Dean&Francis
ISSN 2959-6157

Research Progress of Sodium-Ion Cathode Materials

Jiaya Zhang[1, *]

[1]Shenzhen College of International Education, Shenzhen, China
*Corresponding author: krrz77ttkx@gmail.com

Abstract:

Sodium-ion batteries have attracted extensive attentions as a promising alternative to lithium-ion batteries due to the abundant natural resources of sodium and the expected low production cost. This paper presents a detailed review on recent advances of sodium-ion battery cathode materials, which are considered as the most important part contributing to the overall performance of a battery. According to structural features, electrochemical behavior, advantages and disadvantages, sodium-based polyanionic compounds, Prussian blue analogues and layered transition metal oxides as cathode materials are reviewed in this article. Moreover, different from lithium-ion battery, much bigger ionic radius of sodium ion results in much more complicated working mechanism. The technical challenges of sodium-ion batteries including low energy density, poor cycling stability and limited rate capability are analyzed in details. The strategies to solve above problems are discussed in details. These strategies include elemental doping, surface coating, nano-structuring and novel structural engineering strategies including high-entropy stabilization. The emerging research trends and future development directions are identified based on materials development, structure optimization, cost reduction and environment friendliness. The conventional idea is summarized and detailed discussions are offered to guide the further advance of high-performance sodium-ion batteries towards commercialization.

Keywords: Sodium-ion battery; cathode materials; prussian blue analogues.

1. Introduction

All The worldwide energy industry is facing a challenging situation due to the need to cope with climate change and move away from fossil fuels. Since the renewable energy share is growing dramatically and the number of electric vehicles is increasing, there is an increasing demand for small, affordable, and environment-friendly energy storage systems. Due to their high energy density and well-developed tech-

ISSN 2959-6157

nology, lithium-ion batteries have been the main technology in battery systems for over two decades. However, the increasing cost of lithium and its limited resource base, along with geopolitical issues related to supply chains, create a strong need for new battery systems. At this point, sodium-ion batteries have emerged as one of the most promising candidate technologies for mass-scale energy storage applications.

Sodium-ion batteries have advantages. Sodium is abundant in the earth's crust and has been widely spread, and therefore it can be counted as an available source at relatively low cost for being accessed from the environment. Moreover, by virtue of the physical properties of sodium, sodium-ion batteries can use the same 'rocking-chair' mechanism as lithium-ion batteries and the knowledge and production experience can be simply transferred. However, due to the larger ionic radius and larger molecular weight relative to lithium ions, the diffusion kinetics of sodium ions are slower, and, in fact, this also becomes their volume expansion in charge and discharge states. These inherent characteristics make challenges for the cathode materials, since they play a fundamental role in determining the overall performance, cycle life, and safety of a battery, as they are involved in both the electrochemical reaction and the volume change during charge and discharge. [1].

Theoretical research work has been done to develop high-capacity cathode materials for sodium-ion batteries. Currently, the most studied material classes are polyanionic materials, Prussian blue analogues and layered transition metal oxides. Polyanionic materials, for example phosphates and sulfates, have advantages of strong framework, high operating voltage, and high thermal stability. However, the practical application of these materials is limited by their low intrinsic electronic conductivity. Prussian blue analogues have open structure framework to facilitate fast migration of sodium cations and an economic advantage due to simple synthesis routes. They, however, have been found to contain structural water and vacancies that induce electrochemical characteristics degradation [2]. Layered transition metal oxides have high specific capacity and easy synthesis, but they experience phase transformation and structure degradation during cycling, which leads to capacity fading. Recently, works have been developed to overcome these disadvantages through different approaches, including elemental doping, surface coating, nanostructuring, and composite synthesis. These approaches can be used to enhance ionic and electric conduction, electrode structure stability, and interfacial properties. There has also been increased interest to develop cost-effective and environment-friendly materials to accelerate the commercial integration of sodium-ion batteries [3].

In this article we would like to discuss the research on cathode for sodium-ion batteries and attempt to summarize the characteristics and performance of various sodium-ion cathode materials and explore the energy storage behavior of these materials. Several common sodium-ion batteries are reviewed in this article and some suggestions for future sodium-ion battery cathode materials are put forward to pave the way for the development of high energy density and long service life sodium-ion batteries.

