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Review Article

A Review of Design Strategies and Material Challenges for Magnesium-Based Rechargeable Seawater Batteries: Insights from Sodium-RSB Systems

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Abstract
Rechargeable seawater batteries (RSBs) are a new class of seawater-based energy storage technology. In this system, the two electrolytes—the non-aqueous anolyte and seawater as the catholyte—have distinct compositions. As an eco-friendly option, the technology is promising, with the potential to replace traditional rechargeable batteries and reduce harmful environmental impacts. It can also be used in locales without access to power. There are different classes of RSBs, including sodium-based (Na-RSBs). At present, Na-RSBs systems have attracted much more attention due to the availability of solvents derived from abundant sodium sources in seawater and because of their superior material costs and safety compared to lithium (Li)-based batteries. Nonetheless, Na-RSBs are inherently restricted by the relatively low theoretical capacity and electrochemical potential of sodium. As a result, magnesium-based rechargeable seawater batteries (Mg-RSBs) have emerged as a promising alternative. Magnesium is attractive because it offers a higher theoretical volumetric capacity (~3833 mAh cm^{-3}) and a better cost-performance ratio than Li-ion batteries and Na-RSB systems. Given these merits, we summarize the potential of magnesium as a candidate alternative to sodium in RSB applications. To develop their potential, some strategies (alloying, surface modification, bifunctional catalyst design, and solid–liquid hybrid electrolyte construction) are proposed. The perspective concludes with an outlook that emphasizes the importance of accounting for integrated electrolyte–separator design, interface manipulation, and corrosion-mitigation strategies to realize the potential of Mg-RSBs as a high-durability, long-life, and economical battery system, especially in off-grid applications.

Keywords: anode material, energy storage systems, non-aqueous anolytes, rechargeable magnesium–seawater batteries

1. INTRODUCTION

In contemporary society, the advancement of energy technologies is progressively oriented toward renewable energy sources, thereby intensifying the demand for energy-storage systems that are sustainable, secure, and cost-effective. Currently, lithium-ion batteries (LIBs) continue to be the prevailing energy-storage technology, utilized in a broad spectrum of applications. Nevertheless, LIBs are still subject to several constraints, encompassing elevated production expenses, safety issues stemming from their flammable electrolytes, and a reliance on scarce resources like lithium and cobalt [1][2]. Consequently, the development of alternative energy-storage systems has become increasingly crucial to mitigate these limitations.

Currently, sodium-ion batteries (SIBs) are among the more sustainable alternatives to LIBs. SIBs work with closed-cell systems that use Na^+ ions as charge carriers, making them cheaper and more abundant. There have been a few recent reviews on the development of SIB anode materials that cover carbon anodes, alloy-type, and conversion mechanism transition-metal oxides and sulfides [3]. In addition, recent developments include aqueous rechargeable Na-ion systems that operate in seawater and demonstrate desalination capability [4]. Nevertheless, many conventional SIB systems still rely on flammable organic electrolytes and generally exhibit lower energy density.

In this light, rechargeable seawater batteries (RSBs), which utilize benign ion sources and show good performance in marine environments, present a promising novel energy-storage scheme. RSBs have inherent advantages such as using abundant seawater, being more environmentally compliant, and having a promising economic outlook, making them potential candidates for large-scale energy-storage applications. Among the various configurations developed, sodium-based rechargeable seawater batteries (Na-RSBs) represent the most discussed and pioneered systems

