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FABRICATION STRATEGIES FOR MODERN BATTERY TECHNOLOGIES: A COMPARATIVE REVIEW

Ibrahim SULAIMAN[1*], Victor Ndaraba HARUNA[2], Babawuya ALKALI[3], Oyewole ADEDIPE[4], Bala Alhaji SALIHU[5], Aliyu Alhaji ABDULLAHI[6], Ibrahim Ogu SADIQ[7]

[1,2]Mechanical Engineering Department, Federal Polytechnic, Bida, Niger State
[3]Mechatronics Engineering, Federal University of Technology, Minna
[4,6,7]Mechanical Engineering Department, Federal University of Technology, Minna, Nigeria
[5]Telecommunication Engineering, Department, Federal University of Technology, Minna

[*]Corresponding Author: skishk2009@gmail.com

Abstract

The expansion of electrification, renewable energy systems, and portable technologies has increased demand for rechargeable batteries with improved performance, safety, and manufacturability. Although substantial progress has been achieved in battery materials, fabrication processes play an equally critical role in determining electrode microstructure, interfacial stability, ionic transport, and overall cell reliability. This review presents a fabrication-centred comparative analysis of major battery technologies, examining how processing strategies influence electrochemical behaviour and manufacturing feasibility. General principles of electrode preparation, electrolyte formulation, and cell assembly are first outlined, followed by a discussion of fabrication requirements specific to different battery chemistries. Attention is given to lithium-ion, solid-state, metal–air, and flow batteries, highlighting how variations in processing conditions affect microstructural evolution, defect formation, and transport pathways. Comparative evaluation identifies key cross-cutting challenges in battery manufacturing, including slurry homogeneity, binder migration, interface stability, moisture sensitivity, and scalability constraints. Emerging fabrication approaches are also examined as potential pathways for improving performance and manufacturing efficiency. Unlike many existing battery reviews that focus primarily on electrochemical materials or device performance, this work emphasizes the role of manufacturing science in enabling practical battery deployment. By systematically linking fabrication parameters with transport behaviour, structural integrity, and industrial scalability across multiple battery chemistries, the review provides a framework for guiding the development and large-scale production of next-generation energy storage systems.

Keywords
Battery technologies, Electrode processing, Electrolyte, Interfacial stability, Renewable energy

1. INTRODUCTION

The accelerating growth of electrification, renewable-energy deployment, and portable technologies has placed increasing pressure on global energy-storage infrastructure. Rechargeable batteries remain central to this landscape because they offer a balance of performance, versatility, and cost that few other technologies can match [1, 2]. As expectations rise and new application areas emerge, interest is shifting from material innovation alone to the equally important question of how batteries are fabricated and assembled. Fabrication practices shape electrode microstructure, electrolyte compatibility, interfacial stability, and overall safety, and they ultimately determine whether a given chemistry can meet performance targets and scale to industrial production [3].

A wide range of battery technologies has been developed to meet different performance demands and resource considerations. Each operates on distinct electrochemical principles and therefore requires its own set of fabrication strategies. Established systems like lithium-ion batteries benefit from decades of optimisation in electrode coating [4, 5], electrolyte handling [6, 7], and cell assembly [7]. In contrast, emerging technologies such as solid-state and metal–air batteries face persistent challenges, including achieving intimate solid–solid interfaces, producing durable air cathodes, and managing electrolyte stability

[8, 9, 10]. Technologies such as aqueous Zn-ion and flow batteries add further complexity, with fabrication considerations tied to corrosion mitigation, electrode architecture, and fluid-distribution design [11].

While the materials science underlying modern battery systems is widely documented, comparatively less attention has been given to the manufacturing and fabrication processes that translate laboratory-scale materials into practical battery systems [12, 13]. Fabrication is increasingly recognised as a decisive factor in determining technological readiness, as processing conditions strongly influence electrode structure, interfacial stability, and overall electrochemical performance [13]. A clear comparison of fabrication practices across battery chemistries therefore provides an important basis for identifying shared challenges, adapting successful techniques between systems, and guiding the development of scalable manufacturing pathways. Moreover, existing studies typically examine fabrication within a single battery chemistry [14, 12]. In contrast, this review provides a cross-chemistry comparative analysis of fabrication strategies, examining how electrode processing, electrolyte integration, and cell assembly influence performance and scalability in lithium-ion, solid-state, metal–air, and flow batteries. By emphasizing the relationship between fabrication parameters, microstructural evolution, and electrochemical behaviour, this work aims to provide a broader manufacturing perspective that complements conventional materials-focused battery reviews.

This review brings together current knowledge on fabrication strategies for several key battery technologies. It outlines the foundational principles of electrode preparation, electrolyte processing, and cell assembly before examining the fabrication requirements unique to each system. Through comparative analysis, the review highlights how fabrication choices influence performance, safety, manufacturability, and cost. The goal is to provide a coherent fabrication-centred perspective that supports improved manufacturing practices and contributes to the development of scalable next-generation battery technologies. To the best of the authors' knowledge, this study represents one of the first reviews to systematically compare fabrication-driven performance implications across multiple battery chemistries within a unified framework.

2. General Principles of Battery Fabrication

Rechargeable batteries share a common structural layout comprising a cathode, anode, electrolyte, separator or ion-conducting membrane, current collectors, and a housing structure [15]. The cathode and anode function as the electrochemical host materials for ion insertion as depicted in Figure 1, conversion reactions, or metal plating/stripping, depending on the underlying chemistry. Their performance is governed by particle morphology, porosity, electronic conductivity, and the microstructural integrity of the active material–binder–conductive additive network [15].

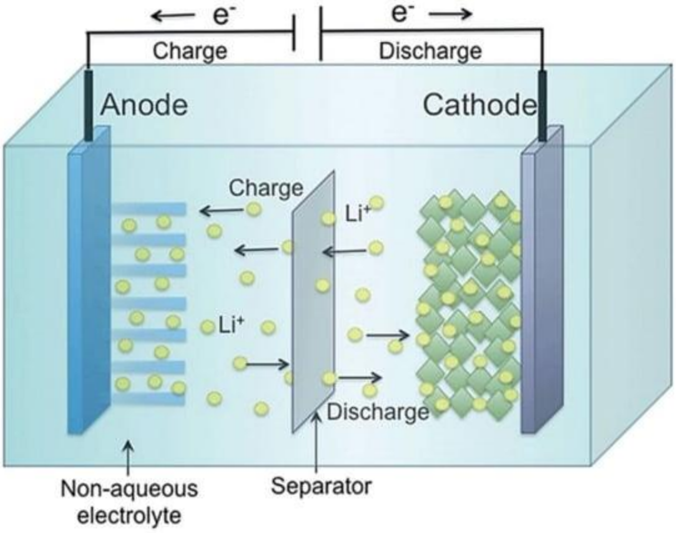

Figure 1: The principle of the lithium-ion battery [15].

The electrolyte provides ionic transport between electrodes and may exist as an organic liquid, aqueous solution, polymer gel, or inorganic solid [16]. In lithium-ion batteries, the composition of the non-aqueous electrolyte (Figure 1) governs ionic conductivity, interfacial compatibility, the formation and stability of the solid–electrolyte interphase (SEI) and cathode–electrolyte interphase (CEI), as well as overall safety performance [17]. A separator or ion-conducting membrane physically isolates the electrodes while facilitating ion diffusion, whereas current collectors (typically Al or Cu foils or porous carbon substrates) establish efficient electron transport pathways. The cell housing constrains component geometry and dictates assembly procedures [18].

The microstructural and interfacial quality of these components is determined primarily by fabrication processes, which ultimately influence internal resistance, energy density, cycle life, and manufacturability [19].

