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Article

Fluoride-ion batteries: The future of high-energy, safe, and sustainable energy storage

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Abstract: Fluoride-ion batteries (FIBs) are emerging as a potential alternative to lithium-ion batteries, offering higher energy densities, improved safety, and the use of more abundant and sustainable materials. Recent advancements in fluoride-ion technology have focused on addressing key challenges, such as the low ionic conductivity of fluoride and the development of suitable electrode materials. Researchers have made progress in creating electrolytes that stabilize fluoride ions during charging and discharging, leading to prototypes with enhanced cycling stability and energy capacity compared to earlier models. However, issues like corrosion and the need for more efficient energy storage remain significant barriers. Ongoing research is dedicated to finding novel materials that can improve conductivity, as well as to developing corrosion-resistant components that will enhance the longevity and safety of fluoride-ion batteries. Additionally, improving the overall energy efficiency and scalability of production is crucial for future commercialization. If these challenges are successfully overcome, fluoride-ion batteries could offer a transformative solution for high-energy applications, including electric vehicles, portable electronics, and large-scale grid energy storage. As research progresses, fluoride-ion batteries hold the potential to become a key technology in the quest for more sustainable, high-performance energy storage systems.

Keywords: fluoride-ion batteries; energy storage; high energy density; sustainable materials; ionic conductivity; cycling stability; corrosion resistance; electric vehicles; portable electronics; next-generation batteries

1. Introduction

As the global demand for cleaner, more efficient energy storage systems continue to rise, researchers are actively seeking alternatives to the widely used lithium-ion batteries. Lithium-ion technology, while dominant in applications ranging from portable electronics to electric vehicles (EVs), faces significant limitations, including safety risks, reliance on scarce raw materials, and moderate energy densities [1–3]. In this context, fluoride-ion batteries (FIBs) have emerged as a promising next-generation energy storage solution, offering substantial potential improvements in energy density, safety, and sustainability [4, 5]. Fluoride-ion batteries work by utilizing fluoride ions (F^-) as the charge carriers instead of lithium ions (Li^+). The battery consists of a metal fluoride cathode, a metal anode, and a fluoride ion-conducting electrolyte, which can be a solid or polymer-based material. During discharge, fluoride ions move from the cathode to the anode through the electrolyte, while electrons flow through an external circuit to provide electric power. At the anode, these ions react with the metal to form a metal fluoride. During charging, an external power source reverses this process: electrons are forced back to the cathode, and fluoride ions return to their original positions, restoring the electrode materials. Fluoride ion batteries offer the promise of high energy density and the use of more abundant elements compared to lithium-ion batteries, but challenges such as low room-temperature conductivity and material stability still need to be addressed.

Reaction at cathode: $CuF_2 + 2e^- \rightarrow Cu + 2F^-$

Reaction at anode: $Ca + 2F^- \rightarrow CaF_2 + 2e^-$

Recent advancements in FIB technology have focused on overcoming some of the early challenges associated with this chemistry, particularly the low ionic conductivity of fluoride ions and the development of suitable electrode materials. Researchers have made notable strides in stabilizing fluoride ions in the electrolyte, which has led to improved cycling stability and energy capacity in early prototype batteries [6, 7]. The elements of the fluoride-ion battery are explored in **Figure 1**.

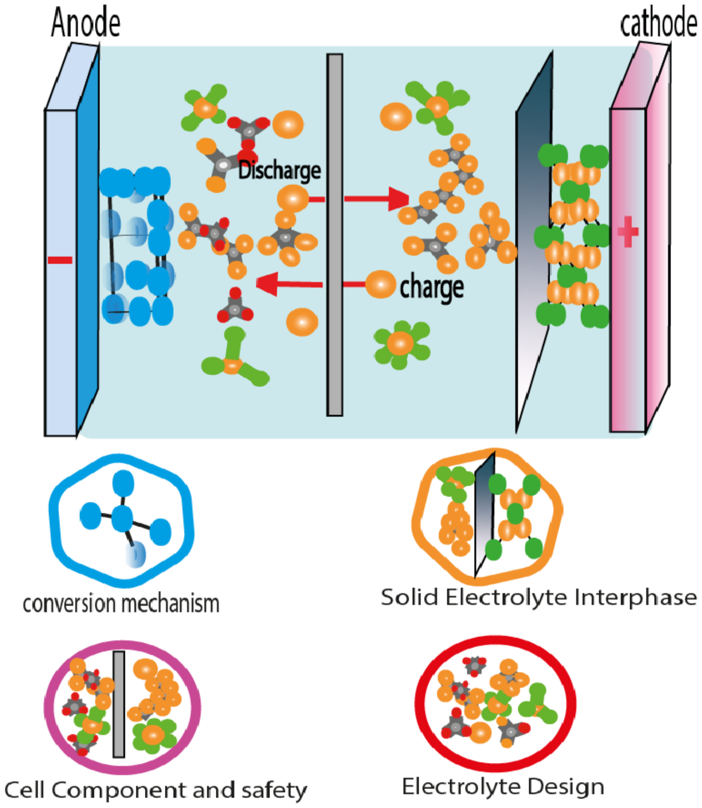


Figure 1. Elements and working principle of fluoride-ion battery.

