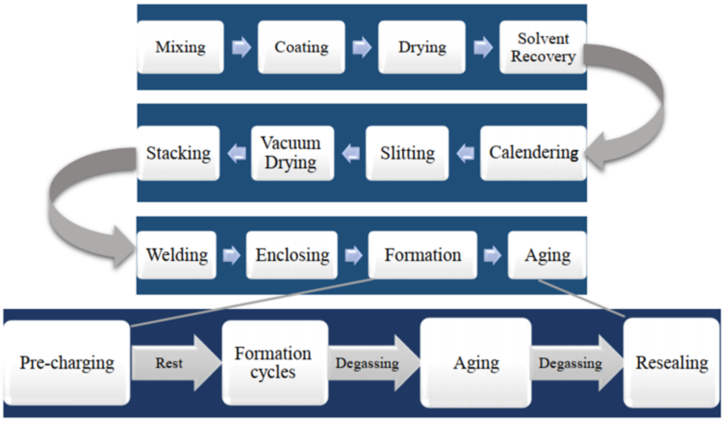

Figure 4. Illustration of Li-ion battery manufacturing processes [18].

gradient power surges. Using batteries in a solar photovoltaic farm demonstrated output power consistency. [19,53]. A PV and battery storage system schematic is given in Figure 3.

5. Li-ion batteries manufacturing process

The present Li-ion battery production process is shown in Figure 4 There are three primary components to the current Li-ion battery manufacturing process: electrode preparation, cell assembly, and battery electrochemistry activation. The active substance, conductive additive, and binder are first combined with the solvent to create a homogeneous slurry. N-methyl pyrrolidone is typically used to dissolve the polyvinylidene fluoride binder for the cathode. The styrene-butadiene rubber binder is dissolved in water along with carboxymethyl cellulose to make the anode. The slurry is then sent to drying machinery, where the solvent will be evaporated after being pumped into a slot die, and coated on both sides of the current collector [18]. The typical organic solvent used to make cathode slurry is hazardous and subject to stringent emission controls. In order to produce cathodes during drying, a solvent recovery process is therefore required, and the recovered organic solvent is then reused. The final electrodes are stamped and cut to the necessary dimension to meet the cell design after all these steps. The excess water is then drained from the electrodes in the vacuum oven. After drying, the moisture content of the electrodes will be examined to verify that side reactions and cell corrosion are kept to a minimum [18].

The electrodes are transferred to the dry room with dried separators for cell manufacture once they have been prepared. The interior structure of a cell is created by surface winding or stacking of the electrodes and separator. The cathode and anode current collectors each include aluminum and copper tabs that are welded to them. Ultrasonic welding is the most used welding technique, while other manufacturers may decide to use resistance welding for their cell designs. Although resistance welding is occasionally used by manufacturers for their cell designs, ultrasonic welding is the most popular way of joining materials [18].

Electrochemistry activation processes are used on these cells to enable operating stability before transferring them to the makers of finished products. A stable solid-electrolyte interface layer can shield the anode from overpotential during fast charging, which could lead to the formation of Li dendrites, and stop the irreversible utilization of electrolytes. For reasons of safety, the gas produced during the formation process needs to be released. The cells are kept on the aging shelves after or during creation cycles. Prior to the cells being fully sealed for future uses, another degassing procedure is planned. This procedure typically takes a few weeks, relevant to the formation methodology and aging temperature [18].

6. Li-ion battery market

The most important markets for Li-ion batteries are road transportation, portable devices, and power supply systems. Less than 5% of the demand for Li-ion battery cells is satisfied by all other systems. Portable electronic devices have been the main market for Li-ion batteries. More than 80% of this sector is devoted to mobile devices, tablets, and laptops combined. A strong 10 percent growth rate is being experienced in the demand for Li-ion batteries for mobile phones and tablets. By 2030, the demand for Li-ion batteries is expected to reach 100 GWh. Japan, Korea, China, and the United States are the major industry players on a global scale. There are some industry players who aren't completely dedicated to Li-ion batteries, which can represent just a small share of their overall portfolio. The same is particularly true for Asian large companies such as Samsung, Sony, and Panasonic [20].