2.1. Electrode Fabrication

2.1.1. Slurry Formulation and Mixing

Most electrode systems are produced from a slurry comprising active material, conductive additives, polymeric binders, and a suitable solvent [20] (Figure 2). For lithium-ion anodes, the active material is typically mesocarbon microbeads (MCMB), a graphitic carbon known for its structural stability, high electrical conductivity, and favourable lithium intercalation properties. Figure 2 illustrates a representative slurry-based fabrication process. Initially, MCMB is mixed with carbon black to enhance electronic conductivity, and carbon nanotubes dispersed in N-methyl-2-pyrrolidone (NMP) are added to form a homogeneous network that improves electron transport pathways. The addition of an 8% polyvinylidene fluoride (PVDF) binder solution ensures mechanical cohesion and adhesion to the current collector. High-shear or planetary mixing and prolonged stirring control slurry rheology, optimizing viscosity, yield stress, and solid content, which in turn influences electrode uniformity and coating quality. Subsequent coating, drying under vacuum at 120 °C, calendaring, and punching not only define the electrode thickness and density but also impact porosity, tortuosity, and interfacial contact, all of which are critical to electrochemical performance. For solid-state and certain metal–air electrodes, dry mixing, PTFE fibrillation, or powder compaction may replace slurry-based processing [21].

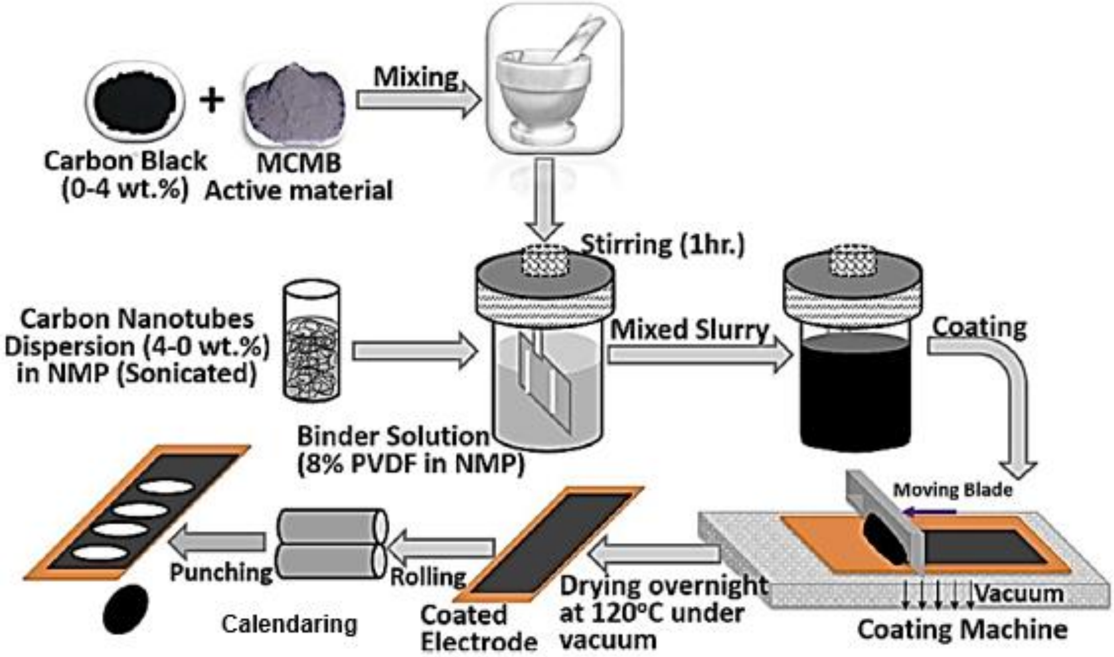

Figure 2. Schematic view for various steps followed for the electrode preparation [20].

2.1.2. Coating and Casting

The slurry is deposited onto current collectors using doctor-blade coating, slot-die coating, tape casting, screen printing, or electrophoretic deposition (Figure 2). Coating uniformity is critical for controlling electrode loading, porosity, and thickness [20]. Industrial slot-die coating allows high-throughput, continuous manufacturing with micrometre-level precision, whereas tape casting is preferred for ceramic-rich or solid-state layers [22].

2.1.3. Drying and Solvent Removal

Drying removes solvent from the coated electrode while preserving the internal microstructure and binder distribution. The drying rate strongly influences binder migration within the electrode film [23]. When solvent evaporation occurs too rapidly, convective solvent flow can transport dissolved binder toward the electrode surface faster than diffusion redistributes it through the film thickness. This behaviour is often described using the Peclet number, which compares the rate of solvent evaporation to the diffusion rate of binder molecules. At high Peclet numbers, binder accumulation near the surface may occur, producing binder-rich upper layers and binder-deficient regions close to the current collector [24]. Such gradients can weaken adhesion, increase internal resistance, and reduce mechanical stability during cycling. Consequently, industrial electrode drying commonly employs staged temperature profiles, controlled airflow, and gradient drying strategies to maintain uniform binder distribution and prevent cracking, pore collapse, or delamination during solvent removal [25].

2.1.4. Calendaring

Calendaring compresses the electrode to achieve the desired thickness, density, and mechanical integrity. This densification improves particle–particle contact and strengthens the electronic percolation network within the electrode. However, compression also modifies the porous structure by reducing porosity and increasing tortuosity of ionic transport pathways [26]. The effective ionic conductivity within porous electrodes is often approximated by Equation 1 [27].

$$\sigma_{eff} = \sigma_{el}(\varepsilon/\tau) \quad (1)$$

Where σ_{el} represents the bulk electrolyte conductivity, ε is the electrode porosity, and τ is the tortuosity factor. Excessive calendaring pressure can therefore increase tortuosity and reduce effective electrolyte transport despite improved electronic conductivity. Optimal densification must balance these competing effects, ensuring sufficient electronic contact while maintaining adequate pore connectivity for electrolyte infiltration and ion diffusion [28, 29]. High-energy cathodes such as Ni-rich layered oxides therefore require carefully controlled calendaring conditions to avoid transport limitations at high charge–discharge rates [20].

2.2. Electrolyte Preparation and Handling

The electrolyte classification presented in Figure 3 categorizes electrolytes into liquid electrolytes and solid-state or quasi-solid-state electrolytes, with further sub-classifications as illustrated.

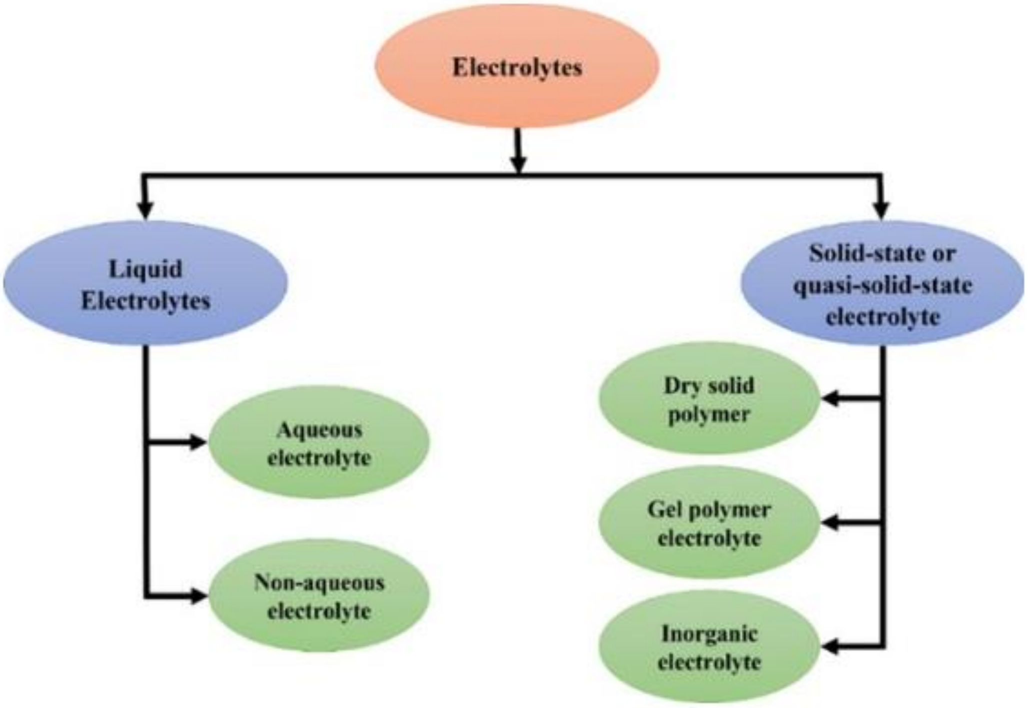

Figure 3: Classifications of electrolytes [30]

2.2.1. Liquid Electrolytes

Liquid electrolytes are prepared by dissolving conductive salts such as $LiPF_6$, $NaPF_6$, $ZnSO_4$, or other metal salts in appropriate solvents. Preparation is carried out under controlled humidity conditions (typically <50 ppm H_2O for non-aqueous systems) to suppress salt hydrolysis and minimize formation of acidic by-products. Salt concentration is optimized to achieve the required balance between ionic conductivity, viscosity, and electrochemical stability [31].