2. Cathode Electrode Material for Sodium Ion Batteries

2.1 Sodium-ion Batteries

Sodium-ion batteries (SIBs) are a major class of electrochemical energy storage devices that operate on principles fundamentally similar to their lithium-ion cousins, albeit with a few specific derived properties that come directly from the nature of sodium ions. It is helpful to appreciate the fundamental workings of how SIBs in order to both praise their virtue as well as appreciate their limitation as energy storage systems.

At the most fundamental level, a SIB consists of two major parts along with an electrolyte that only allows the movement of ions but not electrons. At charging, sodium ions are pulled out of the cathode material, migrate through the electrolyte medium, and are inserted into the anode material. At the same time, electrons negotiate the external circuit from cathode to anode, generating an electric current that may be used to energize devices or saved for future use. Furthermore, upon discharge, the reverse occurs —sodium ions migrate back from anode to cathode through the electrolyte as electrons migrate through the external circuit, delivering electrical energy to devices. This eversible movement of the ions has come to be referred to poetically as a 'rocking-chair' mechanism, imagining the back-and-forth movement of sodium ions between both electrodes during charge/discharge cyclings.

Electrochemical properties of SIBs are mainly determined by the intrinsic nature of sodium ions. Having an ionic radius around 1.02 Å, sodium ions are considerably larger than the ones of lithium (0.76 Å). This value significantly impacts the design as well as the functioning of the battery. Due to their larger radius, there are slower diffusion kinetics during electrode materials, i.e., sodium ions diffuse more slowly throughout the cathode and anode materials' crystal structures. As a direct result, this automatically restricts the rate capability of the SIBs — to charge and discharge quickly — their rate capability — is worse than that of LIBs. Furthermore, the insertion as well as the extraction of the bigger sodium ions usually results in bigger volume changes among the electrode materials. Repeated expansion as well as contraction during the cycle results in the creation of various mechanical tensions, which yield particle cracking, degradation of the structure, as well as ultimate loss of capability, in the long run [4].

From the point of view of the thermodynamics, the standard electrode potential (Sodium-2.71 V, vs. Standard Hydrogen Electrode) is slightly positive as compared to the value (lithium-3.04 V, vs. SHE). It implies that, all other things being constant, SIBs normally hold their operating cell voltages lower than LIBs, meaning lower energy density — the energy stored per unit weight or unit volume. Sodium's higher atomic mass than the value also adds to this disadvantage of energy density based on gravimetric measurements.

Nevertheless, sodium has several advantages that justify the many research efforts dedicated to studying SIBs. Sodium is roughly 1000 times more abundant in the Earth crust than lithium, is more uniformly distributed geographically, and there are deposits of sodium on each continent. This results in considerably lower raw materials cost and supply chain risk division. In addition, sodium compounds themselves are typically cheaper than their corresponding lithium ones, and the aluminum current anode collector could be used preferably in SIBs as compared to LIBs, where the use of copper is needed, generating other economies and weight savings. SIBs' operating principles also enable the possibility of being compatible with most of the already-existing LIBs' manufacturing technologies and infrastructure, facilitating the ease of transition to commercial-scale production. These considerations make SIBs very appealing to the applications of bulk-scale, stationary energy storage applications, like the grid storage applications that enable the integration of the renewable energy, where cost, safety, as well as cycle life, usually dominate the considerations rather than the maximum energy density. Sodium environmental compatibility also offers the benefits regarding the sustainability as well as the minimization of the environmental disruption compared to the mining required for the attainment of the lithium. Recently some work about the SIB mechanisms have been proposed to face with the challenges brought by the physicochemical properties of sodium. New electrolyte compositions are being sought after to facilitate the fast ionic transport as well as the interface stability. Specialty solid electrolytes for the solid-state SIB is also an interesting approach to enhance the safety while aiming at a higher energy density. Advanced characterizations, in situ as well as operando, are employed to see and characterize the structural transitions that happen during the cycling of the electrode materials and thus deliver the crucial information necessary to conceive stronger materials [5].