Despite these breakthroughs, several hurdles remain. One of the most significant challenges is finding efficient and stable materials that can effectively host fluoride ions within the battery's electrodes. Fluoride ions are relatively large compared to lithium ions, and their movement through the electrolyte is slower, making it more difficult to achieve fast charge and discharge rates [8, 9]. Additionally, fluoride ions tend to be highly reactive, which can cause corrosion and degradation of battery components over time, reducing their overall lifespan and efficiency [10, 11]. Another challenge is optimizing energy efficiency, as fluoride-ion batteries must match or exceed the performance of existing technologies to be commercially viable [12,13].

Future research will likely focus on addressing these challenges by developing novel materials with higher conductivity and better stability to support fluoride-ion transport. In particular, new electrolyte formulations and electrode compounds need to be engineered to ensure that fluoride ions can move efficiently throughout the system without causing degradation. Researchers are also working on improving the overall safety of fluoride-ion batteries, as the reactivity of fluoride ions could pose risks if not properly managed. Additionally, scaling up production methods to create large quantities of fluoride-ion batteries at competitive costs will be essential for their commercial adoption. If these challenges are successfully overcome, fluoride-ion batteries could revolutionize the energy storage industry. Their high energy density and potential for safer, longer-lasting storage make them ideal candidates for a variety of applications, from powering electric vehicles with longer driving ranges to providing large-scale energy storage solutions for renewable energy systems. Moreover, the use of fluoride, an abundant and less environmentally impactful material compared to lithium or cobalt, could lead to more sustainable battery manufacturing processes, addressing some of the environmental concerns associated with current battery technologies.

As researchers continue to push the boundaries of fluoride-ion battery technology, the future of energy storage looks increasingly promising. The successful development and commercialization of fluoride-ion batteries could mark a significant step forward in achieving a more sustainable and efficient energy future.

2. Advancements in fluoride-ion battery technology

Recent advancements in fluoride-ion battery (FIB) technology have focused on addressing key challenges that have traditionally hindered the performance and scalability of this promising alternative to lithium-ion batteries. Two of the most critical issues are the low ionic conductivity of fluoride ions and the development of stable, efficient electrode materials. Both of these challenges have slowed the progress of fluoride-ion batteries, but recent breakthroughs are paving the way for their potential commercialization. A comparison between F-ion and Li-ion batteries is illustrated in **Table 1**.

2.1. Low ionic conductivity of fluoride ions

One of the primary obstacles in fluoride-ion battery technology is the low ionic conductivity of fluoride ions (F^-) at room temperature [14, 15]. Fluoride ions are relatively large and have a low charge-to-radius ratio compared to lithium ions (Li^+), making them harder to move through the electrolyte. In lithium-ion batteries, the smaller lithium ions can easily migrate between the anode and cathode, allowing for fast charging and discharging rates. However, in fluoride-ion batteries, the larger fluoride ions face greater resistance as they move through the electrolyte, which can slow down the charge and discharge cycles, leading to inefficiencies. **Table 2** explores the ionic conductivity of various F-ion and corresponding crystallographic structures.

Table 1. A comparison between F-ion with Li-ion and Li-sulfur batteries.

Feature	Fluoride ion battery	Lithium-ion battery	Lithium-sulfur battery (Li–S)
Ion used	Fluoride ions (F−)	Lithium ions (L+)	Lithium ions (Li^+)
Electrolyte	Solid or molten fluoride electrolytes	Liquid or solid lithium-based electrolytes	Liquid electrolytes with lithium salts
Charge carrier	Uses F-anions as charge carriers	Uses carbon compounds and an oxide layer	Uses Li^+ cations
Energy density	can have up to 10 times more energy density than LIBs	Lower compared to FIBs	Higher (~400–500 Wh/kg theoretical)
Operating temperature	High (often 150 °C)	Room temperature (~25 °C)	Room temperature, but thermal management is needed
Anode materials	Metal such as copper, Bismuth or Lanthanum	Graphite or Lithium metal	Lithium metal
Cathode materials	Metal fluorides (e.g., PbF2, BiF3)	Lithium metal oxides (e.g., $LiCoO_2$, $LiFePO_4$)	Sulfur
Cycle life	Still under research, but promising	Long cycle life (~2000+ cycles)	Moderate (~300–500 cycles, improving with research)
Charging speed	Slower than LIBs	Faster charging capability	Moderate, can suffer from polysulfide shuttling
Environmental impact	Less environmentally impactful than LIBs.	Concerns over lithium mining impact	Sulfur is abundant and eco-friendly, but lithium is not
Safety	Safer than LIBs because they don't overheat	Risk of thermal runways and fires	Moderate safety; sensitive to dendrite formation
Commercial availability	Experiment at stage, not widely available	Widely used in consumer electronics and EVs	Limited; under active development and pilot-scale testing

Table 2. Ionic conductivity of various F-ions with crystallographic structure.

