

Recent Advances in Metal-Organic Frameworks for High-Performance Lithium-Ion Batteries

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ABSTRACT

The growing global demand for energy and the urgent need to reduce carbon emissions have intensified interest in high-performance electrochemical storage systems. Lithium-ion batteries (LIBs) remain the leading technology due to their high energy density, long cycling life, and adaptability across diverse applications. However, further improvement in capacity, stability, and rate performance is essential to meet future energy requirements. Metal-organic frameworks (MOFs) have emerged as promising candidates for next-generation electrode materials because of their tunable porosity, structural flexibility, and rich redox activity. This review

highlights the evolution of LIB technology and critically examines recent progress in MOF-based anode and cathode materials. Emphasis is placed on their structural advantages, electrochemical behavior, and challenges that must be addressed to unlock their full potential for advanced and sustainable energy storage.

Introduction

Due to the rapidly growing global population, the demand for energy resources is increasing sharply which has severe impact on our natural energy reserves which cause them to be depleted very fast. This phenomenon exerts a profound influence on the global economy while simultaneously amplifying the increasing of global temperatures, thereby accelerating the progression of climate change on an annual basis. [1-5] To address this challenge, renewable energy sources have increasingly been regarded as a preferable alternative due to their potential to reduce carbon emissions and mitigate the progression of global warming. Nevertheless, the long-term sustainability and dependability of these energy sources remain subjects of considerable scholarly debate. [6, 7] Recent technological advancements in energy storage, particularly in battery development have attracted significant attention. Batteries are now recognized as a promising solution for enhancing the stability and operational efficiency of renewable energy systems thereby facilitating a cleaner, more dependable, and environmentally sustainable mode of energy storage. [8, 9]

In 1859, the French physicist Gaston Planté developed the first rechargeable energy storage device, known as the lead–acid battery, which proved highly valuable across multiple sectors such as automobiles, telecommunications, and industrial applications. Its ability to be recharged repeatedly has made it a cost-effective option for long-term use. Despite the emergence of newer battery technologies, lead–acid batteries continue to be widely employed owing to their robustness and low production cost. [10] Subsequent advancements in electrochemical storage were marked by the invention of alkaline batteries by Waldmar Jungner in 1899, [11] followed by significant improvements such as Edison’s nickel-iron battery, the introduction of sealed cells, and the development of nickel-metal hydride (Ni-MH) and nickel-cadmium (Ni-Cd) batteries. [12, 13] These innovations enhanced battery performance substantially and by the early 2000s they had become integral to a wide range of applications including medical devices, aviation, hybrid electric vehicles (HEVs), and various industrial systems. [14]

However, Ni–Cd batteries were found to suffer from the so-called “memory effect,” which led to gradual in capacity fading if not fully discharged. [15] Additionally, their cadmium content poses significant environmental and disposal challenges due to toxicity. In contrast, Ni–MH batteries offered higher energy density but were limited by a shorter lifespan, relatively high self-discharge rates, and greater manufacturing costs compared to lithium-ion batteries (LIBs). [16, 17] As the demand for high-performance portable electronic devices continued to rise, these earlier systems could no longer meet technological requirements. Consequently, research into LIBs began in the mid-1980s, leading to transformative advances in energy storage science. [18, 19]

First Generation of Lithium-Ion Batteries

Since their introduction of LIBs have demonstrated numerous advantages such as low cost, high energy and power density, minimal self-discharge, rapid charge–discharge capability, long operational lifespan, and the absence of memory effect [20, 21] Extensive research has made on LIBs to improve their electrochemical performance in term of capacity, rate test and cyclic performance. Rechargeable LIBs operate through the reversible movement of lithium ions (“rocking-chair mechanism”) between the electrodes during charge and discharge cycles. [22] The concept of this mechanism emerged in the late 1970s and was experimentally demonstrated during the early 1980s. However, in 1991 that Sony Corporation successfully commercialized this technology, marking the beginning of the modern Li-ion era. [23] Structurally, a typical Li-ion cell comprises four essential components: the anode, cathode, electrolyte, and separator. Metal oxides commonly serve as cathode materials, while graphite is employed as anode. [24] The electrolyte consists of Li salt dissolved in an organic solvent which facilitates the transport of Li^+ ions between the electrodes. The separator maintains a physical barrier to prevent short-circuiting while the anode and cathode are responsible for energy storage and release through redox reactions. [25]