2.2 Classification and Characteristics of Cathode Materials

Cathode material is likely the most important factor both in the overall performance, cost, and feasibility of sodium-ion batteries. Different from the anode, where the carbonaceous materials analogue to those found in LIBs usually work satisfactorily, cathode materials of SIBs need customised design to support the larger sodium ions as well as ensuring the stability of the structure and high capability. It has been extensive research that aligned into three key cathode material categories, which include their specific structure features, electrochemical properties, as well as their developmental trends.

2.2.1 Polyanionic compounds

Polyanionic compounds are a significant category of cathode materials defined through their framework structures, wherein transition metal cations are coordinated through the polyanionic groups like phosphate $(PO_4)^{3-}$, sulfate $(SO_4)^{2-}$, or silicate $(SiO_4)^{4-}$. Their name originates from the polyanions that constitute the structure framework, establishing rigid three-dimensional structure compartments that house sodium ion migration.

The most remarkable one should be conferring the so-called 'inductive effect' by the polyanion groups. Due to the strongly covalent bonding inside the polyanions (more than P-O, S-O or Si-O bonds), an electron-withdrawing effect should be caused, which increases the working voltage of redox couples of transition metals. Therefore, many polyanionic compounds shall exhibit working voltage over 3.0 V vs. Na/Na^+, and some shall even exhibit over 3.5 V vs. Na/Na^+. As mentioned before, high voltage results in high energy density, which is an extremely important parameter and indispensable to the definition of the battery.

In addition to their desirable voltage behaviors, polyanionic compounds usually also exhibit high thermal stability and framework structure strength. Due to the strongly covalent bonding between framework atoms, the framework structure materials are more stable against thermal degradation compared to other cathode material families. This intrinsic stability also contributes to the desirable safety properties, which is an important feature for bulk-scale energy storage applications. Moreover, open framework structure based many polyanionic compounds shall exhibit high cycle durability through reversible sodium insertion/extraction with little structure change.

The NASICON (Na Superionic Conductor) family shall be the most studied family of polyanionic cathodes. $Na_3V_2(PO_4)_3$ shall be noted as an example, which exhibits a sharp voltage plateau around the value of about 3.4 V based on the V^{4+}/V^{3+} redox couple, and also exhibits reasonable structure stability based on the NASICON structure as well as a theoretically high capacity around about 117 mAh/g. Three-dimensional diffusion channels for sodium ions are provided by the NASICON structure, which can

ISSN 2959-6157

take support for reasonable rate capability. $Na_2Fe_2(SO_4)_3$ shall be noted as the other remarkable polyanionic material, which exhibits an ultra-high operating voltage around about 3.8 V, among the largest that have been reported so far for iron-based cathode materials used in SIBs [6].

Nevertheless, poly anion compounds have come with limitations that have limited their wide application. The biggest is their normally low intrinsic electronic conductivity. Due to the strongly ionic and covalent character of the bonds in the material, they have poor electron transport and as a result, limit the rate capability and power density, especially apparent at high charge/discharge rates when the voltage polarization spans most of the usable capacity.

Much effort has gone towards overcoming this poly anion limitation of conductivity. The only way to do this is nanostructuring where the particle size is collapsed such that the ion and electron transport distances are minimized. Enhancing electronic connectivity by making composites with conductive carbon materials--in situ carbon coating, graphene, carbon nanotube integration, etc. is very effective. Doping the element at multiple sites in the crystal structure is also able to increase both electronic and ionic conductivity as well as stabilize the crystal structure. It is not surprising that Liu et al. reporting recent advances in optimizing the polyanionic cathodes. In optimizing the voltage output by rational elemental substitution as well as optimizing the carbon coating process to yield more effective conductive networks they have achieved significant improvements in high-rate capacity retention as well as cycle stability. This is a good example of the value of multi-faceted optimizing research as the best research to push the polyanionic cathode-based anode materials into technological use in SIBs.