Currently, the market for Li-ion batteries used in road transportation has surpassed that for portable electronics. The overall battery demand for road transportation might increase to 137 GWh in 2025 and 245 GWh in 2030, primarily due to the rising need for battery cells for electric vehicles. After 2030, used Li-ion batteries might play a significant role in the market. Due to slow acceleration and limited range, an electric vehicle's battery is deemed obsolete once its power and capacity fall below 80% of its nominal value. However, these batteries are still functional enough to have a second life in power supply systems. After 2030, when a considerable number of electric vehicles will have been retired, this major source will become even more important. [20].

7. Role of artificial intelligence applications in development of Li-ion batteries

In material science, artificial intelligence (AI) is a new method. To produce accurate, repeatable choices and outcomes, machine learning (ML), the foundational element of AI, can uncover the statistical law underlying highly dimensional data. It assures great accuracy and can predict new materials or attributes quickly. The properties of battery materials have been accurately predicted by ML mo dels such as artificial neural networks (ANN), support vector machines (SVM), random forests (RF), partial least squares regression (PLS), and logistic regression (LR) [54]. The quantity and quality of the data determine how accurate the data-driven method will be, which could cause issues with over and under-fitting of the data [55].

The many electric car fire accidents in recent years have led to high demands for battery management systems (BMS). As a result, it is critical to research develop sophisticated and intelligent battery management systems capable of accurately predicting the state of charge and health of batteries. The efficiency of calculation and the accuracy of predictions made using models still have a clear trade-off. Fortunately, because ML models have tremendous computational abilities to deal with any complex nonlinear function, they can predict the condition of the battery [54].

The core of the battery system is the BMS. It performs its functions by measuring and logging the battery's voltage, current, and temperature using sensors. A precise and reliable battery model is necessary for many BMS operations. Due to its adequate accuracy, low computational effort, and stability when applied to the most common commercial Li-ion battery chemistries, the equivalent circuit model (ECM) is the battery model that is most frequently employed in BMS applications. The ECM characteristics frequently get more complex and challenging to estimate when measurement mistakes or BMS sensor problems mount, making it difficult to predict how the battery system will behave. More advanced and accurate battery algorithms than the ECM, including machine learning battery algorithms, can be incorporated into the BMS for electric vehicles as a supplemental strategy to support the current battery control approaches [56].

In the Gaussian process regression (GPR) system, the residual and the standard deviation of the battery supply methods are estimated using the long short-term memory (LSTM) model [55]. Prediction of the SOC of battery is made using a new model based on a deep neural network. Although the real-time SOCs predicted are incorrect, the approach suggests that the anticipated SOCs converged quickly. The non-linear radial basis function neural network algorithms used in the inclusive analogy circuit model are created to forecast the approximate SOC value [57].

There are still some restrictions on deep learning. The applicability of this approach under conditions of fluctuating ambient temperature is another crucial factor. For each case study, the results apply to a specific temperature. However, when the ambient temperature varies significantly, this method won't work unless the effect of temperature is taken into account. This is because temperature variations can have a substantial impact on capacity [58].

Fewer studies have been identified so far on the use of machine learning technology to enhance battery production, in contrast to battery management, where practical solutions are accessible. To assess failure modes and parametric impacts, for instance, a data-driven method was suggested. This helps improve battery manufacturing [59]. This subject still has several limitations and challenges that must be addressed. 1) The majority of studies merely use traditional procedures to forecast battery production characteristics; little has been done to thoroughly assess data-driven approaches to boost their effectiveness in this field. 2) While engineers are interested in directly quantifying the value of battery production attributes, commonly utilized machine learning techniques such as support vector machines and neural networks only produce forecasts of battery production properties. Engineers might use this information to do sensitivity analyses for efficient feature selection and production chain optimization to further improve the performance of manufactured batteries and reach cleaner battery production [60].

Due to their extreme complexity, battery material reverse designs have not yet proven computationally practical. Finding chemical elements and material structures that can be produced in a lab is the main challenge. The first phase in the process of material discovery and design is to come up with key descriptors or qualities that are closely related to the desired material properties. Constructing a precise model between the characteristics and the goals is the next phase. Technically, the inverse design can be carried out to find new materials with the desired qualities, according to the ML model trained by a given dataset [54].