Structural Components of Lithium-Ion Batteries

The structural configuration of **LIBs** is designed to ensure efficient energy storage, high power output, extended operational lifespan, and enhanced safety and stability. A conventional LIB consists of several essential components that collectively determine its electrochemical performance. As we discussed above that **anode** of a typical LIBs is commonly composed of **graphite** which serve as hosts for Li-ion intercalation during the charging and discharging processes. During discharge, Li-ions migrate from the anode to cathode, and during charging, they return to the anode. Functionally, the anode acts as the **negative electrode** during discharge and as the **positive terminal** while charging. [26] The **cathode** is generally fabricated from **lithium-based metal oxides**, such as **LiCoO_2** or **LiPF_6** , which enable Li-ion deintercalation during discharge. In contrast to the anode, the cathode serves as the **positive electrode** in discharge and the **negative terminal** during charging. The electrochemical behavior of the cathode largely dictates the overall energy density and voltage output of the cell. [27] The **electrolyte** typically consists of a **lithium salt**, such as **lithium hexafluorophosphate (LiPF_6)**, dissolved in organic carbonate solvents such as **dimethyl carbonate (DMC)** or **ethylene carbonate (EC)**. This medium enables the transport of Li-ions between the electrodes during charge-discharge cycles. For optimal battery performance, the electrolyte must exhibit **chemical and electrochemical stability**, **low volatility**, and **high ionic conductivity** while remaining inert to both electrode materials. [28] The **separator** is a **microporous polymer membrane**, often fabricated from **polyethylene (PE)** or **polypropylene (PP)**. The primary function is to **physically isolate** the anode and cathode, thereby preventing short circuits while simultaneously permitting the **selective passage of Li-ions** through its porous structure. The structural integrity and thermal stability of the separator are critical to the safety of the cell. [29] The **current collectors** typically made of **copper (Cu)** for the anode and **aluminum (Al)** for the

cathode are thin metallic foils that facilitate electron transport between the electrodes and the external circuit. These foils are uniformly coated with active electrode materials (graphite for the anode and metal oxides for the cathode) to ensure efficient electronic conductivity and uniform charge distribution throughout cycling. [30, 31] A schematic representation of a standard lithium-ion cell, illustrating these major components and their functional relationships, is provided in **Figure 1**.

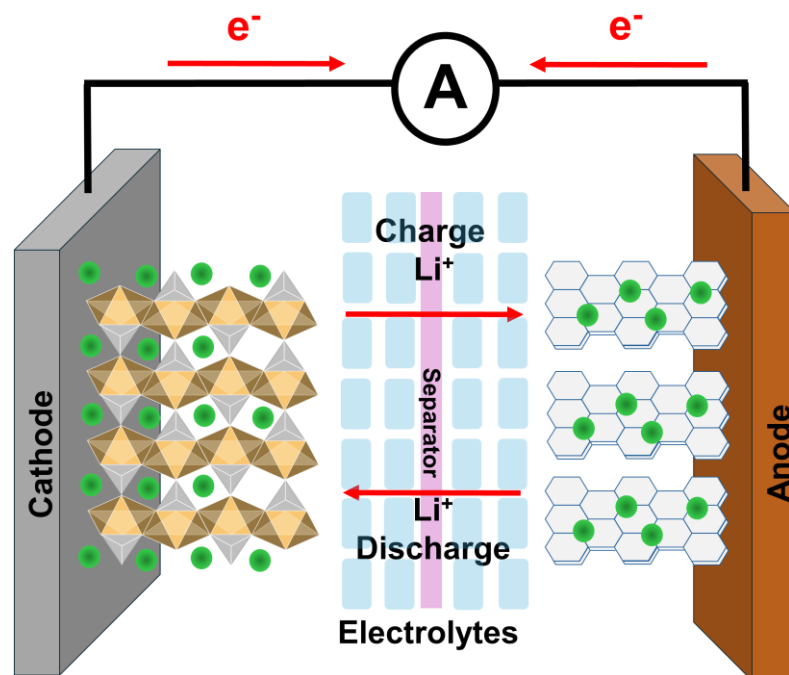


Figure 1. A schematic representation of LIB

Charging mechanism of LIBs

The operational mechanism of LIBs is complex and remains an active area of scientific investigation. A conventional rechargeable LIB is composed of a cathode, typically made from a transition metal oxide or phosphate-based active material, and an anode, commonly constructed from graphite. During the charging process, lithium ions are extracted from the cathode and migrate through a porous separator toward the anode via the electrolyte. Once fully charged, the cathode becomes a high-potential host structure depleted of Li, while the anode accommodates a high concentration of Li at a comparatively lower potential. During discharge, when the battery is connected to an external circuit, Li-ions move back from the anode to the cathode through the electrolyte. Concurrently, electrons flow through the external circuit, supplying electrical energy to the connected load. The returning Li-ions reinsert themselves into the cathode crystal lattice without causing significant structural degradation. This reversible process of ion transfer and electron flow constitutes the charge-discharge cycle, enabling repeated energy storage and release according to the electrochemical reactions governing battery performance. [32, 33]

Lithium-ion batteries possess several noteworthy advantages that distinguish them from other rechargeable battery technologies. These benefits are: (i) High Energy Density: LIBs offer exceptionally high energy and power densities compared to

traditional battery systems such as lead-acid or nickel-cadmium batteries. This characteristic enables them to store more energy within a compact and lightweight form factor, making them ideal for portable electronics, electric vehicles (EVs), and other energy-demanding applications. (ii) Extended Cycle Life:

LIBs exhibit significantly longer cycle life than most other secondary batteries. They can endure hundreds to thousands of charge-discharge cycles with minimal capacity degradation, contributing to their long-term cost efficiency and reliability. (iii) Low Self-Discharge Rate:

LIBs demonstrate remarkably low self-discharge rate, which minimizes energy loss when the battery is idle. This feature is particularly advantageous for devices that are used intermittently but must retain stored energy over extended periods. (iv) Light weight Nature: Due to their high gravimetric and volumetric energy densities LIBs are relatively lightweight compared to other electrochemical systems. This characteristic is particularly critical for applications such as electric vehicles and portable electronics, where weight directly influences performance and efficiency. (v) Rapid Charging Capability: LIBs are capable of faster charging than many other rechargeable battery chemistries. The development of advanced electrode materials and electrolytes has further enhanced their fast-charging performance, which is increasingly important in modern EVs and high-demand electronic devices. (vi) Absence of Memory Effect: Unlike older rechargeable batteries such as nickel-cadmium systems, LIBs exhibit little to no memory effect. As a result, LIBs maintain consistent performance across various operating conditions and partial charge states. (vii) Environmental Advantages: Although the extraction and processing of Li-ions and associated materials can pose environmental challenges, LIBs are generally more environmentally benign than lead-acid or nickel-cadmium counterparts. They contain fewer toxic substances and are more amenable to recycling and sustainable end-of-life management. (viii) Scalability and Versatility: One of the defining strengths of Li-ion technology is its scalability. LIBs can be engineered for a wide range of applications, from small single-cell configurations in consumer electronics to large-scale battery energy storage systems integrated with renewable energy grids. This versatility underscores their vital role in modern energy storage solutions and the transition toward sustainable technologies.[34-37]

MOFs as anode materials

LIBs is also much studied for excellent energy, power, long cycle life, and low weight and not hazardous for environment. [38] Although the researchers are more focused, anode materials has much study in advance batteries [39] such like carbon base materials 2D, 3D materials such as MOFs, COFs, MXene and other 2D metal oxide which makes investigator more eager to form improved anode material employed in LIBs but these materials do not have sophisticated potential to convince the extend desire for high energy required for the user. So it is necessary to synthesized novel materials for anode having higher power and energy densities, for long life span. [40, 41] Organic electrode materials can undergo multi-electrons and multi-steps redox reactions during charge/discharge cycles, enhancing energy storage capacity and efficiency. [42] However, organic electrode materials also face challenges such as stability issues during cycling, dissolution in electrolytes, and generally lower

electronic conductivity. Currently MOFs have been considered as approving candidates for anode materials. MOFs are able of accommodating many electrons during electrochemical reactions and the stable structure help in reduce issues like solubility in electrolytes and enlargement of volume during cycles thus enhance lifespan. Ferey et al [43] initiate an iron based compound, was one of the initial MOFs to be study as a cathode material for lithium ion batteries. These materials showed a specific capacity of 60 mAh g^{-1} within voltage range from 4.2 to 5.4 V vs Li^+ ion and Li. Because of the reversible de-insertion/ insertion of Li^+ and the redox transition among Fe^{+3} and Fe^{+2} Due to their limited lithiation capacity and comparatively less density (2.9 g cm^{-3}), other researcher focused on searching other novels MOFs structure to increase lithium storage capabilities. Song et al [44] introduced (cerium and Ln: praseodymium)bi metallic coordination polymers having the formulas $\text{C}_{10}\text{H}_3\text{CeO}_8$ (cepma) and $\text{C}_9\text{H}_2\text{LnLiO}_6$ (Ln:Ce (CeLipma) and Pr (prLimpa) by Applying hydrothermal method. These compounds completely characterize by techniques like XRD ,TEM ,SEM ,FTIR, and single crystal XRD . these compounds have triclinic symmetry.in these compounds cerium or praseodymium and Li-ion are attached to oxygen obtain from pyro metallic acid, follow in the formation of 3D structure.so when we used these materials as electrode for LIBs the framework should be free of lattice water. ceLipma shows magnificent capacity of 701 mAh g^{-1} at 1.5 A g^{-1} , keeping 81.5% of its capacity after 45 cycles at 2 A g^{-1} . The high performance of lanthanide base coordination polymer argue their potential for better applicant as energy storage device. Jin et al [45] investigate the use of MOFs for emerging many electrodes materials like metal chalcogenide , metal oxide and porous carbon or sometime used as direct in electrode materials but pristine MOFs again and again faces many problems like less stable structure and low electrical conductivity. But authors prepared two dimension bi metallic NiCo MOFs graphene composite by solution based methode as shown in the Figure 2.1a. The NiCo MOFs nano-sheets coated on graphene nanoflakes in a solution consist of benzene dicarboxylic acid , NiCl_2 and CoCl_2 . the $-\text{COOH}$ in BDC^{-2} form chelation with Co^{+2} and Ni^{+2} ion and graphene surface which form a stable 2D NiCo MOFs G hybrid structure. So it bring down the charge transport distance without keeping a stable aromatic conjugated framework, to increase cycling performance. This graphene nanoflakes increases the electrical conductivity and structure of composite's which results in high electrochemical performance. It show excellent rate capability and outstanding cyclic performance i.e 650 mAh/g at 2.5 A g^{-1} more than 600 cycles, with extraordinary speed stability of 425 mAg^{-1} at 4 A g^{-1} as shown in Figure 2.1 b and c.

