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Review of Al_2O_3-based composite separators for lithium-ion battery

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A B S T R A C T

Lithium-ion batteries (LIBs) have faced safety and performance challenges due to aluminum oxide (Al_2O_3)-based composite separators. This review aims to give you a comprehensive summary of recent advances in the design, fabrication, and application of Al_2O_3-modified separators. With their high surface activity, excellent hydrophilicity, and excellent thermal stability, Al_2O_3 ceramics are widely used as separators to improve thermal resistance, electrolyte wettability, and ionic conductivity, while effectively preventing lithium dendrite growth and improving mechanical strength, among other properties. A variety of composite architectures are discussed, including polymer/Al_2O_3 blends, ceramic-coated polyolefin membranes, and nanocellulose/Al_2O_3 hybrids, which have superior electrochemical properties, high porosity, and robust antishrinkage properties. Various mechanisms explain how Al_2O_3 contributes to improved separator performance, and the advantages of Al_2O_3-based systems in terms of safety, cycle stability, and rate performance are clearly demonstrated. Furthermore, the review outlines current challenges and provides perspectives on future research directions towards the practical implementation of Al_2O_3-based composite separators in high-performance LIBs of the future.

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1. Introduction

The LIB has been developed for a number of energy storage applications over the past few decades, including portable electronic devices and electric vehicles. Their high energy density, high power density, lightweight, flexibility, slow self-discharge, high charging rate, and long cycling life make them ideal for portable electronic devices and electric vehicles [1-4]. Nevertheless, the effect of the separator on LIB safety and performance will be critical. The separator physically isolates the electrodes and allows ionic transport between them [5-7]. It is widely used to separate liquids and solids by using polyolefin-based separators, such as polyethylene (PE) and polypropylene (PP) [8, 9]. They are, however, relatively thermally unstable and limited in their wettability with liquid electrolytes, which compromises the safety and performance of the battery during high temperature or high-rate conditions [10, 11].

Conventional separators are prone to thermal shrinkage and electrolyte affinity decline, increasing the risk of internal short circuits and capacity fade. Therefore, new separator technologies are urgently needed [9]. Among the potential solutions to these challenges is the use of composite separators incorporating Al_2O_3. Providing high surface activity, excellent hydrophilicity, and outstanding thermal stability, Al_2O_3 can effectively modify separators as an additive or coating. By integrating Al_2O_3 into separators, either as nanoparticle coatings, ceramic-polymer composite materials, or using advanced fabrication techniques, additional wettability, mechanical strength, and thermal resistance are enhanced. The improvements address safety risks as well as enhance electrochemical performance by increasing rate capacity and extending cycle life [9, 12]. Advances in Al_2O_3-based composite separator fabrication techniques, such as electrospinning and dip coating, have been recently demonstrated. In this way, tailored pore structures can be achieved, as well as high porosity and uniform Al_2O_3 distribution, which will increase ionic conductivity and reduce the barriers to lithium-ion migration [13, 14]. As well as improving performance, composite separators based on Al_2O_3 offer practical benefits for large-scale manufacturing. In order to achieve consistent quality and desirable electrochemical properties, low-cost and scalable fabrication techniques are used to manufacture separators. As a result, commercial and industrial applications are increasingly requiring high-performance LIBs [14]. Al_2O_3 has been incorporated into separator structures via a variety of strategies, including coating polyolefin membranes, electrospinning fibers, and engineering multidimensional pores [9]. Using Al_2O_3-based composite separators, the growth of lithium dendrites was suppressed, and self-discharge was reduced while structural integrity was maintained under demanding operating conditions [13].

It has been several years since Al_2O_3-based composite separators emerged, but some challenges remain. Ceramic content must be maximized, mechanical flexibility maintained, and interfacial stability ensured for long-term use [15, 16]. This paper discusses developments in Al_2O_3 composite separators. This article covers different types of separators, their roles in battery performance, and battery chemistry. Next, Al_2O_3 and its composites are investigated as separators. In LIBs, composite separators made from Al_2O_3 were evaluated for their effectiveness.