8. Li-ion battery recycling

Market sales of Li-ion batteries rose by an exponential rate from $12 billion in 2011 to $50 billion in 2020. By 2024, estimates predict a rise of $77 billion [61,62]. The total amount of Li-ion batteries that will have reached the end of their useful life is anticipated to reach 11 million metric tons by 2030, and the annual waste flows from electric vehicle batteries will increase to 340,000 metric tons by 2040 [47]. Due to the depletion of natural resources and the contamination of land and groundwater due to the non-recycling of used Li-ion batteries, this growth has severely negative effects on the environment. Sustainable recycling technologies must be used to build a circular economy for the Li-ion battery sector [61]. Recycling can bring down the price of materials and disposal, lowering the price of electric vehicles. Battery recycling can also decrease the demand for raw materials and reliance on imports [63].

Most initiatives to increase recycling in a financially viable method have concentrated on recovering valuable metals from the active cathode components, particularly cobalt and nickel. Recycling other materials, including graphite, metal foils, and

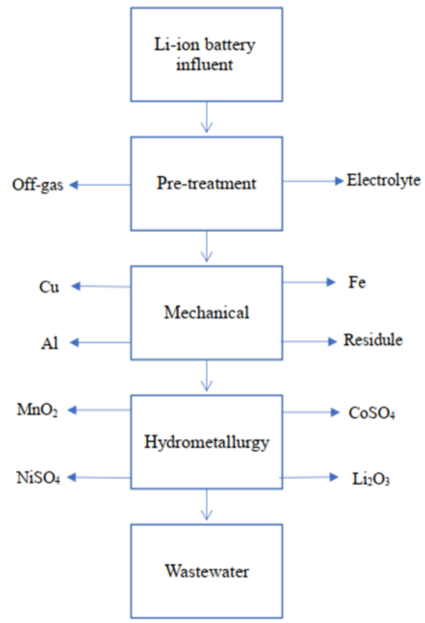

Figure 5. Process overview for hydrometallurgical recycling method [61].

electrolytes, in addition to cathode recovery, could increase recycling revenues and enhance profitability. The pyrometallurgical, hydrometallurgical, and direct recycling procedures are the three methods used to recycle Li-ion batteries. In contrast to direct recycling, which recovers and restores electrode materials for use in developing new batteries at the lab scale, the pyrometallurgical and hydrometallurgical recycling procedures are commercialized by recovering valuable metals and salts [47]. Figure 5 and Figure 6 show the block flow diagrams for the hydrometallurgical and pyrometallurgical processes, respectively and Figure 7 graphically represents a typical direct recycling process.

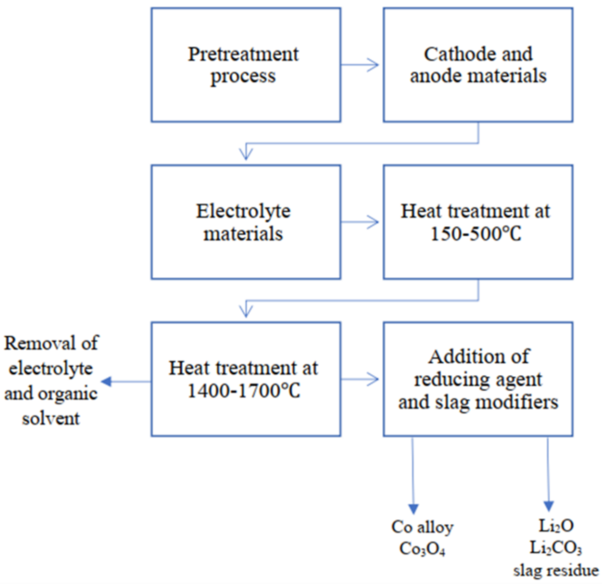

Figure 6. Process overview for pyrometallurgical recycling method [72].

Although pyrometallurgical recycling (smelting) of Li-ion batteries recovers valuable transition metals, lithium and aluminum are left in the slag and are therefore challenging to recover. To provide process heat and lower the transition metals, all organic materials, together with aluminum, are oxidized. Lithium iron phosphate cathodes cannot be used to recover any value product. High capital investment is additionally required for an efficient industrial-scale smelting facility. The critical benefit of smelting is that it can process batteries with mixed cathode compositions, but before reusing, the elements must finally be separated by leaching. Direct recycling and hydrometallurgical processing (leaching) are potentially cost-effective on a smaller scale and operate at lower temperatures, necessitating a lower initial investment. Even though they must be separated, the copper and aluminum foils can be quickly recovered as pure metals. The recovery of transition metals and lithium from the cathode is the primary goal of hydrometallurgy; direct recycling goes a step further and aims to recover cathode materials with proper morphology. This method is particularly appealing for LFP and LMO cathodes because it is the only one developed to recover their substantial value. Additionally, electrolyte and anode materials could be recovered [63].