2.2.2 Prussian blue analogues (PBAs)

Prussian Blue Analogues (PBAs) are an interesting group of cathode materials that exhibit rare structural features making them highly desirable cathodes for sodium-ion cells. Product compositions are as follows: $A_xM[Fe(CN)_6]_1 \cdot zH_2O$, where A is the alkali cations (commonly Na^+), M is the transition metals stands for $[Fe(CN)_6]$ vacancies, and z is the number of water molecules within the framework. PBAs exhibit face-centered cubic structure where an open lattice framework comprising M^{+n} & Fe^{+3} centers joined together with cyanide (CN^-) bridges results into very spacious interstitial voids where sodium cations intercalate.

Best among the virtues of PBAs is the open framework structure that offers voluminous channels facilitating swift diffusion of sodium ions. This is the structure that gives PBAs very high rate capability, making fast charging as well as fast discharging very easy—a very desirable quality that many applications would find attractive. Preparation of PBAs is very easy, and the common preparation method is the simplest precipitation techniques directly from aqueous solutions either at or around ambient temperature. As opposed to numerous other cathode materials that need high-temperature processing, PBAs are very cheaply likely to be produced on a very large scale.

Various transition metals within the M site enable the adjustment of the electrochemical properties. Iron-based PBAs (FeFe-PBAs) are specific interest, as iron is cheap, plentiful, and environmentally benign. These materials, as a whole, exhibit about 3.1-3.3 V based on the redox couple Fe^{3+}/Fe^{2+} within the high-spin sites of the metals. Manganese-based PBAs (MnFe-PBAs) are capable of achieving higher operating voltages (~3.6 V) yet tend to suffer issues with dissolution of the manganese as well as lack of stability within the structure. Mixed transition metal PBAs provide the capability to optimize the performance where the benefit of varying metal centers is balanced.

Even though their attractive properties, PBAs are challenged critically, which has prevented their successful commercial exploitation. Of first order is the problem related to defects that are intrinsic to their structure. As the usually fast precipitation synthesis takes place, there is the possibility that a high percentage of $[Fe(CN)_6]^{4-}$ sites will be unfilled, leaving vacancies within the structure. Again, the vacancies are usually filled up, or the transition metal ions coordinated to, by the water molecules. Co-ordinated water, although in some amount stabilises the structure, too much or ill-bound water can be harmful to the material during electrochemical functioning.

The presence of water in the structure can lead to gas evolution with cycling, especially at high voltages, which can lead to electrode swelling and possibly impact cell safety. Water molecules can also participate in side reactions with the electrolyte, which can lead to irreversible capacity loss and poor Coulombic efficiency. Additionally, structural vacancies and water content are often correlated with low crystallinity, which also impacts electronic conductivity and structural stability during cycling.

A lot of work has gone a long way in solving these issues. Kitchamsetti et al. have highlighted the supreme importance of strict control of synthesis to reduce defects in PBAs. As the authors of this work have shown, PBAs with drastically lower vacancy concentrations as well as controlled moisture content can be attained through proper control of the synthesis parameters, such as concentration, addition rate, temperature, as well as the use of complexing agents. This controlled synthesis methodology leads to the production of material with enhanced crystallinity, high initial Coulombic efficiency as well as improved cycling stability [7].

Another possible approach is surface modification of PBA. The formation of coatings on PBA particles is able to suppress surface side reactions with the electrolyte while avoiding bulk degradation. We also discovered that the initial sodium content in the framework is an important factor that affects the initial Coulombic efficiency for practice cells. Peng et al.'s extensive review offers significant insight into PBAs' future development path as SIBs. Through their refraction, they trace the history of the materials back to the initial research curiosity based on structure research, indicating the significant milestones that paved the way to the potential practical candidate. They insist that future research must aim to control the structure and composition exactly at various scales, ranging from the defects that occur on the atom scale to particle morphology. Detailed characterization protocols are allowing an unprecedented understanding of the functioning of the water molecules and sodium cations within the PBA structure during the electrochemical functioning, paving the path further to rationalizing the material designing [8].