Material	Ionic conductivity (S cm^{-1})	Crystal structure	References
CaF_2	5×10^{-5} (550 K)	cubic "fluorite" (Fm3m)	Doyle et al. [16]
SrF_2	10^{-3} (900 K)		Jacobs and Ong [17]
MgF_2	10^{-11} (578 K)	Tetragonal "rutile" (P42/mnm)	Derrington et al. [18]
PbF_2	10^{-7} (303 K)		Park and Nowick [19]
LaF_3	5.4×10^{-6} (633 K)	rhombohedral "tysonite" (P3c1)	Patro and Hariharan [20]
CeF_3	2×10^{-5} (454 K)		Kumar et al. [21]
YF_3	10^{-11} (293 K)	orthorombic (Pnma)	.Mori et al. [22]
AlF_3	2×10^{-11} (278 K)	rhombohedral (R3c)	Keeffe [23]
SnF_2	2×10^{-6} (345 K)	monoclinic (C2/c)	Takami et al. [24]

To address this issue, researchers have been working on improving the ionic conductivity of fluoride-ion electrolytes. Recent innovations include the development of solid electrolytes that can better facilitate fluoride-ion movement. Solid-state electrolytes, such as fluoride-based glass ceramics, offer advantages over liquid electrolytes by reducing the risks of leakage or combustion while enhancing ion conduction [25–27]. The lithium-containing metal fluorides including Li_3ScF_6 and Li_3AlF_6 investigated as potential solid electrolytes for all-solid-state fluoride ion batteries due to their high ionic conductivity and stability, offering a promising path towards safer and more energy-dense batteries. Additionally, research into hybrid electrolytes—combinations of solid and liquid materials—has also shown promise in improving ionic conductivity while maintaining stability [28, 29]. Another key advancement is the creation of fluoride-ion-conductive polymers and ionic liquids, which offer both improved conductivity and flexibility compared to traditional solid-state electrolytes. These polymer electrolytes can enable better interaction between the fluoride ions and the electrodes, allowing for higher efficiency in ion transport and reducing resistance during battery cycling. Ternary crystallographic phase diagram of Li_3ScF_6 and Li_3AlF_6 solid electrolytes is illustrated in **Figure 2**.

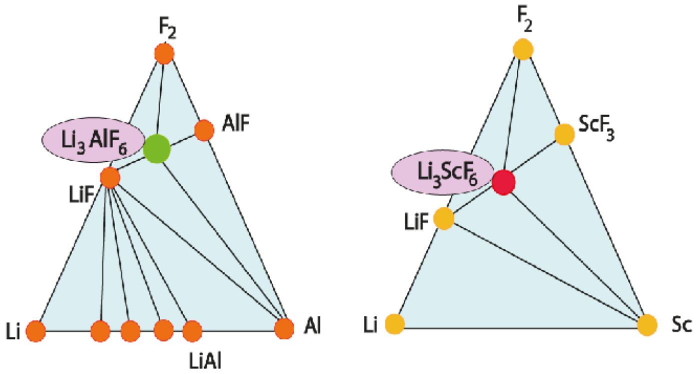


Figure 2. Li-M-F ternary crystallographic phase diagram.

2.2. Development of suitable electrode materials

The next major challenge in fluoride-ion battery technology is finding electrode materials that can efficiently and reversibly host fluoride ions during charge and discharge cycles. Unlike lithium ions, which can be easily inserted and extracted from conventional electrode materials, fluoride ions tend to be more reactive and larger in size, making them harder to manage in the battery's electrodes. One of the significant breakthroughs in this area is the development of new cathode materials that are better suited to the insertion and extraction of fluoride ions. Materials such as metal fluorides, particularly those containing transition metals like manganese, iron, and copper, have been explored for their ability to reversibly host fluoride ions [30–32]. Researchers have also looked into compounds like lithium fluoride (LiF) [33,34] and cobalt fluoride (CoF_2) [35,36], which show promise due to their structural stability and ability to accommodate fluoride ions during cycling. In terms of the anode, fluoride-ion batteries face additional challenges. Traditional lithium-ion anodes, such as graphite, are not effective for fluoride-ion systems due to the size mismatch and the highly reactive nature of fluoride ions. Researchers have turned to alternative materials, such as graphene-based composites, metallic anodes like tin or zinc, and carbon-based materials that can offer higher surface areas and better structural integrity when exposed to fluoride ions [37,38]. These materials are being engineered to provide a suitable environment for the reversible insertion of fluoride ions without compromising the battery's overall performance.