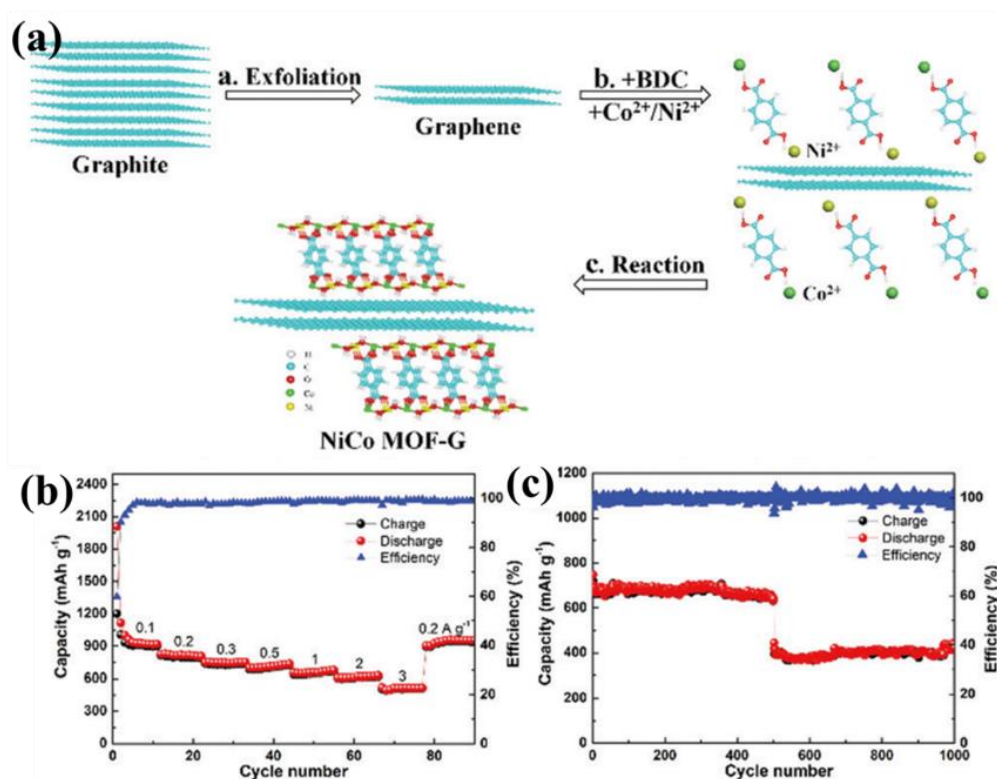


Figure 2: (a) Schematic of the fabrication pathway of hierarchical 2D NiCo-MOFs-G hybrid.(b) rate test, (c) cyclic performance.

Similarly, xiao chun et al [46] presented a simple way to prepared tin MOFs hexahedra by aqueous solution and at below temperature which are used to prepared SnO@C, Sn and SnO@C nano composites by hydrogen reduction at several temperature and showed excellent crystallinity Figure 3a and b. When SnO obtain and connected in the hexahedron carbon frameworks rise in nano rods and nano sphere structure .when these composites are used are as anode materials in such batteries like SIBs and LIBs , they show extraordinary performance due to hexagonal structure assumes from MOFs pattern. Particularly the Sn and SnO@C composites show good performance (498.2 mAh/g for LIBs and 141.3 mAh/g for sodium ion batteries at 3000 mA g⁻¹) and large cycling stability (921.8 mAhg⁻¹ for LIBs at 2000 mA g⁻¹ after 300 cycles and 398.4 mAh/g for sodium ion batteries at 300 mA/g after 300 cycles (Figure 3 c and d). These results show that Sn and SnO@C composites show high electrical conductivity and cycling stability if these composites used for anode material in both batteries such as lithium ion batteries and sodium on batteries. Sun et al [47] create a new method they manufacture SnO₂ nano materials by calcining Sn based MOFs precursors. The material was characterized by technique like BET, FESEM, XRD and TEM. When SnO₂ used as anode materials in LIBs it show best performance. This excellent performance is due to reduce electron and Li⁺ diffusion length these two enhance electrolyte-electrode interface which is offer by SnO₂ nano structure. This method is priceless and simple. This method is used for the production of large scale SnO₂ base composite which plays a crucial rule when used as anode

material for LIBs.