Liquid electrolytes are classified into aqueous and non-aqueous systems as follows:

a. Aqueous Electrolytes

Aqueous electrolytes are formulated by dissolving salts or redox-active species in deionized water. They are widely applied in Zn-ion batteries, Mn-based systems, and redox flow batteries. Control of pH is essential to mitigate metal corrosion, suppress hydrogen evolution, and stabilize multivalent ions. Additives such as buffers, surfactants, chelating agents, and coordination modifiers may be introduced to adjust the solvation structure, inhibit dendrite growth, and extend the effective electrochemical stability window [32].

Pre-use conditioning typically involves filtration, degassing, and adjustment of ionic strength. For flow-battery systems, viscosity, redox stability, and diffusion coefficients are additionally optimized to ensure efficient pumping and mass transport during operation [33].

b. Non-aqueous Electrolytes

Non-aqueous electrolytes are prepared using organic carbonate, ether, ester, or ionic-liquid-based solvents with dissolved lithium, sodium, or other conductive salts. Stringent moisture control is required due to the high sensitivity of most salts to hydrolysis. Functional additives such as vinylene carbonate (VC) and fluoroethylene carbonate (FEC) are incorporated to promote stable solid–electrolyte interphase (SEI) formation on anodes and cathode–electrolyte interphase (CEI) stabilization on high-voltage cathodes [34, 35].

After formulation, electrolytes are filtered and degassed to remove particulates and dissolved gases that could increase impedance or trigger parasitic reactions. The final electrolyte composition is tailored to ensure high ionic conductivity, thermal stability, and electrochemical durability [35].

c. Solid-State or Quasi-Solid-State Electrolytes

Solid-state and quasi-solid-state electrolytes provide enhanced safety, mechanical stability, and leakage-free operation. In accordance with the classification in Figure 1, these electrolytes are grouped into dry solid polymer electrolytes, gel polymer electrolytes, and inorganic electrolytes.

i. Dry Solid Polymer Electrolytes

Dry solid polymer electrolytes are fabricated by dissolving conductive salts in solid polymer matrices such as poly(ethylene oxide) (PEO), polyacrylonitrile (PAN), poly(methyl methacrylate) (PMMA), or related polymers. Fabrication routes include solvent casting, hot pressing, and melt processing, followed by controlled solvent evaporation or thermal treatment [36].

Ionic transport is governed by polymer segmental motion and polymer–salt interactions. Therefore, crystallinity control, salt dispersion, and molecular weight selection are critical to achieving acceptable ionic conductivity and mechanical integrity [37].

ii. Gel Polymer Electrolytes

Gel polymer electrolytes are produced by incorporating liquid electrolytes into polymer networks such as Poly(vinylidene fluoride-co-hexafluoropropylene) (PVDF-HFP), PEO, PAN, or PMMA, forming a quasi-solid structure. Preparation methods include in situ polymerization, solvent casting followed by crosslinking, or physical gelation [38].

Plasticizers, ionic liquids, and ceramic fillers are commonly added to enhance segmental mobility, improve ionic conductivity, and reinforce mechanical stability. Careful control of solution homogeneity, solvent evaporation, and crosslinking density is essential to obtain membranes with uniform structure, high conductivity, and strong resistance to dendrite penetration [39].

iii. Inorganic Electrolytes

Inorganic solid electrolytes include oxides, sulphides, and halide-based systems. Powder synthesis routes commonly involve solid-state reactions, sol–gel processing, wet-chemical precipitation, or mechanochemical milling to achieve phase purity and controlled microstructure [40, 41].

Densification techniques such as cold pressing, hot pressing, spark plasma sintering, and tape casting followed by high-temperature sintering are employed to reduce porosity and grain-boundary resistance. Sulphide-based electrolytes are handled in inert atmospheres due to moisture sensitivity and the risk of H_2S evolution. Post-sintering surface treatments and interfacial coatings are often applied to improve electrode compatibility and reduce interfacial impedance [29].

2.3. Cell Assembly

2.3.1. Electrode Stacking and Winding

Cell geometry strongly influences the assembly methodology. Cylindrical formats typically employ a jelly-roll configuration, in which coated electrodes and separator sheets are wound into a compact spiral to maximise volumetric energy density and maintain uniform pressure distribution [42, 43]. Prismatic and pouch cells, however, commonly rely on stacked or Z-folded architectures to achieve precise layer alignment and stable electrode–separator interfaces over large surface areas. As illustrated in Figure 4, three representative stacking approaches are used. In the conventional stacked configuration (Figure 4a), electrodes and separators are placed sequentially in alternating layers, providing straightforward assembly but requiring careful alignment to avoid interfacial defects. An alternative design employs stacked electrodes with a Z-folded separator (Figure 4b), which improves separator continuity and reduces the risk of misalignment during high-speed manufacturing. In the fully Z-folded configuration (Figure 4c), both electrodes and separators follow a folded architecture that enables continuous processing, enhances mechanical stability, and promotes more uniform pressure distribution across the electrode stack. These structural choices influence not only assembly efficiency but also ionic transport pathways, interfacial contact, and overall cell reliability during long-term cycling [44].

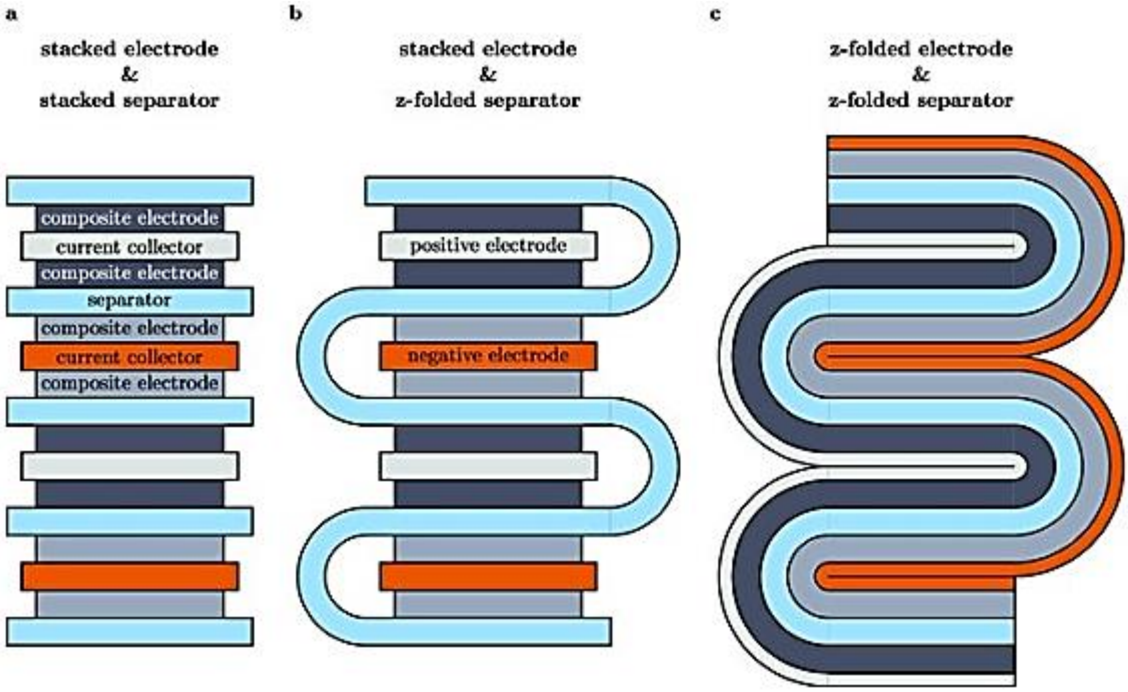

Figure 4. Modelled electrode and separator configurations [44]

Solid-state cells introduce additional complexity due to the rigidity of solid electrolytes and the need for intimate solid–solid contact. Assembly commonly involves warm pressing, lamination, or sequential multi-layer consolidation to reduce interfacial resistance and ensure uniform electrode–electrolyte contact. Across all formats, stack uniformity, alignment accuracy, and mechanical stability remain critical for minimising localised current densities, mitigating hotspot development, and achieving reproducible electrochemical performance [45].