2. Lithium-ion batteries: Fundamentals and components

The LIB is widely recognized for its remarkable capacity to store energy, making it a crucial component in portable electronics, electric vehicles, and renewable energy technology [17]. To grasp the operations and potential applications of these batteries, one must understand their fundamentals and components. When lithium ions are charged and discharged, the electrolyte facilitates the movement of lithium ions between the positive and negative electrodes. In addition to the electrolyte, the LIB contains several other essential components [18]. Electrolytes serve as conductors, allowing ions to flow while blocking electrons. The positive electrode typically comprises lithium metal oxides, such as lithium cobalt oxide, that supply lithium ions [19]. During charging, the negative electrode is usually made of graphite or other carbon-based materials that host lithium ions. Permeable membranes separate the two electrodes, allowing lithium ions to travel between them while preventing electron movement. Furthermore, current collectors ensure efficient energy flow within the battery by collecting and distributing electrical current. A successful electrochemical reaction and energy storage process requires harmonious coordination of these fundamental components [20, 21].

2.1. Lithium-ion batteries

LIBs have been an integral part of our daily lives since Sony Corporation introduced them in 1991. Currently, LIBs are the primary source of power for electric vehicles and portable electronics. LIBs have reached 260 W/h/kg and 700 W/h/L/1 at cell level after rapid growth for the past 27 years [22, 23]. LIBs are the result of decades of concentrated research on solid-state chemistry of materials. The field has advanced significantly due to the discovery of new materials as well as an intensive study of the relationship between structure-composition-property-performance of these materials [24].

Due to their high energy density and design flexibility, lithium-based batteries, which account for 63% of sales in portable batteries worldwide, currently perform better than other technologies [25, 26]. There are several benefits to using lithium batteries over other battery chemistry. The batteries are safe and reliable, with no fear of thermal runaway and/or catastrophic meltdown, which are significant dangers with other lithium batteries. Some manufacturers offer batteries with a 10,000-cycle warranty, which is the highest in the industry. Battery technology that delivers highly efficient round-trip efficiency of up to 98% is gaining traction within the industry as a result of high discharge rates and continuous recharge rates upwards of C/2 [27].

2.2. Components and working principles of lithium-ion batteries

There is a separator, an organic electrolyte, and a cathode in a LIB. These electric contacts are formed by laminating cathodes, anodes, and separators by pressing. Carbon graphite, conductors, PVDF binder, and additives are combined with copper to create the anode. An aluminum plate coated in active cathode materials, electric conductors, PVDF binder, and additives serves as the cathode [28]. LIB separators consist of polyolefin membranes that have thin micropores. Anodes and cathodes are separated by this membrane in order to prevent contact between them, while allowing Li ions to pass between the two. The separators can be classified into three main categories based on their production methods, each with a different morphology and characteristic that suits different battery types [29].

As shown in Fig. 1, lithium-ion batteries contain two electrodes separated by an electrolyte containing dissociated lithium salts, which is responsible for transporting lithium ions between the electrodes [30, 31]. Typically, electrolytes are separated from cathodes and anodes by porous membranes that prevent physical contact. In order to charge the battery, electrons are injected into its anode with the help of an external electrical power source. While the cathode is releasing lithium ions, they move through the electrolyte to the anode and remain there. In this process, chemical energy is converted into electricity in the battery. During discharging, the lithium ions move back to the cathode across the electrolyte, releasing electrons in the outer circuit to carry out the electrical work [32, 33]. In current LIBs, the active powder materials (graphite in the anode, and $LiFePO_4$ in the cathode) are used mostly for portable applications (such as cell phones and laptops). Since lithium ions diffuse long distances in powder materials and electrode reactions are slow, current LIBs do not reach their full potential [31]. Therefore, advanced LIBs are needed to outperform current technologies and be capable of being used on a large scale. New energy-storage materials and electrodes are needed to achieve these benefits [34].