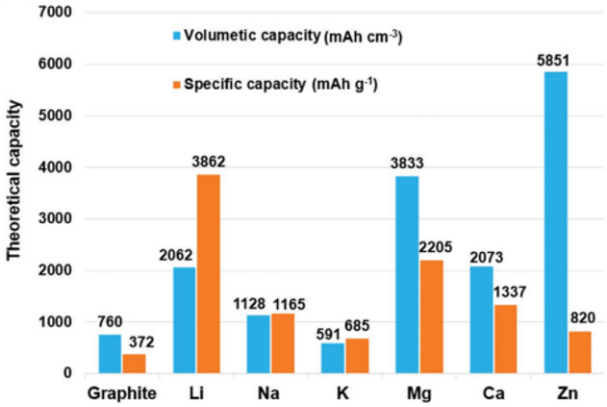

Figure 1. Comparison of theoretical capacity of graphite anode and various metal anodes, including volumetric and specific capacity. Adapted with permission from Liu et al. [5].

to date. The development of Na-RSBs has been supported by the use of ion-selective ceramic separators, particularly NASICON ($Na_{1+x}Zr_2Si_xP_{3-x}O_{12}$), which facilitates effective Na^+ transport. While promising, Na-RSBs still have drawbacks, mainly due to sodium's lower theoretical voltage and capacity compared to lithium, which ultimately limit the device's energy density. These limitations have encouraged growing interest in the development of magnesium-based rechargeable seawater batteries (Mg-RSBs) as a promising alternative. In this context, Mg is important to consider as a host material because it possesses a high maximum volumetric capacity (3833 mAh cm^{-3}), nearly twice that of lithium (2062 mAh cm^{-3}; see Figure 1), as well as a low standard reduction potential (−2.37 V vs SHE) and high abundance in the Earth's crust, particularly in comparison with lithium [5].

However, unlike Na-RSBs, which have been developed earlier and more extensively, the further development of Mg-RSBs is still hindered by several intrinsic limitations of Mg, including low Mg^{2+} mobility in electrolytes, high desolvation energy, and a strong tendency toward surface passivation, particularly in Cl^--rich environments [6][7]. In addition, significant anode corrosion, parasitic hydrogen evolution, and poor electrode–electrolyte interfacial stability simultaneously accelerate the deterioration of system performance [7]. Direct contact between the Mg anode and seawater catholyte can also trigger severe galvanic corrosion. These conditions indicate that although Mg is highly attractive as a host material due to its high volumetric capacity, its implementation in RSB systems requires more complex design strategies, including the use of chemically compatible non-aqueous electrolytes and ion-selective separators [7][8].

In this context, thermodynamic analysis of the binary Mg–Na system also provides an important basis for understanding the position of Mg in the development of Mg-RSBs. Previous studies have shown that the Mg–Na system exhibits a large degree of immiscibility in the liquid phase, while the solubility of Na in solid Mg and that of Mg in solid Na is extremely low or negligible [9]. These results indicate little interaction between Mg and Na at equilibrium conditions and no significant solid solution between the two metals. In the context of this paper, these characteristics emphasize the need to treat Mg as a support material requiring careful design, rather than assuming it functions analogously to sodium-based systems like Na-RSB.

In view of these challenges, the development of Mg-RSBs requires more specific design strategies than those applied to Na-RSBs to date, including catalyst engineering, solid–liquid hybrid electrolyte systems, and anode surface modification, while previous advances in Na-seawater battery design provide useful conceptual guidance for such development [10]. In addition, the fundamental understanding developed from magnesium-ion batteries (MIBs) and rechargeable magnesium batteries (RMBs) is also important, as it provides a basis for understanding Mg^{2+} transport, electrode–electrolyte interfacial stability, and electrolyte compatibility in Mg-based systems [8].

This review not only presents the development

of cathode, anode, separator, and electrolyte materials in RSBs, but also examines the potential of Mg as a candidate host material for Mg-RSBs. By using Na-RSBs as a comparative foundation and integrating insights from MIBs and RMBs, this review aims to identify the design strategies required to realize the Mg-RSB concept. In this light, attention is specifically drawn towards the design of proper ion-selective separators and the choice of compatible non-aqueous electrolytes that can enable Mg^{2+} transport as well as stability in Mg-based systems.