(i) Cathode materials (positive electrode)

Cathode materials in FIBs are generally transition metal fluorides, which act as the source of fluoride ions during discharge. These compounds undergo a conversion reaction where the metal fluoride is reduced to its metallic form, releasing fluoride ions into the electrolyte [39,40]. Common cathode materials include copper(II) fluoride (CuF_2), iron(III) fluoride (FeF_3), and bismuth(III) fluoride (BiF_3). Others such as cobalt(II) fluoride (CoF_2), nickel(II) fluoride (NiF_2), and manganese(III) fluoride (MnF_3) are also studied for their potential. These materials offer high theoretical capacities and operate at relatively high voltages. However, challenges such as poor electronic conductivity and structural degradation during cycling exist. To address these issues, researchers have developed composite cathodes, such as carbon-coated metal fluorides and fluorinated perovskite materials, which offer improved conductivity and structural stability [41, 42]. The ideal cathode should demonstrate high reversibility, thermal and chemical stability, and compatibility with the fluoride-conducting electrolyte.

(ii) Anode materials (negative electrode)

The anode in a fluoride ion battery is typically a metal that reacts with fluoride ions to form a metal fluoride during discharge and reverts back to the metal during charging. Common anode materials include calcium (Ca), magnesium (Mg), lanthanum (La), yttrium (Y), and copper (Cu) [43, 44]. Among these, calcium and magnesium are particularly attractive due to their high capacity and abundance, though they are highly reactive with air and moisture, which poses challenges for practical use. Lanthanum is notable not only as an anode but also because its fluoride form, LaF_3, is often used as a solid electrolyte. During discharge, the metal anode is oxidized, combining with fluoride ions to form a fluoride compound, and this reaction is reversed during charging. Desirable anode properties include high reactivity with fluoride ions, good reversibility, and stability during cycling. Charge and Discharge mechanism between two positive and negative electrodes is shown in **Figure 3**.

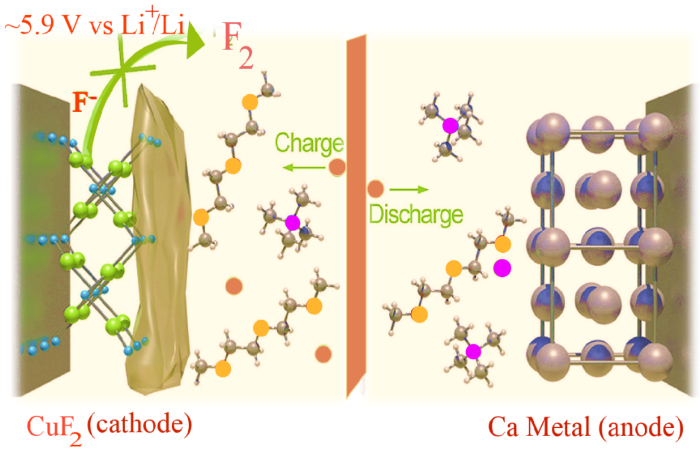


Figure 3. Charge and discharge mechanism between transition metal fluorides and metal anode.

(iii) Emerging and research materials

To overcome current limitations such as low conductivity and poor cycle life, researchers are exploring advanced materials and structural modifications. These include nano-sized metal fluorides, solid-solution electrodes that reduce structural changes during cycling, and carbon-coated active materials that enhance conductivity and protect against side reactions. Hybrid anodes combining metals with carbon or alloy supports are also being studied to improve mechanical strength and reversibility. These innovations aim to make FIBs more stable and efficient, especially for room-temperature operation.

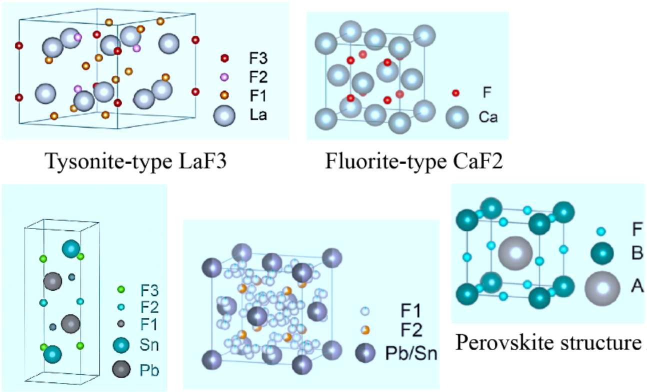
2.3. Stabilizing fluoride ions in the electrolyte

One of the breakthroughs that has led to prototypes with enhanced cycling stability and improved energy capacity is the development of electrolytes that stabilize fluoride ions during the charge and discharge cycles. Fluoride ions are highly reactive and can lead to the formation of unwanted side products if they are not effectively stabilized in the electrolyte. For instance, fluoride ions can react with certain materials in the battery, leading to the degradation of the electrolyte and the electrodes, which would reduce the lifespan and efficiency of the battery [45,46].