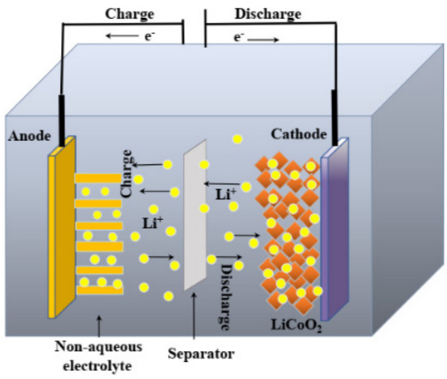

Fig. 1. Schematic of a lithium-ion battery [30].

2.3. Role of separators in battery performance

LIBs, in particular, function as multiple vital components that directly affect safety, efficiency, and longevity with separators playing a crucial role [35]. As a matter of principle, separators physically separate cathodes from anodes in order to prevent short circuits from forming, which can result in hazardous conditions such as thermal runaway [36]. Lithium ions must pass through pores in separators during charge and discharge cycles to function, facilitating the vital ionic transport required for battery operation [37]. In order for a battery to produce and store electrical energy efficiently, it must simultaneously function as an electrical insulator and an ionic conductor (Fig. 2) [38, 39].

There is a significant relationship between the separator properties and key performance metrics such as cycle life, energy densities, power densities, and battery safety. In order to resist thermal shrinkage and mechanical corrosion, the separator must be mechanically strong, chemically resistant, and thermally stable [35, 40]. By improving thermal tolerance and reducing thermal runaway risks, advanced separators, such as those containing ultra-high molecular weight polyethylene (UHMWPE) or inorganic materials, can improve battery performance and lifespan [41].

Separators also serve as a shutdown device when the battery malfunctions at elevated temperatures. Fusing and blocking ion transport effectively stops the battery from operating. The thermal response in LIBs is a crucial safety feature that mitigates the risk of fires or explosions. [39].

The separator should facilitate ion transport through its pores, enhance interfacial compatibility, and improve the safety of LIBs. Recent research and development initiatives focus on enhancing electrolyte management of separators, reducing internal resistance, and improving electrode compatibility [42]. As a result of these advancements, battery performance improves, cycling life is prolonged, and the battery operates safely. Through numerical modeling and simulation studies, next-generation separators can be developed with superior performance and safety characteristics, guiding research into separator behavior under different conditions [9, 43].

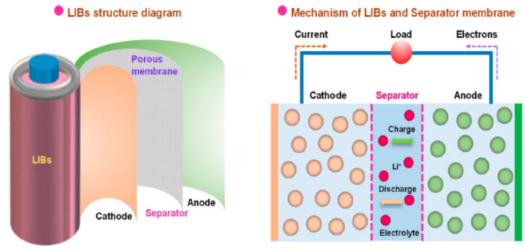

Fig. 2. Schematic illustration ofLIBs and the role of separators in battery performance [44].

3. Separator materials for lithium-ion batteries

The materials used in LIBs separators include polyolefin membranes, polymers, composites with inorganic coatings, and natural mineral materials. Various materials have been researched and evaluated to optimize separator performance for next-generation lithium-ion batteries [41].

3.1. Requirements for separators

Battery safety and electrochemical performance are determined by the separator, a passive component of LIBs. Separators should contain interconnected parameters [45]. This section outlines the parameters of a basic separator and explains how to enhance separator properties to improve battery safety [46].

For specific applications, it is essential to consider several factors when selecting a separator. Additionally, the material properties must remain consistent and stable throughout the expected lifetime of the application, as well as have optimal initial properties. The performance attributes listed above are crucial for achieving high energy and power densities in applications that require these characteristics [40].

3.2. Traditional separator materials

LIBs play a pivotal role in their safety and efficiency by using traditional separator materials. A porous polymer film is typically used as the separator material, but PE and PP are also available [40, 47].

Various battery applications require separators fabricated from PE, which are mechanically strong and thermally stable. Battery operation requires high temperatures, and they have a melting point of around 130-140 °C. Electrolytes and separators based on PE exhibit good chemical resistance, which prevents unwanted chemical reactions.

As for PP-based separators, they are excellent, dimensionally stable, and resist shrinkage better than other types. In comparison to PE, PP has a higher melting point, typically around 165 °C, allowing it to be used for high-temperature batteries. When batteries are assembled, PP-based separators are known for their high puncture strength, helping to prevent short circuits [48].