2.3.2. Electrolyte Filling and Sealing

For liquid-based systems, electrolyte introduction is commonly performed under vacuum to enhance pore wetting, remove trapped air, and promote full penetration into the electrode structure. The filling rate, applied vacuum level, and soak duration are carefully controlled to achieve uniform electrolyte distribution. After filling, cells are sealed using heat-sealing, ultrasonic welding, or laser-welding techniques, depending on the cell housing material and targeted hermeticity requirements [46, 47, 48]. Flow battery systems differ fundamentally in that the electrolyte is circulated from external reservoirs. As such, internal filling steps are unnecessary; instead, emphasis is placed on leak-proof manifold design, chemically stable tubing, and efficient fluid-delivery architectures that maintain constant electrolyte flow during charging and discharging [49, 50].

2.3.3. Formation and Conditioning

Formation is a critical step in which the cell undergoes controlled charge–discharge cycling to establish stable SEI and CEI layers, activate redox processes, and equilibrate internal components. The temperature, current rates, rest periods, and voltage limits are precisely managed, as the quality of the interphases formed during this stage strongly influences long-term cycling stability, impedance evolution, and safety characteristics [51]. Conditioning protocols may include low-rate cycling, voltage soaking, or temperature-assisted activation, depending on the chemistry and cell format. For next-generation systems formation strategies are increasingly tailored to address interfacial challenges and optimise ion transport across solid–solid or solid–liquid boundaries [52].

2.4. Fabrication of Specific Battery Technologies

2.4.1. Lithium-Ion Batteries

Lithium-ion electrode fabrication relies on the controlled dispersion of active materials, conductive carbon, and polymeric binders in suitable solvents to form a slurry that can be uniformly coated onto current collectors (Figure 5) [53]. As illustrated in Figure 5, the role of conductive additives such as carbon nanotubes extends beyond simple electrical conductivity. Their high surface area and network-forming ability reduce the percolation threshold, allowing efficient electron transport even at high active material loadings. This structural characteristic enables the production of high-energy-density electrodes by maintaining electrical connectivity while minimizing the fraction of inactive materials. The slurry mixing stage therefore becomes a critical processing step because uniform dispersion determines whether the conductive network forms effectively within the electrode matrix [54].

The coating and calendaring stages shown in Figure 5 further highlight the relationship between processing parameters and electrode microstructure. Controlled compression during calendaring reduces porosity to improve electronic contact between particles, but excessive densification may restrict ionic transport pathways. Achieving the appropriate balance between density and pore connectivity is therefore essential for optimizing electrochemical performance [55]. The schematic representation of the coated electrode also reflects how conductive networks intertwine with binder domains to mechanically stabilize the active material particles during repeated lithiation and delithiation cycles.

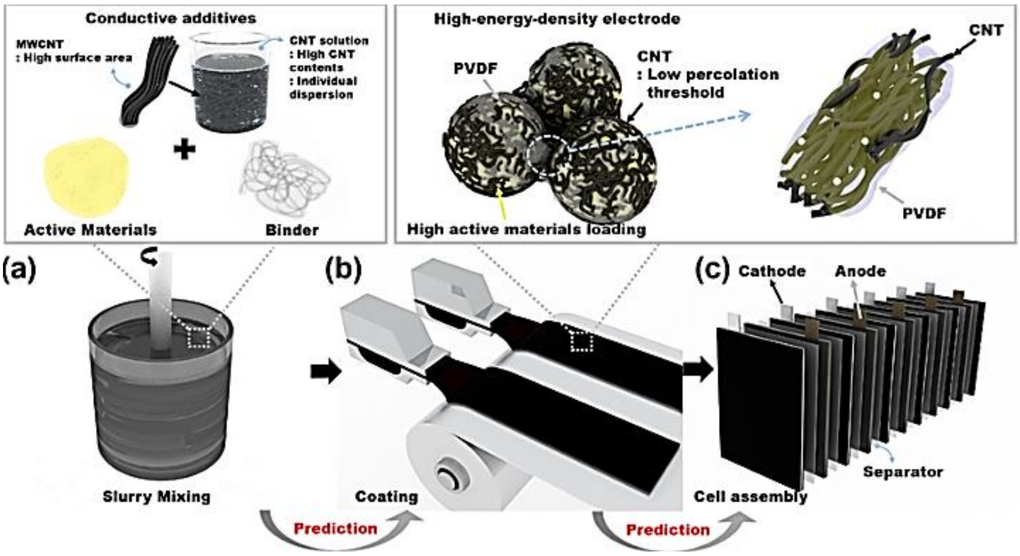

Figure 5: Schematic illustration of the Li-ion battery electrode fabrication process [53]

Electrolyte formulation also plays a decisive role in stabilizing the electrode structure during operation. Conventional electrolytes are typically composed of $LiPF_6$ dissolved in carbonate solvent blends, often supplemented with functional additives such as Fluoroethylene Carbonate and Vinylene Carbonate to enhance solid electrolyte interphase formation, improve thermal stability, and suppress gas evolution. Because $LiPF_6$ is highly sensitive to hydrolysis, strict control of water content and electrolyte purity is required during manufacturing to prevent degradation reactions that could compromise cell longevity [56, 57].

The final stages of cell assembly illustrated in Figure 5 emphasize the layered architecture of lithium-ion batteries, where cathodes, separators, and anodes are stacked or wound into compact structures. Assembly is conducted in dry environments or gloveboxes to prevent moisture contamination, and electrolytes are introduced under reduced pressure to ensure complete infiltration of the porous electrodes. Cells may then be packaged in cylindrical, prismatic, or pouch formats and sealed using thermal or laser welding techniques [58, 59]. Subsequent formation cycling establishes stable interphases at the electrode surfaces, which are critical for long-term electrochemical stability.

Recent advances in lithium-ion manufacturing seek to improve both energy density and process efficiency. These include dry-electrode fabrication methods that eliminate solvent use, pre-lithiation strategies to compensate for initial lithium loss, and thick-electrode designs that increase active material loading without compromising transport properties. Additional innovations such as laser-patterned current collectors and graded heterostructured electrodes aim to relieve mechanical stresses and enhance ion transport pathways, thereby improving the overall durability and performance of advanced lithium-ion cells [60, 61, 62, 21].

2.4.2. Sodium-Ion Batteries

Sodium-ion battery electrodes require material synthesis strategies that account for the larger ionic radius and different intercalation behaviour of Na^+ compared with Li^+ [63]. As illustrated in Figure 6, hard carbon production involves a sequence of controlled processing stages beginning with biomass or organic precursors, followed by crushing, purification, and thermal treatment. These steps are not merely preparatory but determine the final carbon microstructure, which governs sodium storage behaviour. The pre-carbonization stage removes volatile components and initiates structural rearrangement, while the subsequent high-temperature carbonization step develops the disordered carbon framework and nanoporous domains that enable reversible sodium insertion [64]. The resulting turbostratic structure and internal pore networks are essential for accommodating Na^+ ions, which cannot intercalate efficiently into the well-ordered graphite lattice typically used in lithium-ion systems.