Recent research has focused on creating fluoride-ion-stabilizing additives. Fluoride-ion-stabilizing additives, like ethylene glycol (EG) and certain fluorinated compounds, help prevent fluoride ions from reacting with other ions by forming hydrogen bonds or stabilizing the electrode-electrolyte interface, thereby enhancing battery performance and novel electrolyte formulations that can effectively manage the reactivity of fluoride ions. For example, the use of fluorine-containing ionic liquids as electrolytes has shown promise in stabilizing fluoride ions, preventing unwanted reactions that could compromise battery performance [47, 48]. Similarly, fluoride-based ceramic materials have been incorporated into electrolyte designs to provide better control over the ions' behavior during cycling [49, 50]. Another key development is the use of artificial solid-electrolyte interphases (SEIs), which are thin protective layers that form on the electrode surfaces during the initial cycles of charging and discharging. These SEIs are critical for maintaining battery performance and preventing the breakdown of the electrolyte. Researchers have been working on developing SEIs that are specifically designed to interact with fluoride ions, ensuring that they remain stable throughout the battery's lifetime without causing degradation or loss of capacity.

A further progress in the development of electrolytes is the introduction of gel polymer electrolytes (GPEs). Researchers are also focused on developing Gel polymer electrolytes (GPEs) that are considered promising for solid-state batteries like FIBs, LIBs, SIBs, Li-S batteries, etc. These substances leverage the benefits of both solid and liquid electrolytes, providing flexibility, superior conductivity, and improved stability. Gel electrolytes may lower the chances of leakage while preserving high ionic conductivity, and they could provide enhanced cycling performance in comparison to conventional liquid electrolytes [51,52].

Fluoride-conducting substances such as LaF_3 doped with BaF_2 or heterostructure fluoride-based electrolytes (such as NA decorated NGF) show great potential because they provide excellent ionic conductivity and electrochemical stability. These electrolytes are engineered to be chemically compatible with various battery parts and to inhibit degradation, thereby guaranteeing long-term functionality. Two primary types of fluoride-ion solid electrolytes have been established: inorganic solid electrolytes and solid polymer electrolytes, which include complex electrolytes. M. Zhang et al. 2024 [53] briefly outlined that generally, inorganic solid electrolytes demonstrate superior ionic conductivities and fluoride transference numbers compared to solid polymer electrolytes. The key inorganic fluoride-ion solid-state electrolytes are: 1) Tysonite-type structures 2) MF2 fluorite-type structures 3) MSnF4 analogues 4) perovskite structure fluoride-ion electrolytes 5) glass and glass-ceramic electrolytes; 6) mixed-anion compounds; and 7) other inorganic fluoride-ion electrolytes. Crystal structure of some key inorganic fluoride-ion solid-state electrolytes is illustrated in **Figure 4**.



Tysonite-type LaF3

Fluorite-type CaF2

Perovskite structure ABF3

γ-PbSnF4

β-PbSnF4

Figure 4. Crystal structures of various inorganic fluoride-ion conductors.

Currently, the ionic conductivities reported for these pure fluorides are usually insufficient for direct practical use. Nonetheless, the ionic conductivity of these fluorides can be considerably enhanced through various doping techniques that introduce defects, such as fluoride-ion gaps or vacancies within the crystal lattice [53]. F. Gschwind et al. [54] claimed that BiF3 as an electrolyte performed potentially with high stability. Additives that stabilize fluoride ions are shown in **Figure 5**.

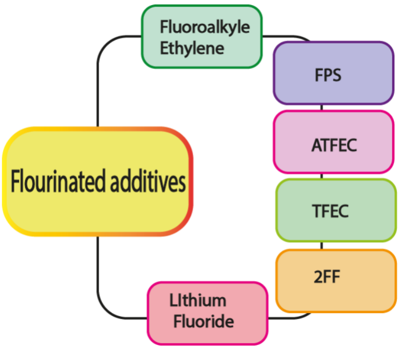


Figure 5. Fluorine-containing additives for stabilizing the electrode-electrolyte interfaces.

2.4. Enhanced cycling stability and energy capacity

The result of these advancements is that recent prototypes of fluoride-ion batteries have shown improved cycling stability and higher energy capacity compared to earlier models. By improving the stability of fluoride ions and ensuring their efficient movement through the electrolyte, researchers have succeeded in increasing the energy density of fluoride-ion batteries, bringing them closer to or even surpassing the performance of current lithium-ion technologies. These improvements also contri-bute to a longer lifespan and fewer degradation cycles, key factors in making fluoride-ion batteries a competitive option for large-scale applications. Prototypes have demon-strated longer-lasting charge cycles, meaning they can undergo many more charge and discharge cycles before experiencing significant capacity loss [55,56]. This is a critical factor for both consumer electronics and electric vehicles, where battery lifespan is a significant consideration.

3. Corrosion and energy efficiency challenges in fluoride-ion batteries

While significant advancements have been made in fluoride-ion battery (FIB) technology, critical challenges such as corrosion and the need for improved energy efficiency still pose significant barriers to their commercialization and widespread use. These issues need to be addressed for fluoride-ion batteries to become a viable alternative to lithium-ion batteries in applications such as electric vehicles, portable electronics, and large-scale energy storage. Below, we explore these challenges in detail.