Because of the challenges of controlling the system, secondary waste generated, and high operating costs, pyrometallurgical or hydrometallurgical methods are not preferred. Biotechnological techniques for metal recovery from Li-ion battery waste may be potential substitutes for pyrometallurgical and hydrometallurgical processes. Microbiological metal dissolution, also known as bioleaching, has grown in favor recently for metal extraction, concentrates, and recycled [25]. This method has some advantages of proper stability, very low environmental pollution, relatively low cost, and high energy efficiency [26]. Biogenic sulfuric acid or organic acids are produced by the microorganisms utilized in bioleaching. Furthermore, optimizing the growth conditions can

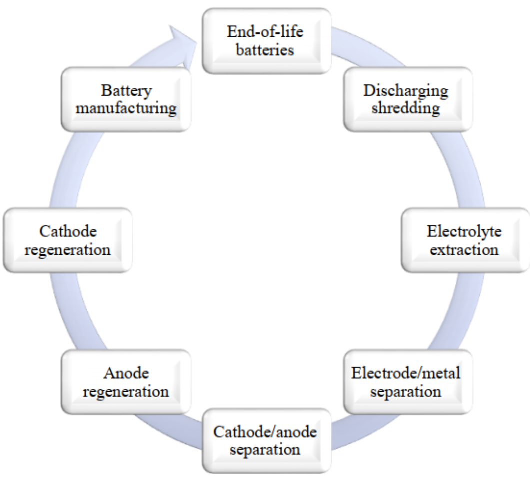

Figure 7. Li-ion batteries direct recycling schematic diagram [47].

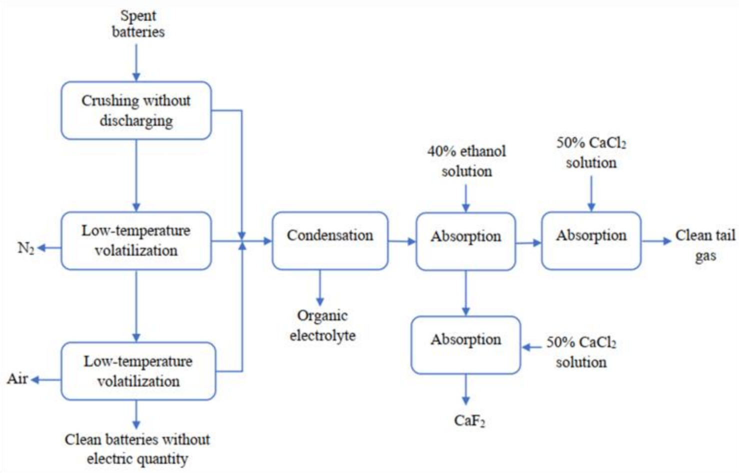

Figure 8. Li-ion battery pretreatment process flow chart [66].

minimize the time necessary to produce microorganisms [64].

One of the methods to increase the recovery efficiency of valuable materials and reduce energy consumption in recycling Li-ion batteries is to use the pretreatment process. For hydrometallurgical and direct recycling technologies, the pretreatment procedure is critical. The primary purpose of pretreatment is to separate various components of Li-ion batteries. In the past, the pretreatment methods of Li-ion batteries were divided into four categories: mechanical separation, mechanochemical process, thermal treatment, and dissolution process. In recent years, more diverse classifications have been introduced: discharging, dismantling, comminution, categorization, separation, dissolution, and thermal treatment [65,66]. Figure 8 illustrates the flow chart for the Li-ion batteries pretreatment process.