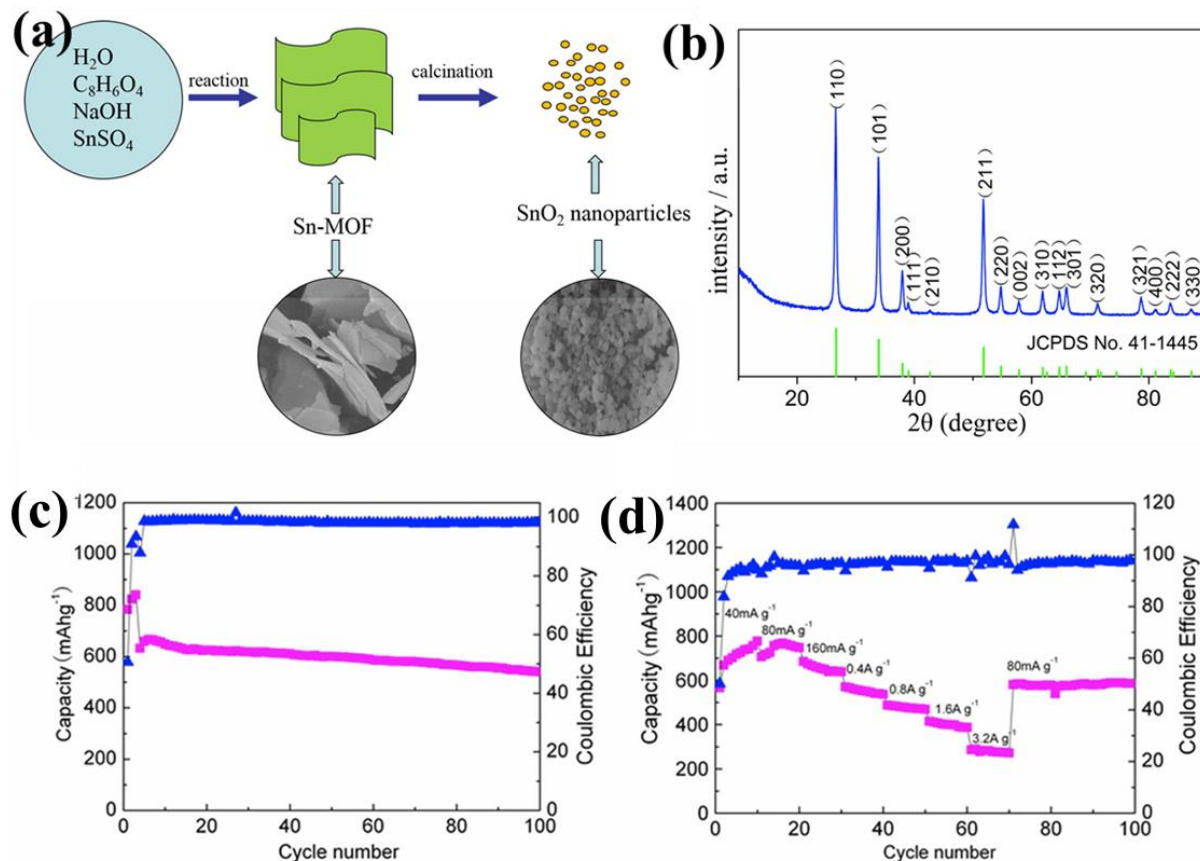


Figure 3. (a) Graphical representation of the construction of SnO₂ nanoparticles. (b) XRD patterns of the as prepared nano-SnO₂. (c) Cycling stability of the nano-SnO₂ electrode at 400 mA g⁻¹. (d) Rate capability of nano-SnO₂ at different discharge currents.

Konda et al [48] the order of Sn nano particles within a porous matrix faces many difficulties when used as anode materials in LIBs. So a new simple way was developed in this way Sn nano particles are coated on carbon with a porous framework for anode purpose by 3D synthesized which is tin base MOFs. [k₂Sn(1,4-bdc)₃](H₂O) (1) BDC=benzene di carboxylate), these tin nano base particles were within a porous carbon host, which results in the formation of Sn@C composites. This materials show extraordinary electrochemical performance during cycling (over 200 cycles) and give best current density(1.3 to 6) . The newly constructed strategy presented here, consuming a single starting material gently mixing NPs size and distribution to strongly accommodate the huge volume change comes from the Li-Sn alloying reaction and assist the fast ion and electron transportation . The TEM morphology of Sn@C is shown in the Figure 4 a and b.