The processing pathway highlighted in Figure 6 therefore illustrates how thermal treatment and precursor selection directly influence electrochemical performance. Adjusting the carbonization temperature and purification conditions alters the balance between graphitic domains and microporous regions, which in turn affects reversible capacity, rate capability, and initial coulombic efficiency [65]. Consequently, the synthesis process is a critical design parameter for sodium-ion anodes, as controlling pore structure and defect density can mitigate diffusion limitations associated with the larger Na^+ ion [65].

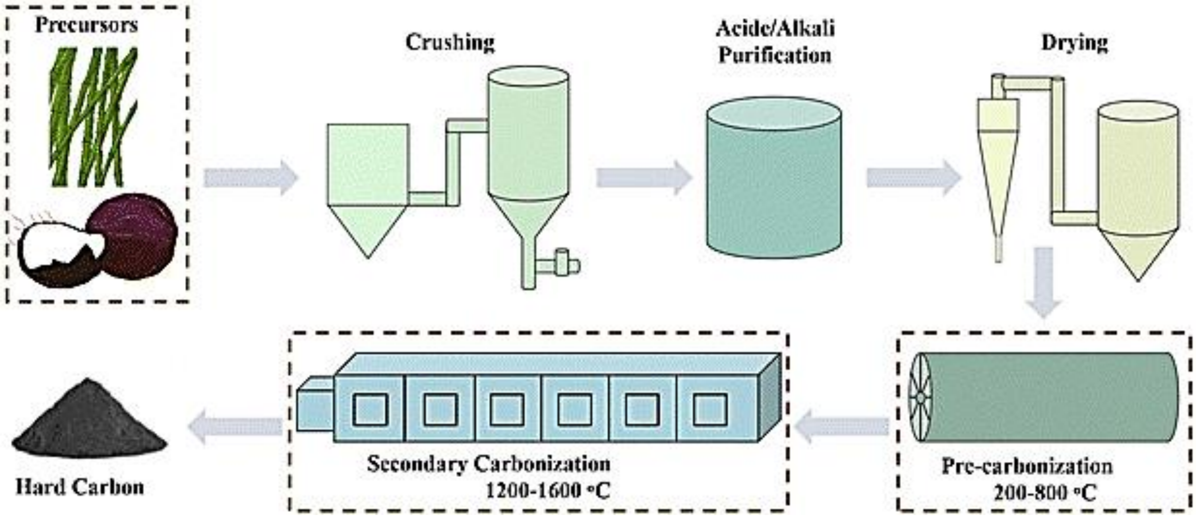

Figure 6: Hard carbon synthesis [64]

Electrode fabrication for sodium-ion batteries generally employs water-based binders and slurry systems due to the comparatively milder reactivity of sodium compounds. The larger Na^+ ionic radius also necessitates electrode architectures with higher porosity and more accessible diffusion pathways to maintain efficient ion transport within the electrode matrix. In addition, sodium-ion systems exhibit greater tolerance to moisture during processing compared with lithium-ion batteries, allowing more flexible manufacturing conditions without severe degradation risks [64].

To address the irreversible capacity loss commonly observed during the first charge cycle of hard carbon anodes, pre-sodiation strategies are sometimes introduced to supply additional sodium and stabilize the initial solid electrolyte interphase layer [66, 67]. Cell assembly principles remain broadly similar to those used in lithium-ion batteries, where cathodes and anodes are arranged in stacked or wound configurations separated by polymer membranes. Electrolytes typically contain $NaPF_6$ or $NaClO_4$ dissolved in carbonate solvents such as ethylene carbonate and diethyl carbonate, although alternative systems including ether-based electrolytes and ionic liquids are increasingly investigated to improve stability and low-temperature performance. While sodium-ion manufacturing benefits from reduced sensitivity to moisture, achieving uniform coating and maintaining mechanical integrity of hard carbon electrodes remain essential to ensure consistent electrochemical performance [67, 68].

2.4.3. Solid-State Batteries

Solid-state electrolytes encompass ceramic sulphides, oxides, halides, as well as polymer and hybrid matrices, each exhibiting distinct crystal structures and ion transport mechanisms. The fabrication pathways illustrated in Figure 7 highlight how synthesis routes directly influence the resulting electrolyte microstructure and ionic conductivity. Solid-state reaction methods, shown in Figure 7a, typically involve high-temperature calcination of mixed precursors to form crystalline electrolyte phases. This route promotes phase purity and structural stability but requires careful control of temperature and stoichiometry to prevent secondary phase formation that may impede ionic conduction [69].

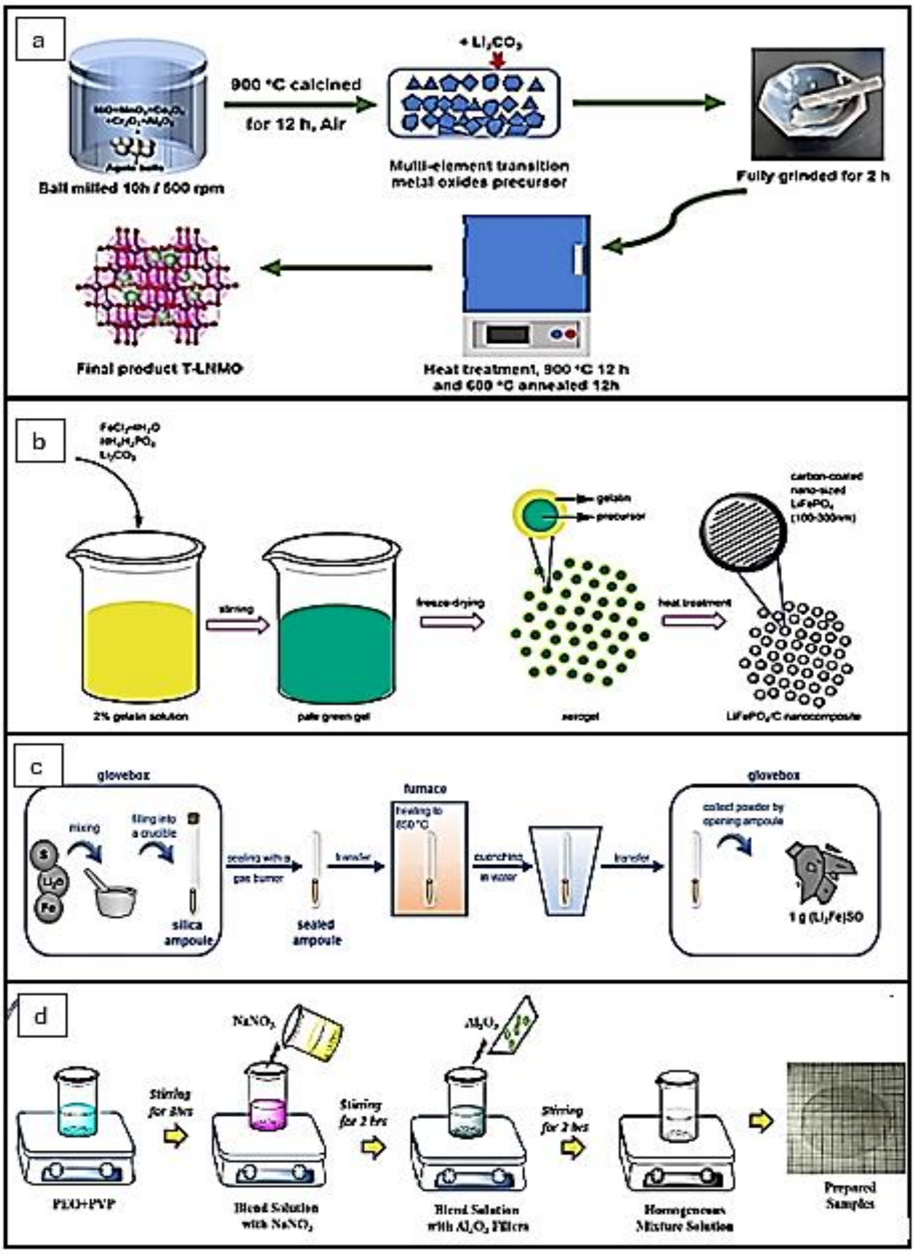

Figure 7: a. Schematic of solid-state reaction method [69]. b. Schematic diagram of the sol–gel process ($LiFePO_4$/C) [70], c. Schematic illustration of the mechanochemical synthesis ((Li_2Fe)SO) [71], d. Solution casting technique [72]