2.2.3 Layered transition metal oxides

Multilayer transition metal oxides, as part of the general composition $NaxMO_2$ (where M is an integer consisting of a transition metal component involving Mn, Ni, Co, Fe, Cu, or Ti) are among the most broadly researched families of cathode materials pertinent to sodium-ion batteries. These compounds exhibit morphologies similar to the layer-structured parent oxides utilized in the case of lithium-ion batteries, where the MO_6 octahedra are edge-shared to form slabs, upon which the sodium ion layers separate. It is the inter-slab, two-dimensional van der-Waals gaps that act to enable the diffusion necessary for the intercalation/deintercalation processes that are central to the functionality of the battery.

The attraction of layered oxides is their moderate to high theoretical specific capacities (customarily 200-250 mAh/g for $x \approx 1$ in Na_xMO_2), uncomplicated synthesis guidelines, and comprehensively understood electrochemical character. Capacity issues revolve around the reversible sodium ion extraction/in Insertion from the interlayer sites, together with redox processes amongst the change steel cations. Working voltage would be optimized through the choice of the appropriate change steel pairings, as increasing voltages corresponded to more electronegative cations. Structural chemistry of the P2 sodium sodium transition metal oxides is significantly more complex than that of their P counterpart. Sodium's larger cationic radius than that of the cation than the cationic radius results in coordination preference and stacking sequence. P2, the two most common structure type, are defined as the sodium cation coordination environment (prismatic or, respectively, octahedral) as well as the amount of the unit cell containing the layers of the transition metals (2 or, respectively, 3). These structure-related factors affect electrochemistry properties in a variety of ways. In general, P2 structure will have better capability rate due to better diffusion paths of Na cation, while they tend to provide lower specific capacitance. O3 structure tends to provide higher specific capacitance, but they tend to be slower kinetically as well as have more complex phase transformations during cycle. An intrinsic issue illposed by layered oxide cathodes is phase transitions during sodium insertion/extraction. As the sodium composition varies during charging and discharging, the material travels through different phase regions with different stacking orders or sodium/vacancy ordering scheme. Any structural change that usually accompanies volume change as well as strain in the lattice will induce particle cracking as well as ultimate capacity fade due to the resulting mechanical degradation. Such mechanical degradation usually comes from two types of behaviors-mostly during deep charge states, gliding of MO_2 slabs will occur and irreversible structure changes will arise. The multi-phases behaviour and corresponded degradation mechanism within the layered oxides are explored extensively by Zuo et al. In their extensive analysis, they shed light on the role of composition on phase stability as well as the electrochemical behaviour among various families of layered oxides. They prove that phase transitions unfavourable to performance could be suppressed through the effective substitution of the transition metals, while desirable structure stability could be achieved through the favourable capacity. Based on their techno-economics evaluation, their results also indicate the significance of the cost of the materials on making commercially viable SIBs, where compositions based on the cheaperly abundant elements, such as iron, as well as manganese, are favoured [9].

Recent advances in layered oxide design have introduced innovative approaches to stabilize these materials against degradation. A particularly promising strategy, demonstrated by Wang and coworkers, involves high-entropy phase stabilization engineering. This approach incorporates multiple different metal cations into the transition metal layer, creating a 'high-entropy' configuration where the increased configurational entropy of the system thermodynamically stabilizes the desired structure. Their work on high-entropy layered oxides shows remarkable suppression of phase transitions during cycling, resulting in exceptional capacity retention over hundreds of cycles. This represents a paradigm shift in cathode design, moving from simple binary or ternary transition metal systems to complex multi-component compositions where entropy stabilization complements traditional chemical stabilization [10].

Further developments in layered oxide cathodes focus on optimizing particle morphology and surface chemistry. Controlled synthesis of hierarchical structures with preferred crystal orientation can enhance sodium ion transport while mitigating mechanical strain. Surface coatings and electrolyte additives are being developed to protect the reactive surface of layered oxides from parasitic reactions with the electrolyte, particularly at high voltages. These multi-faceted approaches are steadily addressing the historical limitations of layered oxide cathodes, positioning them as strong contenders for commercial SIB applications [11].

2.3 Future Trends

2.3.1 Technical challenges to commercialization

Despite recent progress, technical challenges remain that are hindering the performance and lifecycle of sodium-ion batteries relative to the well-established technology of lithium-ion batteries.