3.1. Corrosion in fluoride-ion batteries

One of the most pressing issues in fluoride-ion battery development is the corrosive nature of fluoride ions. Fluoride is highly reactive, and when used as a charge carrier in the battery, it can interact with various materials in the battery, particularly at the electrodes. This reactivity can lead to corrosion and degradation of the electrode materials, electrolyte, and other components, ultimately reducing the battery's overall lifespan and performance [57,58].

(i) Electrode corrosion: The highly reactive fluoride ions can cause the formation of unwanted byproducts that affect the stability of the electrodes. For example, the reaction between fluoride ions and certain electrode materials can lead to the formation of metal fluorides or oxide layers, which can hinder the efficient movement of fluoride ions. This reduces the capacity of the battery and can make the electrodes brittle, resulting in mechanical failures over time. Some of the materials that are most vulnerable to corrosion are those used in the anode and cathode, which undergo significant chemical changes during charge and discharge cycles [59,60].

(ii) Electrolyte degradation: Fluoride ions can also attack the electrolyte, leading to the breakdown of the electrolyte solution and the formation of corrosive byproducts. In liquid electrolytes, this can cause unwanted side reactions, leading to the loss of active materials, the reduction of ion conductivity, and a decrease in overall efficiency. In solid-state fluoride-ion batteries, the corrosion risk is somewhat reduced, but it remains a challenge in terms of material stability and long-term performance [61, 62]. A schematic presentation of electrolyte degradation of a fluoride ion battery is shown in **Figure 6**.

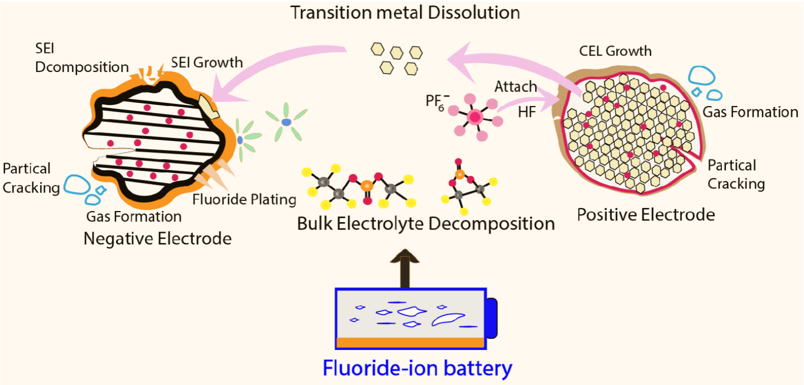


Figure 6. Schematic presentation of electrolyte degradation of a fluoride ion battery.

To mitigate corrosion, researchers are investigating more corrosion-resistant electrode materials and stabilizing additives in electrolytes. For instance, coatings that protect the electrode surfaces from direct exposure to fluoride ions are being explored, as well as fluoride-tolerant materials that are more stable under the high reactivity conditions. The development of solid electrolyte interphases (SEIs) that can form protective layers on the electrode surfaces during battery cycling is another potential solution.

3.2. Energy efficiency challenges

Another key barrier to the commercialization of fluoride-ion batteries is achieving high energy efficiency. While fluoride-ion batteries have the potential for higher energy densities than lithium-ion batteries, their overall efficiency remains a challenge, particularly when considering charge and discharge rates, capacity retention, and energy loss during cycling.

(i) Slow ionic movement: One of the primary factors contributing to energy inefficiency in fluoride-ion batteries is the relatively slow movement of fluoride ions within the electrolyte. Fluoride ions are larger and heavier than lithium ions, which increases the resistance to ion transport and reduces the overall speed of charging and discharging. This slower ion movement not only limits the rate at which energy can be stored and released, but it also increases the energy loss during these processes, further reducing the battery's efficiency [63, 64]. To address this, researchers are exploring novel electrolyte formulations, such as fluoride-based ionic liquids or fluoride-conducting polymers, which can improve the mobility of fluoride ions and reduce resistance. In addition, the optimization of the electrode-electrolyte interface to minimize energy loss is an ongoing area of research.

(ii) Energy efficiency: Another aspect of energy efficiency is the ability of the battery to maintain high-capacity retention over many charge and discharge cycles. Currently, fluoride-ion batteries struggle with capacity fade over time, primarily due to the mechanical and chemical degradation of the electrode materials as they undergo repeated cycling. This degradation not only reduces the effective capacity of the battery but also leads to increased internal resistance, which results in energy loss during charging and discharging. Improving electrode material stability and cycle life is crucial for enhancing the efficiency of fluoride-ion batteries [65, 66]. Researchers are exploring new fluoride-compatible materials for electrodes that can better withstand the stresses induced by the insertion and extraction of fluoride ions without degrading. Nanostructuring and surface engineering of electrode materials are also being considered as ways to improve energy efficiency by increasing surface area and reducing resistance.