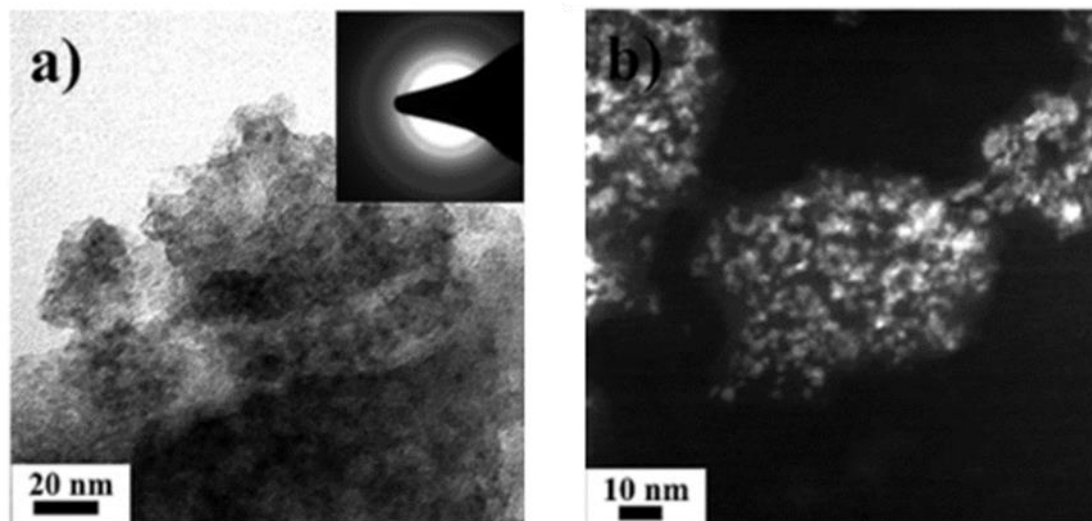


Figure 4: TEM image of Sn@C nanocomposites.

Jizhang et al [49] using SBA-15 silica as rigid pattern iron-copper compound was prepared which contain active(Cu_6Sn_5), inactive (Cu_3Sn), and iron phase which has high BET surface area $202.9\text{ m}^2\text{ g}^{-1}$. we use it as anode for LIBs. The composite cycling performance is enough stable with minor capacity deterioration between 2nd and 20th cycle at 600 mA g^{-1} . This performance notably exceed massive Sn-Cu composite with no mesomeric structure. The improved cycling stability is due to mesomeric structure which enable greater contact between electrolyte and active material, also reducing the volumetric growth during repetition of cycle. the electrochemical impedance spectroscopy shows the advantages of mesoporous structure that it improves charge transfer process. Furthermore, Zheng et al., [50] prepared porous Nano structure of Co_3O_4 is a promising material used for making better anode for LIBs because of its high storage capacity and density. By heating MOFs directly porous cubides of cobalt (II, III) oxides was formed. When the obtained materials was used as anode in LIBs porous cuboids performed exceptionally in cycling performance, i-e after 300 cycles, they showed capacity of 885 mAh g^{-1} at 100 mA g^{-1} and outstanding rate performance. The unique porous structure improves electrochemical performance which facilitates Li-ion and electron diffusion, boosting overall effectiveness of charge during cycling. Similarly, Aluminum-MOFs was grown on the surface of rGO sheets which increased structure stability as well as conductivity of electricity due to mutually beneficial electrostatic interaction. The obtained Al-MOFs@rGO anode showed remarkable specific capacity of 469.6 mAh g^{-1} after 1500 cycles at 2.5 A g^{-1} , they observed an amazing prolong cycling stability and capacity preservation which has outstanding Li storage performance this is because of their flexible, 3d structure with pores MOFs are getting popular and got attention. MOFs are good choice to use them as electrode for LIBs because of its porous structure and large surface area. This resolve an important aspect that was not explored thoroughly under the lithiation and delithiation how it change the structure of MOFs use as anode. To examine it deeply, Al-MOFs $\text{Al}(\text{OH})[\text{O}_2\text{C}-\text{C}_6\text{H}_4-\text{CO}_2]$ particles were synthesized and then coated with graphene to generate Al-MOFs@graphene hybriide material. Aluminum-MOFs particle

structure was changed by lithiation and delithiation especially order-to-disorder transition, creating more channels for Li-ion diffusion and storage. Yang et al., [51] A flower like cobalt-TCPP MOFs was prepared and combined with rGO by one step solvothermal method ,where cobalt meso-tetrakis(4-carboxyphenyl)porphyrin (Co-TCPP MOFs) was mixed together with reduced graphene oxide as depicted in Figure 5a. In the composite electrode, rGO played an important role because it prevent MOFs particles from aggregation, similarly rGO also create conductive network. Which consist of interlinked graphene and cobalt-TCPP MOFs which increase the electron transport. Cobalt-TCPP MOFs and rGO composite nanosheet has very thin and uniform morphology which increase the surface area making active sites exposed for reaction (Figure 5b-i). it also decrease the distance that Li-ions need for diffusion and as a result overall electrical conductivity increased by means of interaction with carbon matrix. When the electrode materials was used as anode in LIBs the Cobalt-TCPP MOFs/(16 wt %) rGO composite electrode showed incredible specific capacity of 1061 mAh g^{-1} at 200 mA g^{-1} after 200 cycles and maintain capacity of 660 mAh g^{-1} at very high current density i-e 2000 mA g^{-1} after 300 cycles (Figure 5j and k). the improved chemical activity of composite electrode is due to rGO which hinder the sidewise expansion of Cobalt-TCPP metal organic framework crystals and increasing the electrical conductivity.