In both types of separators, the electrical resistance is low, allowing efficient ionic transport between electrodes within the battery. They facilitate ion movement within batteries by absorbing and retaining liquid electrolyte [49]. Traditional separator materials have limitations. Batteries can short-circuit and melt because of thermal shrinkage. In addition, chemical reactions and mechanical stresses may deteriorate their mechanical integrity over time, which can impact their long-term performance and lifespan [47].

Researchers continuously develop separator materials that are thermally stable, puncture-resistant, and shrink-resistant to address these limitations. These advancements aim to improve LIB safety, performance, and reliability across various applications [40].

3.2.1. Latest advancements in separator technology

In recent years, LIB technology has improved regarding temperature stability, ionic conductivity, and compatibility with high-energy-density chemistries. Despite the advantages of polyolefin separators, this type of material presents several challenges, including poor electrolyte wettability, limited thermal stability, and significant shrinkage at elevated temperatures. As a result, batteries made from lithium-ion can be compromised [50].

3.2.1.1. Advanced polymer materials

Compared to traditional polyolefin membranes, nanofiber membranes made from Polyacrylonitrile (PAN) and Polyvinylidene Fluoride (PVDF) offer superior thermal stability and porosity. However, the limited interactions among fibers result in these materials being less mechanically robust with respect to electrolyte wettability and thermal resistance [51].

A range of polymers that exhibit excellent heat resistance, mechanical strength, and chemical stability is examined. These polymers include aromatic polyamides, polyimides, polyethylene terephthalate (PET), polyether ether ketone (PEEK), cellulose, and fluorine-containing polymers. Specifically, aromatic polyamides are compatible with polar electrolytes and have high dielectric constants, which promote lithium salt ionization and enable them to function as wet separators [41].

3.2.1.2. Composite and coated separators

Polyolefin separators can enhance thermal and electrolyte wettability by coating them with inorganic particles such as SiO_2, Al_2O_3, TiO_2, and ZrO_2 [41, 52]. In the process of coating the separator, however, the separator thickness increases, potentially increasing internal resistance and reducing battery capacity. As well as particle detachment, particle collisions may lead to internal short circuits as well [41]. There are several natural minerals that are used as composite separators, such as halloysite nanotubes, attapulgite, sepiolite, montmorillonite, zeolite, and diatomite. In addition to excellent thermal and mechanical stability, these minerals provide ion transport via their unique nanopore structure, as well as environmental friendliness and cost efficiency. Thermal shrinkage and safety issues related to polyolefin separators are also addressed [53].

3.2.2. Al_2O_3-based separators in lithium-ion batteries

The advancement of Al_2O_3-based separators has become significant in LIB technology thanks to their remarkable combination of high thermal stability, electrolyte wettability, corrosion resistance, rigidity, and safety [54-56]. Ceramic materials, including Al_2O_3, are utilized as modified additives for separator materials. These serve as coatings on conventional polyolefin membranes and composite materials. In addition to their high surface activity, Al_2O_3 also demonstrates notable hydrophilicity, which enhances electrolyte uptake and ionic conductivity [57, 58]. With their ability to resist thermal shrinkage and maintain dimensional integrity at elevated temperatures, Al_2O_3-coated separators outperform traditional polyolefin separators like PP or PE [9].

Therefore, they have a significantly lower risk of short circuits during thermal runaway. Alumina particle separators exhibit high puncture strength due to their hardness, which limits dendrite penetration and enhances mechanical robustness [59]. In addition to improving cell safety and cycle life, the ceramic coating also boosts the separator's mechanical strength and compatibility with various liquid electrolytes.

Separators made from Al_2O_3 help suppress lithium dendrite growth, a critical safety concern for lithium-metal batteries [60, 61]. As well as offering improved performance at low, mid, and high temperatures, Al_2O_3 separators can also be used in solar panels. The high energy density, improved safety, and long-term reliability of lithium-ion batteries are attributes that make Al_2O_3-modified separators attractive for next-generation lithium-ion batteries [60].