(iii) Voltage efficiency: Another factor affecting energy efficiency is the voltage efficiency of fluoride-ion batteries. While fluoride-ion batteries have the potential to deliver high energy densities, their voltage output can vary depending on the materials used, the cycling conditions, and the stability of the electrolyte. Inconsistent voltage performance can lead to energy loss and reduce the overall efficiency of the battery, particularly in high-demand applications such as electric vehicles or grid storage [5, 42]. To address voltage inefficiencies, researchers are working on developing more stable and high-voltage cathode materials and improving the overall battery architecture to ensure consistent performance over extended periods of use.

4. Overcoming challenges and paving the way for fluoride-ion batteries in high-energy applications

The potential of fluoride-ion batteries (FIBs) to revolutionize energy storage hinges on addressing several critical challenges that have surfaced during the development process. As ongoing research continues, key areas of focus include improving conductivity, developing corrosion-resistant materials, enhancing energy efficiency, and addressing scalability. By tackling these challenges, fluoride-ion batteries could evolve into a transformative energy storage solution with wide-ranging applications, including electric vehicles (EVs), portable electronics, and large-scale grid energy storage. In this section, we explore these research efforts in detail and their implications for the future commercialization of fluoride-ion batteries.

4.1. Improving conductivity in fluoride-ion batteries

One of the foremost challenges in fluoride-ion batteries is the low ionic conductivity of fluoride ions (F^-) compared to more commonly used ions such as lithium (Li^+). Fluoride ions are larger and more sluggish in comparison, which slows down their movement through the electrolyte, leading to increased internal resistance and inefficiency in charge/discharge cycles. To make fluoride-ion batteries viable, researchers are working on improving the ionic conductivity of both the electrolyte and electrode materials.

Electrolyte improvements are a key area of research. Efforts are focused on developing more conductive solid electrolytes, such as fluoride-based glass ceramics and fluoride-conductive polymers, which can offer better ion transport capabilities and more stable performance at room temperature. Additionally, fluoride-based ionic liquids are being explored as electrolytes because they have high ionic conductivity, low volatility, and thermal stability. These innovations would reduce the resistance to ion flow, thus improving the efficiency of fluoride-ion batteries, enabling faster charging, and enhancing overall energy density. Moreover, developing electrode materials with optimized structures that facilitate faster fluoride-ion transport is crucial. Researchers are investigating the use of nanostructured materials and metal fluorides to improve both the capacity and rate of fluoride-ion intercalation and deintercalation. Nanomaterials can provide a larger surface area and shorter ion diffusion paths, helping to overcome the slower ionic conductivity.

4.2. Developing corrosion-resistant components

Corrosion is one of the most significant challenges in fluoride-ion batteries, as fluoride ions are highly reactive and can degrade battery components over time. The interaction between fluoride ions and the electrodes, as well as the electrolyte, can lead to corrosion, which in turn reduces the lifespan, stability, and efficiency of the battery. Corrosion-resistant materials are being heavily researched to counter this issue. In fluoride-ion batteries, polyvinylidene fluoride (PVDF) and certain stainless-steel alloys (like 304 and 316L), Titanium and its Alloys, and Nickel-based Alloys are corrosion-resistant components that help protect the battery's internal components from damage. Some promising strategies include the development of fluoride-tolerant alloys and coatings that can protect the metal components of the battery from corrosive reactions with fluoride ions. For example, the use of protective coatings on electrode surfaces can prevent direct exposure to fluoride ions and reduce the formation of unwanted byproducts that cause corrosion. Researchers are also looking into corrosion-resistant anode materials like carbon-based composites or graphene, which are more stable when exposed to fluoride ions.

Additionally, solid-state fluoride-ion batteries—here both the electrolyte and the electrodes are in a solid form show promise in reducing corrosion. Solid-state systems can mitigate some of the problems associated with liquid electrolytes, including leakage and corrosion, offering a safer and more durable alternative. Although solid-state fluoride-ion batteries still face challenges in terms of manufacturing and scalability, they present a pathway to overcoming corrosion and improving the overall lifespan of the battery.

4.3. Enhancing energy efficiency

Energy efficiency remains a critical concern for fluoride-ion batteries, especially when compared to lithium-ion batteries. The lower ionic conductivity and the slower ion movement of fluoride ions result in higher internal resistance, which leads to greater energy loss during charge and discharge cycles. Additionally, capacity fading and voltage instability during prolonged cycling can reduce the overall energy efficiency and lifetime of the battery.

To improve energy efficiency, ongoing research is focused on several fronts:

(i) Optimization of electrolyte materials: Researchers are developing electrolytes that are not only more conductive but also more stable under prolonged use. For example, fluoride-based ionic liquids or fluorinated gel polymer electrolytes could offer more stable ion conduction, enhancing the efficiency and lifespan of fluoride-ion batteries.

(ii) Enhanced electrode design: Nanostructured electrodes, designed to improve the surface area and reduce the distance over which fluoride ions must travel, are being investigated to boost efficiency. These electrodes are engineered to maintain their structural integrity during cycling, which can prevent performance degradation and increase charge retention. The function of nanostructured electrodes for F-ion battery is illustrated in **Figure 7**.