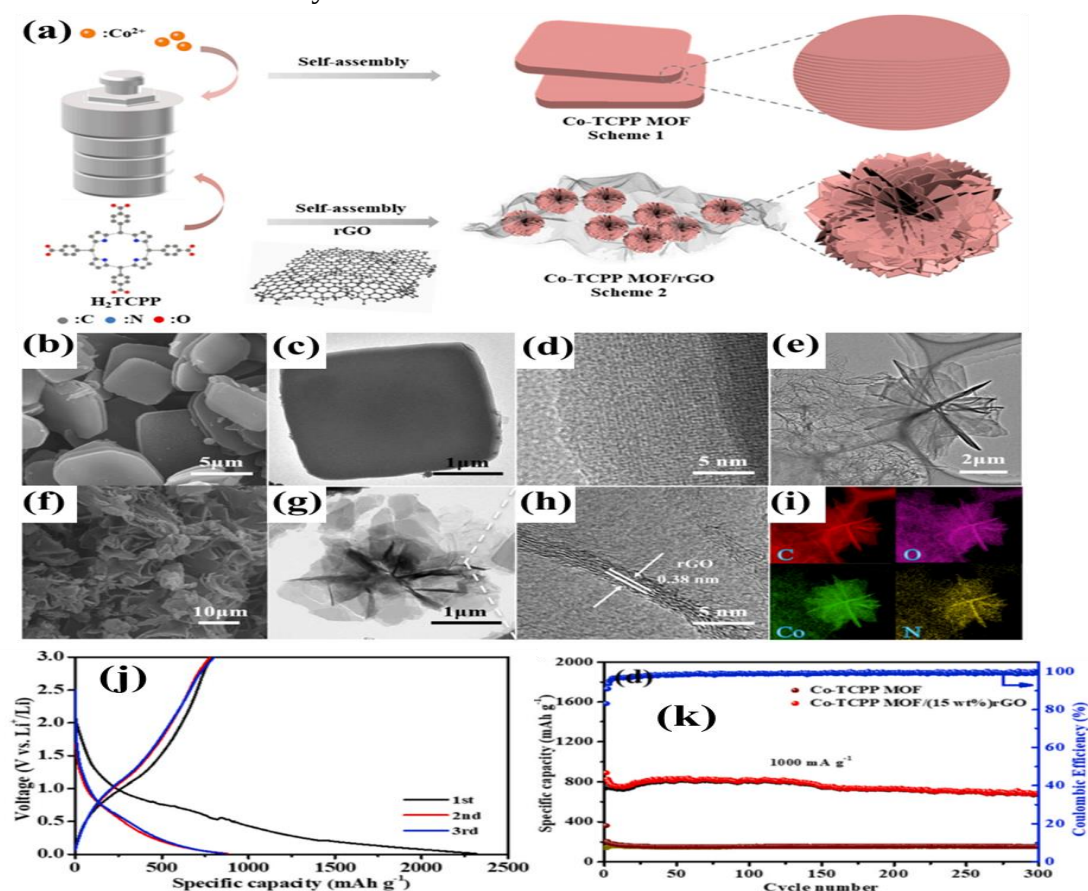


Figure 5. (a) Illustration of the synthesis route of Co-TCPP MOF and Co-TCPP

MOF/rGO composites. (b) SEM morphology of bulk Co-TCPP MOF. (c) TEM morphology of bulk Co-TCPP MOF. (d) HRTEM of bulk Co-TCPP MOF. (e) SEM of flower-like Co-TCPP MOF/rGO(15 wt%). (f) TEM of flower-like Co-TCPP MOF/rGO(15 wt%). (g) High magnification TEM of rGO. (h) TEM image of flower-like Co-TCPP MOF/rGO(15 wt%). (i) Elemental mapping images of O, C, N, and Co. (j) charge-discharge curve of Co-TCPP MOF/rGO(15 wt%) electrode at 100 mA g⁻¹. (k) cycle performance of Co-TCPP MOF/rGO(15 wt%) electrode at 1 A g⁻¹.

Similarly, Chengwei et al., [52] studied tin (IV) oxide (stannic oxide) due to their high theoretical capacity and as well as considered as a good material for LIBs but its use is limited due to its poor cycling stability due to the huge volume changes upon charging and discharging cycle. To boost the activity of SnO₂-based anode, they developed simple but effective method to obtain SnO₂@MOFs/graphene composite is by mixing of SnO₂ with MOFs and graphene. They embedded nanoparticles of SnO₂ within Aluminum-MOFs at optimal proportion of mass, which exhibited notably improved cycling stability, sustaining a capacity of nearly 460 mAh g⁻¹ after 2000 charge and discharge cycles at 3000 mA g⁻¹. Similarly, Yan et al., [53] prepared Ni-based MOFs through simple solvothermal method. Ni-based MOFs present well-defined ion diffusion passages for structural analysis, framework can be obviously recognized. When examined for electrochemical performance the electrode materials showed excellent performance under both lower and high current rate. The anode material indicates its potential a high performance which also displays excellent rate performance significantly. The electrode Ni-based MOFs can be used the potential to utilize in LIBs in this novel and for MOFs-based material in energy storage methods the range of products that can be potentially extend.