The fundamental physicochemical properties of sodium, such as its larger atomic mass and more positive redox potential relative to lithium, place theoretical limits on both the gravimetric and volumetric energy density of sodium-ion technology. Generation sodium-ion cells have achieved typical energy densities of 100-160 Wh/kg at the cell level, far below the 200-300 Wh/kg delivered by commercial lithium-ion cells. As a result, the sodium-ion battery is not well-suited for applications where weight and size are critical constraints, such as consumer electronics and long-distance electric vehicles. The energy density gap can be narrowed by advancing cathode materials with higher specific capacities and operating voltages in combination with anodes beyond hard carbon.

The larger ionic radius of sodium places significant mechanical stress on electrode materials with each insertion and extraction cycle. The stress leads to particle cracking, phase separation, and loss of electrical contact within the electrode composite. The higher solubility of certain electrode components in organic electrolyte relative to lithium systems can also lead to loss of active material and migration between the electrode and electrolyte. Instability at the interface between electrodes and electrolyte also leads to capacity fade through continuous side reactions and growth of the solid-electrolyte interphase (SEI). While some cathode materials, such as certain polyanionic compounds, have been shown to exhibit longevity exceeding 10,000 cycles, many material systems have low capacity retention even over the lifetime of the battery.

The kinetics of sodium ion diffusion in crystal structures is generally slower than lithium, though power density can approach that of equivalent LIB cells through nanomaterials and other morphological control. Sodium-ion batteries are therefore less well-suited for applications requiring fast charging or high power discharge. Advances in electrolyte ionic conductivity and wetting characteristics, in combination with electrode architectures minimizing tortuosity, will enable further improvements in power density.

Coulombic efficiency (initial cycles). For many material systems, the initial charge-discharge cycle results in irreversible capacity loss due to interface formation and other structural rearrangements. The irreversible capacity reduces the usable capacity of the cell, and the initial Coulombic efficiency can be improved for longer cell life.

2.3.2 Development trends

The future technical development of sodium-ion batteries will be driven by several trends that are closely interconnected across materials innovation, manufacturing, and application engineering.

Increased computational guidance will become an increasingly important part of advanced material discovery. High-throughput density functional theory screening combined with machine learning algorithms can rapidly screen out potential compositions and structures prior to synthesis, shrinking the vast circle of trial and error. The success of new design concepts such as high-entropy stabilization, shown by Wang and colleagues, highlights the potential of new material paradigms to bypass traditional constraints, and we will likely see more novel material concepts extending to control properties at all length scales.

Optimization of nanoscale and microscale structure will remain important. Hierarchical architectures where short diffusion paths are created by nanoscale features organized at the microscale for fast packing and electrolyte penetration will be interesting. Mitigation of degradation paths while maintaining high capacity is achievable through innovative core-shell structures, concentration gradi- ents, and engineering of defects. Fine control of electrode-electrolyte interface will be achievable through more effective surface modification methods such as atomic layer deposition, molecular layer deposition, electro grafting, etc.

Sustainability will continue to play an important role in material choice and processing route. Earth abundant elements and non-toxics will continue to be preferred by researchers. Given the large number of elements considered for sodium-ion chemistry, iron-manganese based systems will receive special attention as alternatives to cobalt-based materials. As discussed by Lai and colleagues, the environmental credentials of SIBs are not limited to the elemental composition but extend to the entire SIB life cycle from manufacture to end of life. The comprehensive assessment of life cycle emissions for SIB manufacture relative to LIBs provides some quantification of the environmental impact of using SIBs instead of LIBs. The work by Lai and colleagues shows clear potential for SIBs to have a lower carbon footprint and environmental life cycle profile. We would expect that SIBs will continue to be developed and commercialized as a more sustainable part of the energy ecosystem, and that life-cycle assessment would increasingly be used as a standard evaluation metric in addition to performance parameters.

Manufacturing innovation will focus on two aspects: going from small scale to commercial quantities and minimizing cost and energy. Any optimal electrode processing will focus on minimizing use of solvents and eliminating costly and messy coating and calendering steps. Higher yield will be maximized as well. The similarities to LIB manufacture will provide opportunities for fast scaling of SIB manufacture through production line repurcussion.