4. Al_2O_3-based composite separators (AlCS)

Ceramic-based composite separators comprised of Al_2O_3 particles and polymers provide excellent thermal stability, mechanical robustness, electrolyte wettability, and electrochemical properties. Advanced energy storage systems can benefit from their safety and efficiency features by using them as battery separators [13, 62]. Table 1 shows the effects of some Al_2O_3-based separators in lithium batteries.

4.1. Fabrication techniques of AlCS

Lithium-ion and lithium-metal batteries use Al_2O_3-based composite separators as they are thermally stable, mechanically strong, and electrochemically efficient. Separator structures can incorporate Al_2O_3 either as a coating or as a component of composite membranes through several fabrication techniques. In addition to coating methods, electrospinning is also an important manufacturing technique. By using these methods, separator properties can be precisely controlled, scalability can be achieved, and integration into existing battery manufacturing processes can be made possible.

4.1.1. Coating methods

AlCSs are becoming more and more popular in lithium-ion and lithium-metal batteries because they enhance thermal stability, electrolyte wettability, mechanical strength, and safety overall. Separators are manufactured using various methods, which differ in uniformity, scalability, and performance of Al_2O_3 particles.

Among the most commonly used techniques is blade coating. This method requires dispersing Al_2O_3 nanoparticles in water and adding binders and surfactants such as sodium carboxymethyl cellulose (CMC) and disodium laureth sulfosuccinate (DLSS) to produce a slurry.

Utilizing a blade fitted with a controllable coating layer thickness, the slurry is then applied evenly to a polymer separator substrate, such as a nonwoven membrane made of PVDF or PAN. As soon as the Al_2O_3 layer is applied, the coated separator is baked in an oven until it is firmly adhered. Coatings can be as thin as a few micrometers and are porous and uniform, improving the electrolyte uptake as well as heat resistance. For laboratory experiments and industrial production, blade coating is preferred for its simplicity and cost-effectiveness [61].

Table 1
The effects of different types of Al_2O_3-based separators in lithium batteries.

Separator type	Structure/Composition	Key effects in LIBs	Ref.
PE–Al_2O_3 (Al_2O_3-coated Polyethylene)	PE separator coated with Al_2O_3 nanoparticles	Enhanced puncture strength Thermal stability, wettability and ionic conductivity Slightly lower tensile strength	[59]
PAEK–Al_2O_3 Composite	Electrospun PAEK membrane coated with crystalline Al_2O_3 nanoparticles	Excellent thermal stability (no shrinkage at 150 °C) High degradation temp (>500 °C), superior electrolyte uptake	[9]
ST@Al_2O_3-PE (Yolk-shell Ti-doped SiO_2@Al_2O_3 on PE)	Yolk-shell Ti-doped SiO_2@Al_2O_3 particles with strong Lewis acid sites on PE	Very high ionic conductivity High Li^+ transference number (0.62) Stable cycling (>400 h at 1 ma/cm²) Improved Li plating/stripping Stabilizes Li metal anode Enhanced mechanical/thermal stability	[63]
PVDF/ Al_2O_3Composite	Electrospun PVDF fibers with Al_2O_3 nanoparticle dip-coating	High thermal stability (≤2% shrinkage at 140 °C) Good electrochemical properties, Low capacity loss after cycling	[13]
Al_2O_3/Nanocellulose-Coated Nonwoven	Nonwoven PVDF/polyacrylonitrile coated with Al_2O_3 nanoparticles and nanocellulose	Increased porosity High electrolyte uptake Reduced thermal shrinkage Mitigates Li dendrites Improved safety/stability	[61]
Al_2O_3-coated Polyolefin	Nanotechnology, hybrid coatings, ALD	Enhanced thermal stability & safety Lightweight, flexible, improved energy density Better barrier against dendrite growth Improved cycle life (up to 30% longer) More sustainable, recyclable	[15]
Al_2O_3 ALD-coated PE	ALD of ultrathin Al_2O_3 on PE (Atomic Layer Deposition)	Enhanced electrolyte wettability High ionic conductivity Low interface impedance Improved safety and performance	[64]
α- Al_2O_3 Coated PE (PDA@mAl_2O_3-PE)	Polyethylene (PE), α-PE separator coated with α-Al_2O_3 and polydopamine	Superior thermal stability Mechanical strength Improved electrolyte wettability Enhanced cycling and rate performance	[65]
Al_2O_3/SiO_2 Composite Ceramic Layer Separator	Effect of Al_2O_3/SiO_2 composite ceramic layers on performance of PP separators in lithium-ion batteries	Retains more electrolyte Higher ionic conductivity Improved cell performance	[66]
Al_2O_3-Coated Separator with PEK-C Binder	PP membrane coated with Al_2O_3 using phenolphthalein polyetherketone (PEK-C) binder	Lower thermal shrinkage Improved electrochemical stability Slightly better capacity retention and safety compared to neat PP	[67]
Al_2O_3/TiO_2-Coated PP	Polypropylene (PP) base with ceramic (Al_2O_3/TiO_2) coating	Best improvement in thermal stability (shrinkage 0.6% vs. 6% uncoated) 92% capacity retention at 2C	[68]
MOF-Al_2O_3 Coating Separators	MOF-Al_2O_3 Blended Coating on PE Separators	Improved fast charge-discharge performance Higher capacity retention Lower interface resistance over long cycles	[69]