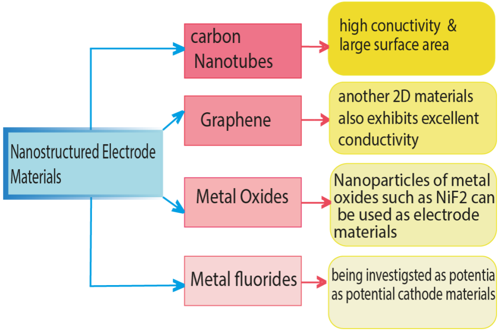


Figure 7. Nanostructured electrode materials for F-ion battery.

(iii) Interface engineering: The interface between the electrode and electrolyte is a critical area where energy losses often occur. Research is focusing on creating solid-electrolyte interphases (SEIs), which are thin, protective layers that form on the electrode during cycling. These SEIs can stabilize the electrode-electrolyte interface, prevent unwanted reactions and reduce energy loss. Through these developments, researchers aim to improve the energy retention of fluoride-ion batteries and reduce voltage inefficiency, making them more competitive with existing battery technologies in terms of overall performance. Experimental and theoretical analyses of the SEI formation process, consist of three major steps. Experimental methods are well-suited to characterize the final form of the SEI (step 3), whereas conventional theoretical methods are mainly applied to the initial electrochemical reactions (step 1). However, it is still unclear how the reaction products interact and aggregate to form the final SEI (step 2), because it cannot be easily approached using conventional methods. An overview of experimental and theoretical analyses of the SEI formation process is shown in **Figure 8**.

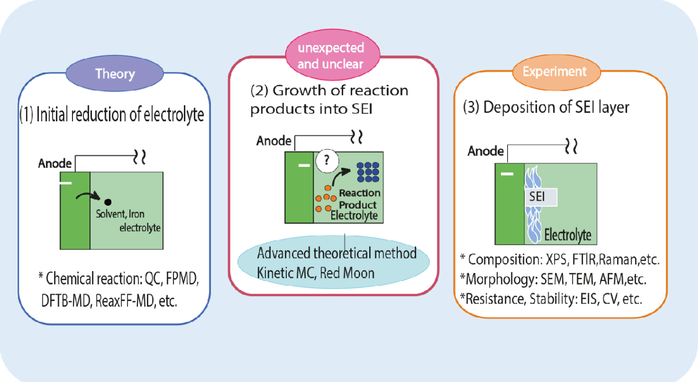


Figure 8. Overview of experimental and theoretical analyses of the SEI formation process.

4.4. Scalability and commercialization

While fundamental research has led to substantial improvements in fluoride-ion battery performance, scaling up production and making the technology commercially viable remains a significant challenge. The manufacturing processes for fluoride-ion batteries, especially those using novel materials like fluoride-based ionic liquids or solid-state electrolytes, are still in the early stages of development. The cost of raw materials, such as high-purity fluoride salts, as well as the complexity of manufacturing processes, could limit the scalability of fluoride-ion batteries if they are not optimized for large-scale production. To overcome these barriers, research is focused on developing cost-effective and scalable manufacturing techniques. Automated fabrication methods, such as roll-to-roll processes or 3D printing of battery components, are being explored to reduce production costs and increase throughput. Additionally, recycling and reuse of materials will be critical in making fluoride-ion batteries sustainable and cost-competitive in the long term. If these scalability challenges are overcome, fluoride-ion batteries could become a powerful solution for various high-energy applications, including:

(i) Electric vehicles (EVs): Fluoride-ion batteries could potentially provide EVs with longer driving ranges due to their higher energy density compared to lithium-ion batteries. Additionally, their inherent safety and thermal stability would make them an attractive option for the EV market.
(ii) Portable electronics: Fluoride-ion batteries could power smartphones, laptops, and other consumer electronics for longer periods, reducing the frequency of charging and increasing convenience for users.
(iii) Grid energy storage: Fluoride-ion batteries could be used in large-scale grid storage systems, providing an efficient way to store renewable energy, such as solar or wind power, for later use. Their high energy density and potential for longer cycle life make them ideal candidates for balancing intermittent energy production and demand.

5. The future of fluoride-ion batteries

Fluoride-ion batteries (FIBs) offer significant potential for high-energy applications, including electric vehicles, portable electronics, and large-scale energy storage, thanks to their high energy density and use of abundant materials. However, challenges such as low ionic conductivity, corrosion, energy inefficiency, and scalability must be addressed for commercialization. Research is progressing in developing high-conductivity electrolytes, corrosion-resistant materials, and energy-efficient electrodes. Solid-state configurations and advanced protective coatings are also promising solutions. Overcoming these challenges will be key to making fluoride-ion batteries viable for widespread use. If successful, they could provide a more sustainable and efficient alternative to current energy storage technologies, benefiting industries that rely on long-lasting, high-performance batteries.

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