Application specific engineering will lead to diversified product profile of SIBs for different use cases. Longevity, safety, and cost of ownership will be the primary considerations for stationary storage, where the focus will not be on achieving the highest energy density but rather the best lifecycle cost. For specific classes of mobility applications, such as urban electric vehicles, low-cost variants of SIBs with moderate performance may find niches in the market. The development of management systems optimized for specialized operation will further optimize the real-world performance and reliability of SIBs.

As research catches up and manufacturing scales up, the world can expect sodium-ion batteries to play an increasingly important role. They will complement rather than compete with lithium-ion technology as the global energy storage landscape expands to accommodate renewable energy and electrified systems across transport, power, and data.

3. Conclusion

Through the research on the positive electrode materials of sodium-ion batteries, this paper reveals that the current mainstream three types of positive electrode materials - poly-anionic compounds, Prussian blue analogues, and layered transition metal oxides - each have their own advantages and limitations in terms of structural characteristics and electrochemical performance. Poly-anionic materials have high voltage and good stability, but poor conductivity. Prussian blue analogues have low synthesis costs and excellent rate performance, but they have problems of crystalline water and vacancy defects. Layered oxides have high specific capacity, but they are prone to phase transformation during cycling, resulting in capacity degradation.

Therefore, future research should focus on improving the comprehensive performance of the materials through multi-element co-doping, surface coating and structural design, and promoting their feasibility in practical applications. The research results of this paper have positive significance for promoting the development of low-cost, resource-sustainable new energy storage technologies, especially for researchers and industrial developers engaged in electrochemistry, materials science and energy engineering. At the same time, this paper emphasizes the importance of material full life cycle assessment, which can provide theoretical basis for the green design and industrialization path of sodium-ion batteries, and promote their application in large-scale energy storage, low-speed electric vehicles and other fields.

References

[1] Hwang, Jang-Yeon, Seung-Taek Myung, Yang-Kook Sun. Sodium-ion batteries: present and future. Chemical Society Reviews, 2017, 46(12): 3529-3614.

[2] Vaal Ma, Chris Toph. A cost and resource analysis of sodium-ion batteries. Nature reviews materials. 2023, 23(49): 1-11.

[3] Nayak, Prasant Kumar, Nan Meet, et al. From lithium-ion to sodium-ion batteries: advantages, challenges, and surprises. Angewandte Chemie International Edition, 2024, 57(11): 102-120.

[4] You, Ya, Arumugam Manthiram. Progress in high-voltage cathode materials for rechargeable sodium-ion batteries. Advanced Energy Materials, 2018, 23(34): 1701785.

[5] Zhang Heng, Hang Tao, Zhao Peng, et al. Long-cycle-life cathode materials for sodium-ion batteries toward large-scale energy storage systems. Advanced Energy Materials, 2023, 32(34): 2300149.

[6] Liu Fang, Su Wan, Xiao Dong, et al. Enhancing Voltage Output in Polyanion-Type Cathode Materials for Sodium Ion Batteries. Batteries & Supercaps, 2024, 43(32): 202400290.

[7] Kitcha Mset, An Barros, Sungwook Min, et al. Prussian Blue Analogs as Cathode Materials for Sodium-Ion Batteries. Batteries & Supercaps, 2025, 12(34): 20250482.

[8] Gao Peng, Wan Jian, Wang Dong, et al. Prussian blue analogues for sodium-ion batteries: past, present, and future. Advanced Materials, 2022, 34(15): 2108384.

[9] Zu Peng, Wen Hua, Zhang Peng, et al. Layered oxide cathodes for sodium-ion batteries: storage mechanism, electrochemistry, and techno-economics. Accounts of chemical research, 2023, 24(55): 284-296.

[10] Wang Pen, Yang Bing, Chan Wang, et al. High-Entropy Phase Stabilization Engineering Enables High-Performance Layered Cathode for Sodium-Ion Batteries. Advanced Energy Materials, 2024, 23(33): 2401090.

[11] Li An, Si Qing, Wang Song, et al. Recent developments of layered transition metal oxide cathodes for sodium-ion batteries toward desired high performance. Asia-Pacific Journal of Chemical Engineering, 2022, 23(34): 2332762.