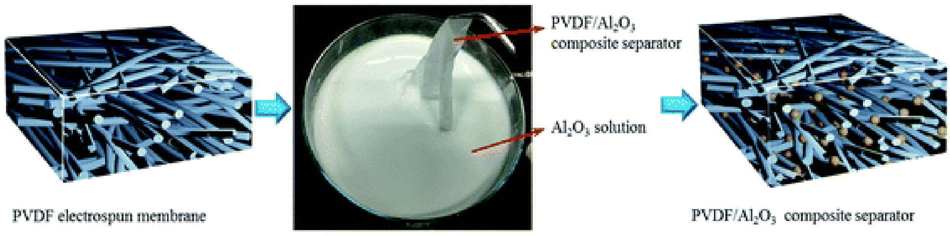

Fig. 3. Preparation of the PVDF/Al_2O_3 composite membrane via the dip-coating process [13].

Manufacturing on a large scale typically uses roll-to-roll processing. During continuous processing, the polymer separator advances through a coating station, where the Al_2O_3 slurry is sprayed on it or passed through a bath [68]. Following coating, the separator is dried, allowing the ceramic layer to be deposited evenly and rapidly over long lengths of material. Commercial battery separators are often produced using roll-to-roll coating because of its high throughput and precise control of coating thickness [14, 68].

In order to achieve optimal coating performance, it is crucial to select the right binders and additives for the coating slurry. A binder such as poly(vinylidene fluoride-cohexafluoropropylene) (P(VdF-coHFP)) is used to adhere the Al_2O_3 powder to the separator's surface and ensure mechanical integrity [61, 70]. Al_2O_3 nanoparticles are dispersed more evenly in slurries containing surfactants. The composite separator can be made more hydrophilic and electrolyte-absorbent with the addition of nanocellulose [61].

Separators with Al_2O_3 coatings are more thermally stable than those without, which helps prevent thermal runaway and short circuits in batteries. A ceramic layer enhances the wettability of a separator's surface, thereby improving ionic conductivity and electrolyte absorption.

In addition to prolonging battery life and ensuring battery safety, coated separators prevent mechanical deformation and dendrite penetration [68]. Al_2O_3-coated separators have been found to improve cycling stability, higher rate capability, and capacity retention over uncoated separators, according to electrochemical testing [61, 70]. Table 2 outlines the advantages of Al_2O_3-based separator coating techniques.

Table 2
The advantages of Al_2O_3-based separator coating Technique.

Technique	Key features	Advantages	Ref.
Blade Coating	Slurry cast, thickness-controlled	Scalable, uniform, precise	[61]
Dip-Coating	Immersion in nanoparticle suspension	Simple, conformal coating	[13]
Slurry/Tape Casting	Water-based, uses surfactants and binders	Eco-friendly, improved wettability	[68]
Roll-to-Roll Processing	Continuous, industrial-scale	High throughput, commercial-ready	[68]

With the use of blade coating, dip coating, and roll-to-roll methods, Al_2O_3 can be applied to polymeric separators to enhance their thermal, mechanical, and electrochemical properties. For next-generation lithium batteries to be safe and perform well, these improvements are essential [13, 61, 68, 70].