In contrast, the sol–gel pathway depicted in Figure 7b demonstrates how solution-based chemistry can achieve improved compositional homogeneity at the molecular level. The formation of a gel network followed by drying and thermal treatment enables the synthesis of finely distributed particles and controlled morphology. Such structural uniformity can shorten ion diffusion pathways and enhance electrochemical performance compared with conventional solid-state synthesis routes [70]. Mechanochemical synthesis, illustrated in Figure 7c, provides an alternative approach in which high-energy mechanical milling induces solid-state reactions at lower temperatures. This technique can produce metastable phases and highly defective structures that increase ionic mobility by introducing lattice disorder and expanded diffusion channels [71].

Polymer and composite electrolytes, represented by the solution casting method in Figure 7d, rely on dissolution and subsequent film formation to produce flexible electrolyte membranes. In these systems, ionic transport is closely linked to polymer chain mobility and the distribution of salt or ceramic fillers within the matrix. Controlled casting and solvent evaporation therefore determine the final film morphology, mechanical integrity, and ionic conductivity of the electrolyte layer [72].

Despite the advantages of solid electrolytes, interfacial contact between the electrolyte and electrode remains one of the most critical challenges in solid-state battery design [73]. Unlike liquid electrolytes, which can easily infiltrate porous electrodes and establish continuous ionic pathways, solid electrolytes depend on intimate solid–solid contact for ion transport [74]. Surface roughness, particle size mismatch, and interfacial voids can significantly reduce the effective contact area between materials, leading to constriction resistance and increased polarization losses. As a result, the performance of solid-state cells is strongly governed by interfacial engineering rather than bulk electrolyte conductivity alone [75].

To address these limitations, fabrication strategies aim to increase the real contact area and improve chemical compatibility at electrode–electrolyte interfaces. Techniques such as surface polishing, thin interlayer coatings, composite cathode architectures, and pressure-assisted consolidation are widely employed to reduce interfacial gaps and enhance ion transport. During cell assembly, the application of stack pressure further improves interfacial contact by deforming surface asperities and eliminating microvoids. These measures collectively reduce interfacial impedance and enable more efficient ionic conduction across the solid–solid interfaces that define the performance of solid-state battery systems [76, 77].

2.4.4. *Flow Batteries*

Flow battery electrodes are commonly modified through thermal activation, surface functionalization, or catalyst deposition to improve redox reaction kinetics and increase the number of electrochemically active sites [78]. In practical cell architectures, as illustrated in Figure 9, the porous carbon felt electrodes are positioned adjacent to the ion exchange membrane, allowing electrolyte to permeate through the electrode thickness while facilitating electron transfer to the external circuit. The thickness and porosity of these electrodes govern the balance between electrochemical surface area and hydraulic resistance, thereby influencing both mass transport efficiency and pumping energy requirements.

The ion exchange membrane located between the electrodes serves as the ionic conductor while preventing the mixing of positive and negative electrolytes. Membranes fabricated through extrusion, casting, or electrospinning are often subjected to chemical stabilization and reinforcement treatments to minimize crossover of redox active species and maintain long term electrochemical stability [79]. In the configuration shown in Figure 9, the membrane acts as the central separator that sustains charge balance while maintaining electrolyte isolation.

Cell assembly integrates electrodes, membranes, and current collectors within a structural framework composed of flow frames, gaskets, and graphite bipolar plates. These elements define the electrolyte flow channels and ensure uniform distribution of the positive and negative electrolytes across the electrode surfaces. The bipolar plates simultaneously function as current collectors and electrical interconnects between adjacent cells, enabling series electrical connection within the stack. Precision machining and controlled compression through gaskets maintain sealing integrity and uniform contact resistance across the active area. Through the internal manifold system, electrolyte is distributed across multiple cells, allowing modular stacking that scales the electrochemical power output while maintaining controlled flow and electrochemical performance [80].

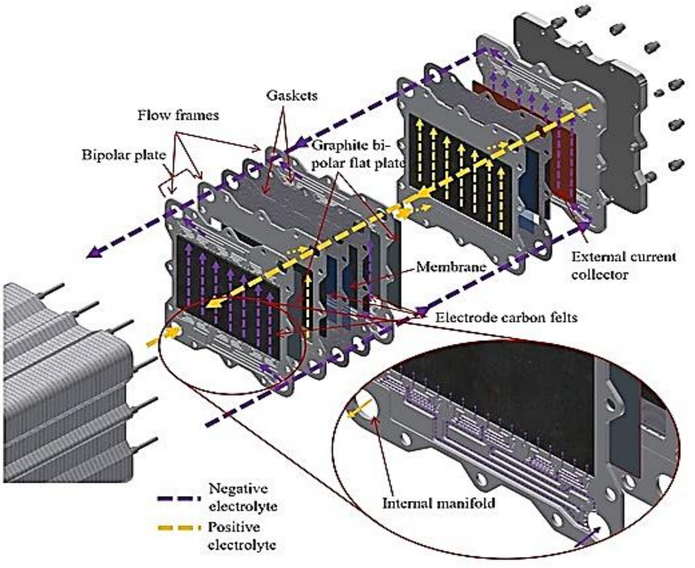

Figure 9: Flow battery assembly [81]

2.4.5. Metal–Air Batteries

Metal–air systems rely on composite air cathodes comprising carbon supports, catalysts (e.g., MnO_2, Co–N–C, Pt-based), and hydrophobic binders (Figure 10). Fabrication may involve slurry casting onto gas diffusion layers or forming multilayer catalyst–diffusion structures. Metal anodes (Zn, Al, Li) are typically cast or rolled and treated to control dendrite growth and corrosion. Electrolytes range from aqueous alkaline solutions to non-aqueous formulations as depicted by [82], depending on the metal type. Assembly must account for oxygen permeability, moisture management, and chemical stability of catalysts.

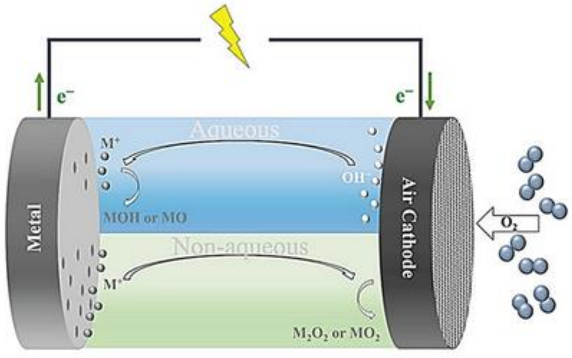

Figure 10: Metal–Air Batteries [82]

Air cathodes must balance oxygen transport with protection from contaminants (CO_2, humidity) [85]. Cell housings incorporate air pathways, breathable membranes, or filters. Ensuring mechanical durability of the air electrode and preventing electrolyte drying or flooding are central fabrication challenges [83].

2.4.6. Aqueous Zinc-Ion Batteries

Cathode materials for aqueous zinc-ion batteries are commonly synthesized through solution reactions, hydrothermal processes, or solid-state routes to obtain structures that support reversible Zn^{2+} insertion and extraction. As illustrated in Figure 11, the cathode typically consists of manganese-based active materials such as δ-MnO_2 integrated with conductive carbon additives including graphite and carbon black [84]. These conductive networks improve electron transport within the electrode and stabilize the host structure during repeated Zn^{2+} intercalation and deintercalation. Electrodes are generally fabricated by coating aqueous slurries of the active material, conductive additives, and binders onto current collectors to form porous layers that allow electrolyte penetration and efficient ion transport [84].