2. CHALLENGES IN DEVELOPING RECHARGEABLE SEAWATER MAGNESIUM BATTERIES

The RSB configuration that has been most extensively studied to date is the Na-RSB, which generally employs a dual-electrolyte design. In this system, the non-aqueous anolyte in the anode compartment is separated from the seawater-based catholyte by an ion-selective solid ceramic separator. This architecture enables selective transport of Na^+ ions between the two compartments, while ORR/OER reactions occur at the cathode side, in contact with the seawater catholyte. In principle, the double-electrolyte architecture used in Na-RSBs is also applicable to Mg-based systems, as Mg anodes require a more stable electrolyte environment. Nevertheless, applying this concept to Mg-RSBs remains a challenge. Unlike Na-RSBs, the direct use of Mg^{2+} as a charge carrier from seawater remains highly challenging because of its low solubility and strong tendency toward surface passivation, both of which hinder electrochemical reactions [11][12]. Therefore, the development of Mg-RSBs remains far less mature than that of sodium-based systems. This situation further underscores that Mg cannot be treated as an alternative to sodium; it should nevertheless be regarded separately as a host material with its own intrinsic properties.

It is worth noting that Mg–air batteries can also operate using seawater or neutral brine as the electrolyte, in which oxygen reduction governs the cathodic reaction [13][14]. Nevertheless, since most Mg–air systems are primary batteries, their rechargeability is still limited due to serious anode passivation, self-corrosion, and electrolyte problems [13][15]. In comparison, rechargeable seawater batteries comprise a dual-electrolyte architecture that is commonly structured by an ion-selective solid electrolyte to facilitate enhanced tunability of ion transport with limited direct contact between the Mg anode and ambient seawater [16][17]. This architecture is promising for rechargeable Mg-based seawater systems, yet it faces inherent material and interfacial barriers [11][17][18]. Recent studies on Mg–air batteries have also provided useful insights into cathodic ORR catalysis and anode degradation behavior, which are relevant for the future development of Mg-RSBs [13]-[15].

Currently, in Na-RSB, ion-selective solid ceramic separators such as NASICON have been reported to selectively enable the transfer of Na^+ ions from seawater catholyte to non-aqueous anolyte compartment. This two-compartment design not only separates anode and cathode, but also enables differentiation of electrolytes with various chemical properties. Nonetheless, this type of ion-selective separator has not been fully developed for Mg-RSBs, and few established experimental reports are available [11][18]. This situation highlights a significant technological gap between Na-RSBs and Mg-RSBs. Therefore, when Mg is used as a host material, the development of compatible ion-selective separators is a key prerequisite for realizing Mg-RSB systems.

To clarify the discussion above, the dual-electrolyte configuration underlying Na-RSBs is shown in Figure 2, which was adapted from previous literature to represent the typical architecture of rechargeable seawater batteries [16]. In this design, the Na metal anode is placed in a compartment containing a non-aqueous electrolyte and is separated from the seawater catholyte by an ion-selective solid ceramic separator (Figure 2(a)). Although this architecture was not specifically developed for Mg anodes, its conceptual framework remains relevant as a reference point for understanding the need for electrolyte separation and selective ion transport in Mg-RSBs, even though it cannot be applied directly. In addition, the simulated Pourbaix diagram for seawater at 25 °C (Figure 2(b)) indicates that hypochlorite (ClO^-) formation may occur near neutral pH during

charging, although the oxygen evolution reaction remains thermodynamically more favorable [16].