MOFs as Cathode Materials

Layered oxide cathode materials, such as LiCoO₂ [54], Li(Ni_xMn_yCo_z)O₂ [55], Li(Ni_{1-y-z}Co_yAl_z)O₂ [56], and spinel oxide types like LiNi_yMn_{2-y}O₄ [57], along with polyanion-based compounds such as LiFePO₄ and lithium iron (II) pyrophosphate have shown great promise electrode material for the next generation of LIBs. These materials offer effective solutions for sustainable energy storage, especially for charging electric vehicles and replacing gas-powered transport. Though metal oxide cathodes are preferred for their rich redox sites and strong structure, there are several challenges that stop them from being widely used. These issues are important for meeting the growing need for energy storage technology and keeping lithium-ion batteries competitive in transportation.

Recent studies have looked into using MOFs as possible cathode materials for LIBs. For instance, Kimizuka et al. [58] studied the properties of MIL-101 (Fe), an iron-based MOF that showed a capacity of 74 mAh/g (0.65 Li/Fe) after 200 charge-discharge cycles. This capacity was slightly higher than its original value of 70 mAh/g, showing the material retained its structure over time. Besides iron-based MOFs, Jacobson et al. [59] also studied vanadium-based MOFs such as MIL-47(V) and VIV(O)(benzene dicarboxylic acid), which have similar structures to MIL-53(Fe). These vanadium-based MOFs offered high reversible lithium-ion uptake (0.80 Li per V), thanks to their open-channel structures and strong V–O bonds that improve stability. Moreover, Vittal et al. [60] introduced a V⁴⁺ and V⁵⁺ redox couple in a

crystalline MOF, which reported a high voltage of 6.2 V compared to commercial lithium iron phosphate (4.6 V). This material also had a high specific capacity of 69 mAh g⁻¹, close to the theoretical capacity of the V⁴⁺/V⁵⁺ couple. To improve the stability of cathode materials, Zhang et al. [61] made a MOF called Cu(2,7-AQDC), where the organic ligand 2,7-H₂ AQDC contains redox-active sites both on the metal clusters and on the ligands. In the voltage range of 4.9–5.3 V, this MOF showed an initial discharge capacity of 207 mAh g⁻¹, nearly matching its theoretical capacity of about 165 mAh g⁻¹. After 50 cycles, it maintained a capacity of 108 mAh g⁻¹, indicating good stability. The electrochemical behavior showed that Li-ion were reduced at the active sites (both metal centers and organic ligands) and inserted into the open spaces in the MOF structure. However, because MOFs are not very conductive, their electrodes can lose some Li-ion during the discharge, making it hard to recharge them and leading to capacity loss. To address this, Kunio et al. [62] made a redox-active MOF, Mn₇(2,7-AQDC)(2,6 AQDC)(DMA)₆, and introduced a new "bipolar charging" method. During charging, PF₆⁻ ions go into the MOF and oxidize Mn²⁺ to Mn³⁺. During discharge, PF₆⁻ ions return to the electrolyte, and Li-ions enter the MOF, reducing the organic ligands and improving overall battery performance. Yamada et al., [58] made a MOF that includes iron (III) and mellitic acid and used single-crystal XRD to determine its structure. The structure was similar to MIL-116. When used as a cathode material, this MOF showed a capacity of around 200 mAh g⁻¹ after 70 charge-discharge cycles. It also had a capacitance of 45 mAh g⁻¹ at high charge and discharge rates of 30 C, showing promise for fast charging and discharging applications. Hameed et al. [60] highlight the potential of LIBs as a key technology for supporting sustainable electric vehicles and making better use of renewable energy sources. However, the high initial cost of LIBs mainly because of expensive components, remains a major challenge for widespread adoption in the electric vehicle market. To make electric vehicles more competitive with traditional cars, it is important to reduce the cost of LIBs. In their study, they develop a new type of cathode material made from reduced graphene oxide and a metal-organic phosphate open framework (rGO/MOPOF) that works within a voltage range of about 4 volts. This material is made using a simple, low-cost method at room temperature, without needing any special treatments like high-temperature annealing with argon or argon-hydrogen gas. The material is created by mixing with water and then heating it to 80 degrees Celsius to remove the water, which results in the anhydrous form needed for making electrodes. While the pure MOPOF material can store lithium ions, it loses capacity over time. On the other hand, the rGO/MOPOF nanocomposite maintains its performance well over many cycles, with very little loss in capacity. This is because the addition of reduced graphene oxide improves the material's ability to conduct electricity and helps Li-ion move through it more effectively.

Conclusion

In summary, the rapid expansion of energy demand and the shift toward sustainable technologies have intensified the search for advanced, durable, and high-performance battery materials. LIBs remain at the forefront of this transition due to their high energy density, long cycle life, and structural versatility. Recent progress in MOFs has opened promising pathways for enhancing both anode and cathode performance.

Their tunable porosity, structural stability, and ability to host redox-active sites enable improved ion transport, higher capacity retention, and better cycling durability. Although challenges such as limited conductivity persist, MOF-derived composites and hybrid structures demonstrate significant potential for next-generation energy storage. Continued refinement of these materials may substantially advance the efficiency and sustainability of future lithium-ion systems.

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