On the anode side, metallic zinc serves as the electroactive material, where reversible plating and stripping of Zn^{2+} ions occur during charge and discharge. However, this process requires careful surface control because uneven deposition can promote dendrite formation and hydrogen evolution. Consequently, mechanical treatments such as rolling and polishing, as well as protective coatings based on carbon materials, polymers, or alloy layers, are often applied to regulate nucleation and improve interfacial stability [84].

The electrolyte, commonly based on aqueous $ZnSO_4$ as shown in Figure 11, provides the ionic medium for Zn^{2+} transport between electrodes. Alternative salts such as $Zn(CF_3SO_3)_2$ or hybrid aqueous systems may also be used, often incorporating additives that regulate pH, modify solvation structure, and suppress parasitic side reactions. Optimization of electrolyte concentration, buffering capacity, and ion coordination environment plays a crucial role in stabilizing Zn plating and stripping processes and maintaining long-term cycling performance [84].

During operation, Zn^{2+} ions migrate through the electrolyte and across the separator, which electrically isolates the electrodes while permitting ionic conduction. Separator materials are therefore selected to resist dendrite penetration and maintain chemical compatibility with aqueous electrolytes. The aqueous chemistry of the system allows assembly under relatively mild conditions compared with non-aqueous batteries; however, corrosion control, electrolyte purity, and management of gas evolution and water evaporation remain important considerations for reliable operation.

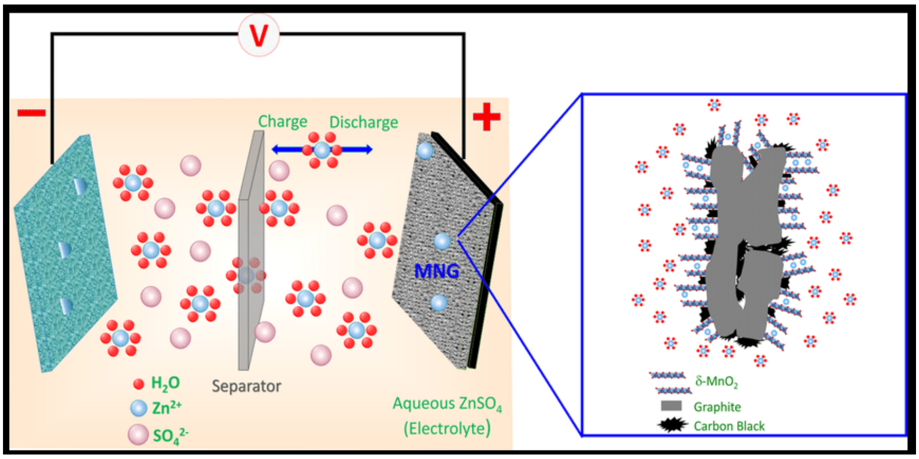

Figure 11: Schematics of the chemistry of the zinc-ion battery [84]

2.5. Comparative Analysis of Fabrication Methods

Fabrication requirements across battery technologies diverge primarily along three axes: processing temperature, environmental control, and structural architecture. As summarized in Table 1, lithium-ion and sodium-ion batteries exhibit the most mature manufacturing pathways, relying on slurry casting, roll-to-roll drying, and calendaring. Their relatively moderate processing temperatures (typically <180 °C during electrode fabrication) and established dry-room environments enable gigafactory-scale production. Sodium-ion systems show a key manufacturing advantage in their greater tolerance to humidity, which reduces dry-room energy demand and improves compatibility with existing lithium-ion production lines.

In contrast, solid-state batteries impose significantly stricter processing constraints. High-temperature ceramic sintering (300–1200 °C) and extremely low moisture tolerance (<10 ppm H_2O) increase both capital and operational costs. These requirements reflect the fundamental need for dense electrolytes and stable solid–solid interfaces, which remain the principal bottlenecks for industrial scale-up.

Architecturally distinct systems such as flow and metal–air batteries shift fabrication complexity from electrode densification toward porous structure engineering and system integration. As shown in Table 2, their electrodes exhibit much higher porosity (40–80 %) than intercalation-based systems, enabling electrolyte circulation or oxygen diffusion but reducing volumetric energy density. Consequently, their scalability depends less on materials processing and more on stack design, membrane durability, and fluid management.

Quantitative comparisons further highlight these trade-offs. Lithium-ion and sodium-ion electrodes typically exhibit densities of 2.2–3.6 g cm^{-3} and porosity levels of 25–45 %, balancing energy density and ion transport. Solid-state systems require much denser ceramic components with porosity below 10 % and stack pressures up to 50 MPa to maintain interfacial contact, explaining their higher manufacturing complexity and cost. By contrast, aqueous zinc-ion batteries operate under the mildest fabrication conditions, tolerating ambient humidity and moderate processing temperatures, which contributes to their comparatively low projected cost.

Overall, the comparative metrics in Tables 1 and 2 indicate a clear manufacturing maturity hierarchy. Lithium-ion technology remains the most industrially optimized, with sodium-ion systems positioned as a near-term extension of existing infrastructure. Solid-state batteries promise improved safety and energy density but require substantial advances in electrolyte densification and interface engineering. Flow, metal–air, and aqueous zinc-ion batteries occupy a different design space in which scalability depends more on system architecture and materials stability than on conventional electrode fabrication.

2.6. Fabrication-Induced Degradation Mechanisms

Although fabrication processes are primarily intended to optimise electrode structure and manufacturing efficiency, they can also introduce structural defects that contribute to long-term degradation or early cell failure. Several common degradation pathways originate directly from fabrication conditions, particularly during coating, drying, calendaring, electrolyte filling, and high-temperature processing.

2.6.1. Delamination and Binder Segregation

Delamination between the electrode coating and current collector is a common failure mechanism linked to slurry formulation and drying behaviour. During solvent evaporation, non-uniform binder migration may occur if evaporation proceeds faster than binder diffusion within the electrode film [105]. This can produce binder-rich regions near the surface and binder-deficient regions near the current collector, weakening adhesion and increasing the likelihood of coating delamination during cycling.

Table 1: Fabrication processes and manufacturing conditions

Battery Technology	Fabrication Methods	Temp. Range (°C)	Humidity Requirement	Atmosphere	Scalability	Key Bottlenecks	References
Lithium-ion	Slurry mixing, slot-die coating, roll-to-roll drying, calendaring, vacuum filling	25–180; up to ~700 (cathode calcination)	<1% RH; dew point −30 to −60 °C	N_2 dry room	Very high	N-methyl-2-pyrrolidone (NMP) recovery; dry-room energy; coating uniformity	[85, 86, 13]
Sodium-ion	Slurry coating, roll-to-roll processing, hard-carbon pyrolysis	25–150; 800–1200 (carbon synthesis)	<20% RH	Controlled ambient	High	Hard-carbon control; lower energy density	[87, 64, 88, 63]
Solid-state	Powder synthesis, milling, tape casting, hot pressing, SPS sintering	300–1200	<1% RH or <10 ppm H_2O	Ar/N_2 inert	Low–moderate	Solid–solid interface resistance; densification	[9]
Flow	Carbon felt activation, catalyst deposition, membrane casting, stack assembly	25–400	30–60% RH	Ambient air	Moderate–high	Membrane crossover; pumping losses	[89, 90]
Metal–air	Gas diffusion electrode fabrication, catalyst deposition, metal foil processing	25–500	20–60% RH	Air cathode	Low–moderate	Air cathode degradation; flooding/drying	[91, 92, 82]
Aqueous Zn-ion	Hydrothermal cathode synthesis, slurry coating, Zn foil processing	25–200	30–70% RH	Ambient	Moderate–high	Zn dendrites; corrosion	[93, 94]

Mechanical stresses generated during electrode swelling and contraction can further amplify this effect, leading to progressive electrical isolation of active material particles and increased internal resistance [106].