In general, alloying strategies are a known approach to increase the electrochemical activity and corrosion resistance of anodes in seawater batteries [19]. For example, the Mg–8Al–0.4Bi. It was reported that alloys have better corrosion and electrochemical performance than either pure Mg or Mg–8Al [20]. During discharge, the in situ-formed $Mg_{17}Al_{12}$ and BiOCl secondary phases act as a disruptive glaze over the passive $Mg(OH)_2$ layer, thereby improving surface activity and augmenting anode utilization efficiency [20]. Although Mg offers high volumetric capacity and is naturally abundant, it still faces several fundamental challenges when used in rechargeable battery systems. Unlike monovalent alkali metals, divalent Mg^{2+} can diffuse through solid materials and across interfaces at much slower rates than the comparable atomic species, resulting in a significantly slower reaction kinetics. Moreover, the formation of a passivation layer or solid electrolyte interphase (SEI) on the Mg anode surface is still one of the critical factors that limits its development, because it generally inhibits Mg^{2+} migration and decreases interfacial stability [11][12].

Cathode material development is also critically important for improving energy density and cycling stability in Mg-based systems. An extensive range of cathode materials, such as transition-metal oxides and other intercalation hosts, has been studied for rechargeable Mg batteries [11][18]. However, unlike monovalent-ion systems, cathode selection is more fundamentally challenging in Mg-based systems due to Mg^{2+}'s divalent nature, which generates stronger electrostatic interactions within the crystal lattice. This stronger interaction tends to slow Mg^{2+} ion diffusion and charge transfer at the electrode–electrolyte interface [11]. Accordingly, in Mg-RSBs, cathode development should not only focus on capacity enhancement but also on host materials that allow more effective and stable transport of Mg^{2+} [11][18].

In addition, to better understand the performance of Mg-RSBs, the role of seawater as the catholyte on the cathode side must also be considered. During discharge, dissolved oxygen (DO) from the air participates in the oxygen reduction reaction (ORR), whereas during charge, the oxygen evolution reaction (OER) occurs [17]. It should be noted that oxygen in seawater functions as a reactant in ORR/OER processes rather than as a conventional solid-state cathode active material. Accordingly, the cathode operates primarily as an electrocatalytic interface, similar to that in metal–air battery systems. A schematic illustration of the ORR/OER reactions at the cathode of a Na-RSB system is shown in Figure 3. Although the figure

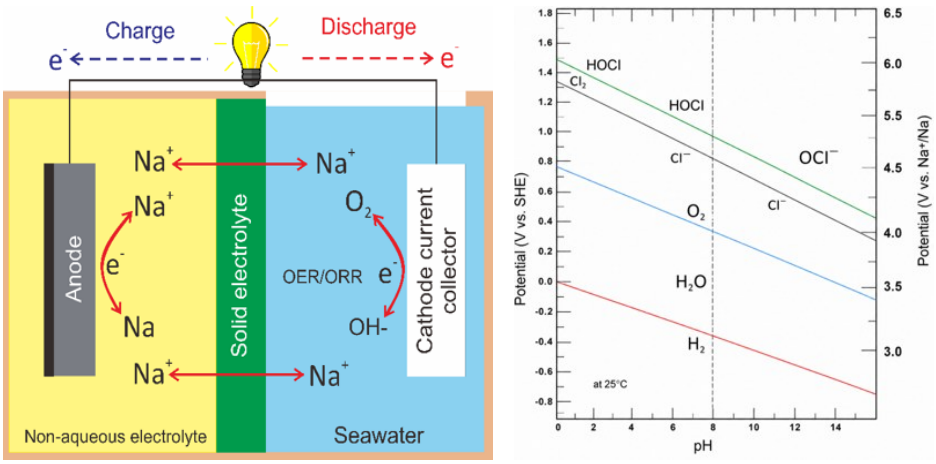

Figure 2. (a) Schematic adapted from a sodium-based RSB system, illustrating a dual-compartment design with a metal anode (originally Na) in NAE, separated from a seawater catholyte by a solid ceramic electrolyte. Although the original system is sodium-based, the ion migration and compartment separation principles are relevant to Mg-based configurations. (b) Simulated Pourbaix diagram of seawater at 25 °C, indicating possible formation of oxidative species such as ClO^- at near-neutral pH during charging. Adapted from Senthilkumar et al. [16].

was originally constructed based on a sodium-based system, it remains relevant as a conceptual reference for understanding cathodic reactions in Mg-RSBs, since the reaction pathway involving dissolved O_2 in the seawater catholyte is not directly determined by the anode material. Therefore, Figure 3 is used in this review as a general illustration of the cathodic reaction mechanism, rather than as a specific representation of Mg-RSB cell design or anode materials [17].