4.1.2. Electrospinning

Al_2O_3 nanoparticle composite separators can be manufactured using electrospinning, a versatile and effective method. LIBs operate safely and efficiently when they have strong and durable composite separators that increase thermal stability, mechanical strength, electrolyte wettability, and electrochemical performance. Using electrospinning, porous nanofibrous membranes with controllable morphology are produced and are suitable for various battery applications.

Direct electrospinning of polymer solutions containing Al_2O_3 nanoparticles is one of the most common approaches. It is possible to create a homogeneous solution by mixing polymers such as poly (aryl ether ketone), polyimide, or polyvinylidene fluoride with Al_2O_3. Electrospun composite membranes containing ceramic nanoparticles are produced from this mixture using polymer matrices that include ceramic nanoparticles [9]. In addition to their high porosity, these membranes demonstrate excellent thermal stability, rarely shrinking at temperatures exceeding 150 °C. Moreover, they are capable of capturing more electrolytes and conductors than conventional membranes, which is essential for efficient ion transport [71].

In addition to electrospinning, tip-induced electrospinning (TIE) is also combined with dip coating (Fig. 4). This method involves electrospinning a PVDF membrane with Al_2O_3 nanoparticles and then coating it with ultrafine PVDF nanofibers using TIE. With this approach, fiber morphology and surface properties are controlled in two steps, resulting in separators that are more thermally stable at 140 °C, exhibit less than 2% dimensional shrinkage, and demonstrate better electrochemical performance, including high ionic conductivity and stable cycling [13].

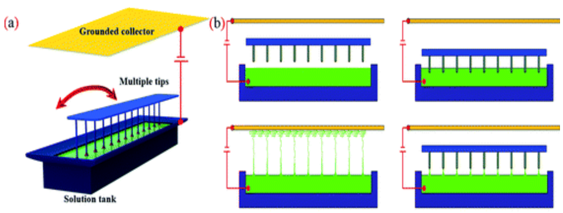

Fig. 4. (a) Schematic diagram of the TIE setup. (b) Illustration of the TIE process [13].

Among the most advanced designs, composite structures consisting of Al_2O_3@PI/polyethylene/Al_2O_3@PI (APEAP) are employed. Electrospun polyimide nanofibers are coated with Al_2O_3 nanoparticles on the outer layers, while the polyethylene core offers protection from contamination. In addition to providing an anti-overheating thermal shut-down function, the Al_2O_3@PI layers provide high thermal resistance and mechanical durability. The core layer of these multilayer separators is typically coated with a metal or resin, resulting in membranes that are high-performing electrochemically as well as being safe [71]. A comparison between Electrospinning techniques used on Al_2O_3-based separators can be found in Table 3.

Table 3
The advantages of Al_2O_3-based separator electrospinning technique.

Separator Type	Electrospinning method	Properties/Advantages	Ref.
PAEK–Al_2O_3 Composite	Direct blend electrospinning	No shrinkage at 150 °C, >500 °C degradation temp, 89.4% porosity, 3.15 mS/cm ionic conductivity	[9]
PVDF/Al_2O_3 Composite	Tip-induced electrospinning + dip-coating	<2% shrinkage at 140 °C, 55.8% porosity, 2.23 mS/cm ionic cond., high cycling stability	[13]
Al_2O_3@PI/PE/ Al_2O_3@PI (APEAP)	Needleless electrospinning + calendaring	Multilayer, thermal shut-down at 123 °C, high safety, excellent cycling performance	[71]

In comparison to conventional separators, electrospun composite separators based on Al_2O_3 offer a number of significant advantages.

A battery's safety depends on its thermal stability, which prevents shrinkage and degradation at elevated temperatures. Its high porosity and large surface area make it an excellent electrolyte wettability and retention device. Therefore, it enhances ionic conductivity.