2.6.2. *Particle Fracture During Calendaring*

Calendaring improves electronic conductivity and volumetric energy density by compressing the electrode structure. However, excessive compression pressure may induce mechanical fracture of brittle active material particles, particularly in layered oxide cathodes and ceramic-rich composite electrodes [107]. Particle fracture increases internal surface area and can accelerate electrolyte decomposition, side reactions, and structural degradation during repeated charge–discharge cycles. In addition, microcracks generated during calendaring may propagate during cycling as a result of electrochemical strain, contributing to capacity fade and impedance growth [26].

2.6.3. *Gas Entrapment During Electrolyte Filling*

Electrolyte infiltration is typically performed under vacuum conditions to ensure complete wetting of the porous electrode structure [108]. Inadequate evacuation or rapid filling rates can lead to trapped gas pockets within the electrode pores or separator structure. Gas entrapment reduces the effective electrolyte contact area and increases local ionic resistance [109]. Over time, these trapped gases may expand during temperature fluctuations or electrochemical reactions, producing localized pressure buildup that can deform electrode structures or promote delamination [110].

Table 2: Quantitative performance/manufacturing metrics

Battery System	Electrode Density (g cm^{-3})	Porosity (%)	Ionic Conductivity (S cm^{-1})	Processing / Sintering Temp (°C)	Stack Pressure (MPa)	Moisture Threshold (ppm H_2O)	Estimated Cost ($ kWh^{-1})	References
Lithium-ion batteries	2.8–3.6	25–40	10^{-3}–10^{-2}	80–150 (electrode drying)	1–5	<500	90–140	[95, 96, 97]
Sodium-ion batteries	2.2–3.2	30–45	10^{-3}–10^{-2}	80–150	1–5	<500	70–120	[9, 66, 98]
Solid-state batteries	3.5–5.2	<10	10^{-4}–10^{-3}	700–1200 (ceramic sintering)	10–50	<10	200–400	[9, 99]
Flow batteries	1.5–2.5 (porous electrodes)	60–80	10^{-2}–10^{-1} (liquid electrolytes)	25–80	~0	<1000	150–300	[96, 100, 45]
Metal–air batteries	1.8–3.0	40–70	10^{-3}–10^{-2}	25–200	0–5	<200	100–200	[101, 102]
Aqueous zinc-ion batteries	2.5–3.5	30–50	10^{-3}–10^{-2}	25–120	0–5	<1000	60–120	[93, 103, 104]

2.6.4. Void Formation in Solid Electrolytes

In solid-state batteries, fabrication defects such as incomplete densification, particle agglomeration, or insufficient compaction can produce voids within the electrolyte layer or at electrode–electrolyte interfaces. These voids interrupt ion conduction pathways and increase interfacial resistance [74]. Furthermore, voids may act as stress concentration sites where lithium plating or dendritic growth can initiate during cycling. Maintaining high electrolyte density through optimized powder processing, controlled sintering, and pressure-assisted assembly is therefore critical for minimizing such defects [74].

2.6.5 Residual Stress from High-Temperature Processing

High-temperature sintering and thermal processing steps used in ceramic electrolytes and certain cathode materials can introduce residual stresses due to differential thermal expansion between phases or between the electrolyte and electrode layers [111]. Upon cooling, these stresses may lead to microcracking, interfacial delamination, or gradual mechanical degradation during cycling. Residual stress is particularly important in multilayer solid-state battery architectures where ceramic electrolytes are laminated with composite electrodes [111].

2.7. Challenges, Opportunities, and Future Directions

Fabrication remains a central determinant of battery performance and manufacturability, and each chemistry introduces distinct processing challenges. For lithium-ion and sodium-ion systems, issues such as slurry uniformity, binder distribution, and consistent electrode porosity continue to influence cycle life and rate capability. Solid-state batteries face more fundamental fabrication barriers: ceramic electrolytes require precise powder processing and controlled densification and establishing stable solid–solid interfaces remain one of the most significant limitations to practical deployment (Figure 12). Flow batteries must accommodate highly permeable electrodes and durable membranes, while metal–air systems depend on air electrodes that combine catalytic activity with engineered gas transport (Figure 12). Aqueous zinc-ion batteries encounter difficulties related to zinc morphology, corrosion management, and electrolyte purity. Across these technologies, several cross-cutting bottlenecks persist. Scaling laboratory processes to high-throughput manufacturing introduces variability in coating thickness, drying behaviour, and interface quality. Moisture sensitivity, contamination, and the difficulty of identifying hidden defects in multilayer structures further complicate production. As electrodes become thicker to increase energy density, maintaining uniform ion transport and structural stability becomes more challenging, underscoring the need for improved process control.

These constraints create meaningful opportunities for fabrication innovation. Solvent-free methods such as dry coating and extrusion can reduce environmental impact and simplify processing. For solid-state batteries, advances in low-temperature sintering, composite interlayers, and engineered interfaces offer promising routes toward more scalable manufacturing.

Figure 12: Challenges of battery fabrication

Flow and metal–air batteries benefit from architected porous electrodes produced through controlled activation or additive manufacturing, while water-based binders and greener solvent systems support more sustainable production for sodium-ion and zinc-ion chemistries. Looking ahead, several emerging directions are poised to reshape battery manufacturing. Additive manufacturing provides new possibilities for tailored 3D electrode architectures with improved transport and mechanical properties. Advanced deposition techniques (such as atomic layer deposition, sputtering, and roll-to-roll vapor coating) enable ultrathin protective layers and solid electrolyte films beyond the reach of slurry-based processes. Increasingly, digital tools including AI-driven process optimisation, robotic stacking, and in-line optical inspection are improving reproducibility and accelerating scale-up.

Collectively, these developments point toward a manufacturing landscape that is more flexible, efficient, and environmentally aligned. The ability to support multiple chemistries on shared production infrastructure, alongside hybrid electrode and electrolyte architectures, represents a likely trajectory for next-generation energy-storage technologies.

3. Conclusion

This review has presented a fabrication-centred comparative perspective on contemporary battery technologies, emphasizing the critical role of manufacturing processes in determining electrochemical performance, safety, and scalability. While different battery systems rely on distinct chemistries and structural architectures, several common themes emerge. Electrode processing, electrolyte integration, and cell-assembly protocols collectively govern microstructural evolution, transport pathways, and interfacial stability, which ultimately influence long-term battery durability and operational efficiency.

Mature manufacturing approaches such as roll-to-roll coating and calendaring remain fundamental to the large-scale production of intercalation-based systems, particularly lithium-ion batteries. In contrast, emerging technologies often require more specialized fabrication strategies involving precise powder engineering, interface modification, controlled porosity, and pressure-assisted consolidation to address solid–solid contact limitations and transport constraints. These differences highlight the increasing importance of tailoring fabrication methods to the specific structural and electrochemical requirements of each battery chemistry.

The comparative analysis presented in this work demonstrates that advances in materials chemistry alone are insufficient for the successful commercialization of next-generation batteries. Equally important are scalable and optimized fabrication routes capable of translating laboratory-scale innovations into reliable industrial production. Emerging manufacturing approaches such as dry-electrode processing, additive manufacturing, engineered pore architectures, and interphase-stabilization coatings offer promising pathways for improving ion-transport efficiency, reducing processing costs, and enabling higher energy densities.

Unlike many existing battery reviews that focus primarily on electrochemical materials or performance metrics, this study emphasizes the often underrepresented role of manufacturing science as a key determinant of practical battery performance and scalability. By systematically comparing fabrication strategies across lithium-ion, solid-state, metal–air, and flow battery systems, the review highlights how processing conditions influence electrode architecture, defect formation, and transport limitations across different chemistries.

Overall, establishing robust, adaptable, and cost-effective fabrication strategies will be essential for advancing next-generation energy-storage technologies. Integrating advanced characterization methods, improved process control, and manufacturability-focused research will help bridge the gap between laboratory discovery and large-scale battery production. Such interdisciplinary efforts will play a vital role in enabling safer, higher-performance, and more sustainable batteries capable of supporting global electrification and the transition toward cleaner energy systems.

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