Seawater, as a natural catholyte, also serves as an ionic medium for redox reactions at the cathode surface. Its ionic composition mainly consists of Na^+, Ca^{2+}, K^+, Mg^{2+}, SO_4^{2-}, and Cl^-, with a total dissolved solids content of approximately 35–36 g L^{-1} [16][21]. The concentrations of these major ionic species are presented in Table 1. In the context of Mg-RSBs, this composition has important implications. On the one hand, the high salinity of seawater supports ionic conductivity in the catholyte; on the other hand, the high Cl^- content creates an aggressive environment for the Mg anode, which can accelerate localized corrosion, disrupt interfacial stability, and reduce coulombic efficiency as well as cycling performance [11][12]. Therefore, the chemical characteristics of seawater must be considered carefully when Mg is used as a host material in RSB systems. In summary, the cycling performance of Mg-RSBs is strongly influenced by three main aspects: (1) the instability of the Mg anode and its tendency toward surface passivation, (2) the still limited performance of ion-selective separators or solid electrolytes for Mg^{2+}, and (3) the aggressive nature of the Cl^--rich seawater catholyte toward cell components. Considering these factors, the following sections of this review discuss in greater detail the strategies required to improve anode, cathode, electrolyte, and separator materials in order to address these challenges in Mg-RSB systems.

3. FUNDAMENTALS OF WORKING PRINCIPLE

It has been explained that RSBs operate through a dual-electrolyte system that combines non-aqueous and aqueous phases, thus enabling selective ion transport and stable redox reactions. This section describes the primary electrochemical processes that underpin the operation of RSBs, including the overall reaction mechanism, the behavior of sodium-based anodes, and the cathode reaction with seawater. This section also discusses the potential of Mg as a candidate replacement for sodium in RSBs, along with its main challenges, including the unavailability of Mg^{2+}-selective solid conductors and the limited availability of compatible non-aqueous electrolytes.

3.1. Overall Electrochemical Mechanism

Rechargeable seawater batteries typically employ a dual-chamber configuration, in which a solid ceramic ion-conducting membrane physically isolates the anode and cathode regions. In most designs, NASICON is used as the separator owing to its high ionic conductivity for Na^+ [17]. The anode compartment is filled with non-aqueous electrolytes, along with a sodium metal electrode, while the cathode compartment contains the current collector interacting directly with seawater (catholyte). In this configuration, Na^+ ions can transfer from the seawater compartment to the anolyte while overall charge neutrality is being preserved in the cell. This configuration is well described in multiple reports on sodium-based RSBs exhibiting robust cycling behavior and has attractive energy conversion performance [19][22][23].

During discharge, metallic sodium at the anode undergoes oxidation to form Na^+, releasing electrons in the process. Concurrently, dissolved oxygen in seawater undergoes electrochemical reduction at the cathode through the ORR, hence maintaining the overall cell reaction. During the charging phase, the process is reversed: Na^+ ions are electrochemically redeposited at the anode as metallic sodium, while hydroxide species at the cathode undergo the OER. The main electrochemical reactions of sodium RSBs are as follows Equations (1) - (5). This system has several practical advantages, such as the ready availability of resources, low material costs, and applicability to remote or off-grid applications [19][22]. But changes in the Na^+ concentration of seawater can modify the ionic conductivity connecting compartments. In addition, the Cl^--rich sea-air environment must be considered, as it can affect the