9. Safety issues of Li-ion batteries

There have been several reports of Li-ion battery fires and explosions in recent years, resulting in property destruction and personal injury [67]. On the other hand, due to the current quickly evolving electronic devices and the ongoing rise in the number of electric cars, battery safety has garnered attention on a global scale. Mechanical, electrical, and thermal abuse are the main factors that contribute to battery fire and explosion. The mechanical abuse issue is significant among these factors. When a Li-ion battery is subjected to mechanical abuse, the battery cell initially deforms mechanically. A short circuit, temperature rise, gas generation, and increased pressure might all result from the mechanical deformation of the separator or electrodes. Internal short circuit development causes a fast rise in temperature known as thermal runaway. Because of the high temperature, thermal runaway can cause a fire in severe circumstances [68].

To improve battery safety, countermeasures should be taken to stop destructive internal processes. Numerous works have been done to improve the cathode materials' thermal behavior. A protective coating and element substitution are the two main methods used. By stabilizing the crystal structure, element substitution can significantly enhance the thermal performance of layered oxide materials. Similarly, cations metals, including Co, Mn, and Mg, can partially replace Ni or Mn to improve their thermal stability [69].

As previously mentioned, a separator avoids a direct electrical connection between electrodes in a Li-ion battery by offering mechanical separation and high electronic resistance when the battery is running. Furthermore, a tiny leakage current known as self-discharge exists in all batteries and passes through a separator. Because of its porous structure, which stores enough liquid electrolyte and offers adequate ionic conductivity, the separator functions as a conduit for transferring lithium ions between electrodes. Separator pores tend to close off when the battery temperature approaches the melting point of the separator; In this situation, separator shutdown occurs. The conduit for ionic conductivity and electrochemical reactions is partially obstructed during the separator shutdown. In order to prevent a separator from shrinking, collapsing, and causing an internal short-circuit that produces a lot of heat energy and eventually causes a battery explosion, the separator must preserve its mechanical integrity [69]. Using appropriate electrolyte is the best way to solve safety problems, and solid-state electrolyte presents a promising opportunity [70].

Most high-power applications require numerous batteries to be packed together in a small area efficiently. However, these batteries contain reactive elements, making it impossible to avoid fire initiation and thermal runaway. This fire can then spread and severely damage nearby batteries. Researchers have suggested several methods to reduce the thermal runaway spread from a failed battery to other cells. For instance, five strategies for reducing the spread of thermal runaway were suggested, including reducing the risk of a battery's steel can bursting, ensuring adequate spacing and efficient heat dissipation across batteries, splicing parallel-connected batteries separately, safeguarding the nearby batteries from hot ejecta, and preventing flames and sparks from leaving the battery enclosures. As one of the methods, heat dissipation or passive cooling, which uses metal plates or phase-change materials as heat sinks for Li-ion battery packs, has been widely used [69].

The most effective strategy to overcome the safety problems with Li-ion batteries may be to find safer materials. In addition to materials, the impressive trend of other supporting devices will provide essential insights into the development and safer use of the next-generation Li-ion batteries. Future battery safety improvements will require the use of new battery technologies. There still needs to be more understanding of the thermal characteristics of Li-ion batteries in places such as cold countries and oceans. For example, information about Li-ion battery fire threats, such as igniting time, safety venting, air pressure, moisture, gas concentration, and so on, is limited. However, it is crucial to remember that suitable action must be taken in every circumstance to decrease the heat threat posed by Li-ion batteries [68–70].

10. Conclusions and Outlook

The advancement of Li-ion battery technology is a prerequisite for a contemporary green lifestyle that includes high-end electric vehicles and cutting-edge electronics. The development of innovative Li-ion batteries with high capacity, extended cycle life, high safety, and cheaper costs has received much attention. The anode, cathode, and electrolyte are the primary elements that require improvement. The most important Li-ion battery characteristics to consider when assessing the battery's current health state are SOH and RUL. Nowadays, Li-ion batteries have various applications, including electric vehicles, portable electronic devices, grid energy storage, implantable medical devices, and renewable energy systems. Three main steps in the current Li-ion battery manufacturing process are cell assembly, electrode preparation, and battery electrochemistry activation. The three most important markets for Li-ion batteries are power supply systems, portable devices, and road transportation. The properties of battery materials are predictable by ML models such as artificial neural networks. The three processes used to recycle Li-ion batteries are direct recycling, hydrometallurgical recycling, and pyrometallurgical recycling. Finding safer materials might be the most efficient way to deal with the Li-ion battery safety issues. The impressive development of other supporting devices will offer crucial insights into the production and safer application of the next-generation Li-ion batteries in addition to materials.

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