By adding Al_2O_3 nanoparticles to the polymer matrix, the mechanical strength and dimensional stability of the material are both improved. LIBs benefit from these improvements by cycling more consistently, retaining capacity longer, and achieving higher rates. A multilayered design with thermal shutdown functionality adds another layer of safety by preventing thermal runaway. In addition to their outstanding properties, AlCS can be produced using electrospinning techniques.In next-generation energy storage applications, ceramic reinforcement combined with nanofibrous architecture can significantly increase battery safety, stability, and electrochemical performance [9, 71].

4.2. Characterization AlCS

A composite separator based on Al_2O_3 has excellent thermal stability. During a research study by Wu et al. [13], PVDF/Al_2O_3 separators, which were exposed for one hour to 140 °C, showed less than 2% dimension shrinkage, while PAEK/Al_2O_3 separators did not suffer any change in shape when exposed for one hour to 150 °C. Moreover, PAEK-Al_2O_3 separators uphold their structural integrity at temperatures exceeding 500 °C, in contrast to PP separators, which shrink under high temperatures [9].

The porosity and morphology of the separator should also be considered when evaluating its performance. Using Al_2O_3 nanoparticles refines the pore structure and creates a more uniform pore size distribution, facilitating ion transport. The porosity of PVDF-Al_2O_3 composites is approximately 56%, while the porosity of PAEK-Al_2O_3 separators is nearly 90%. Due to the high porosity, electrolytes are easily absorbed [9, 13, 14]. The higher ionic conductivity results from the improved electrolyte wettability due to Al_2O_3 nanoparticles. In batteries, enhanced ionic conductivity allows lithium ions to migrate through the electrodes more efficiently [9, 14]. Al_2O_3-based composite separators significantly improve battery cycling stability and rate capability, according to electrochemical characterizations. Batteries with these separators will maintain long-term high discharge capacities [9, 13, 14].

5. Conclusion

The use of AlCSs has enabled lithium-ion battery development to make significant progress, offering greater safety, stability, and performance. In addition to being highly thermally resistant, these composite membranes are also mechanically stronger and provide excellent electrolyte wettability, which contributes to superior ionic conductivity and stable electrochemistry. The structural integrity of these membranes at high temperatures reduces the risk of battery failure and thermal runaway, making them ideal for demanding applications. Additionally, incorporating alumina particles enhances the separator's effectiveness in suppressing lithium dendrite growth, thereby maximizing battery life. In general, Al_2O_3-based composite separators are promising vehicles for improving lithium-ion battery safety and efficiency.

Further refinements in material design and fabrication techniques are required to optimize the properties of Al_2O_3-based composite separators. Advances in nanotechnology and coating methods will enable the creation of more uniform and thinner alumina layers, enhance ionic transport while maintain mechanical robustness. Hybrid materials that combine Al_2O_3 with other functional additives could lead to multifunctional separators, which may include improved thermal management and enhanced chemical stability. Additionally, as the demand for flexible and lightweight batteries grows, flexible Al_2O_3-based separators will become increasingly important. Environmental considerations will also drive research toward sustainable and recyclable separator materials, minimizing the ecological footprint of battery production and disposal. Ultimately, ongoing innovation in Al_2O_3-based composite separators will play a crucial role in meeting the evolving performance, safety, and sustainability requirements of next-generation LIBs. In addition to optimizing the design and fabrication of Al_2O_3-based composite separators, refining the materials will further enhance their performance. The development of nanotechnology and coating techniques will boost ionic transport while maintaining the mechanical robustness of alumina layers. Furthermore, hybrid materials that combine Al_2O_3 with other functional additives could enhance thermal management and chemical stability, providing separators with multifunctional capabilities. As batteries become more flexible and lightweight, the need for developing flexible Al_2O_3-based separators will grow increasingly important. Additionally, environmental considerations will drive the creation of sustainable and recyclable separator materials, minimizing the ecological impact involved in recycling and disposing of batteries. To meet the ever-growing demands for performance, safety, and sustainability in next-generation lithium-ion batteries, ongoing innovation in composite separators based on Al_2O_3 will be essential.

Author contributions

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Conflict of interest

The authors declare no conflict of interest.

Data availability

No data is available.

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