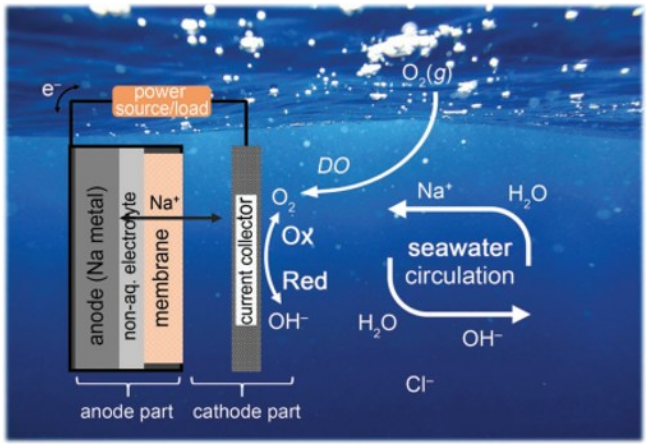

Figure 3. Conceptual schematic illustrating cathodic oxygen reduction and evolution reactions (ORR/OER) in a seawater-based electrochemical system. While the figure is adapted from a sodium–seawater battery, it is used here exclusively to visualize cathodic mechanisms relevant to RSBs employing seawater as the catholyte. The anode labeling refers to the source system and does not reflect the Mg-based anode configuration discussed in this manuscript. Reproduced with permission from Hwang et al. [17].

stability of the interface and the kinetics of cathodic reactions in the long term [17].

Anode (Na) reactions:

Charging : $4Na^+ + 4e^- \rightarrow 4Na$ **(1)**

Discharging : $4Na \rightarrow 4Na^+ + 4e^-$ **(2)**

Cathode (Oxygen) reactions:

Charging : $4OH^- \rightarrow O_2 + 2H_2O + 4e^-$ **(3)**

Discharging : $O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$ **(4)**

Overall Cell Reaction (Discharging):

$4Na + O_2 + 2H_2O \rightarrow 4NaOH$ **(5)**

To date, the concept of Mg-based rechargeable seawater batteries remains far less mature than that of sodium-based systems. This is primarily due to the absence of Mg^{2+}-selective solid conductors comparable to Na^+-conducting solid electrolytes such as NASICON, as well as the still limited availability of non-aqueous electrolytes capable of supporting reversible and stable Mg redox reactions [17]. Therefore, sodium-based RSBs remain an important conceptual reference for the development of Mg-RSB designs. Multiple concepts have been proposed to replace Na with Mg as the active anode material. However, these approaches require the development of new separators and chemically compatible non-aqueous electrolytes that can efficiently facilitate Mg^{2+} transport while remaining electrochemically stable. Therefore, the presentation of sodium-based RSB mechanisms in this section is intended to serve as a theoretical foundation and systematic point of comparison for the conceptual design of Mg-based RSB systems, rather than as a direct description of experimentally established Mg-RSB configurations.

3.2. Anode Reaction

The anode plays a central role in battery systems, including RSBs. In contrast to primary seawater batteries, in which Mg acts as the active material that is permanently consumed by oxidation, Mg in the context of RSBs is more appropriately regarded as a host material, namely as part of an alloy or inorganic compound that stabilizes the electrochemical process. Several studies on SIBs are used here as a conceptual comparison rather than as a direct demonstration of Mg-RSB anodes. These studies show that Mg-based spinel oxides can stabilize anode structures during Na^+ storage. For example, $MgFe_2O_4$/rGO composites have been identified as potential anodes for SIBs. Their electrochemical capacity is mainly governed by the Fe^{3+}/Fe^0 redox couple. In this system, Mg does not serve as the primary redox center. Instead, it acts as a structural element that reinforces the anode framework. The system showed a reversible capacity of about 347.5 mAh g^{-1} after 70 cycles at a current density of 50 mA g^{-1} [24].

A similar electrochemical behavior was also observed during the development of $MgFe_2O_4$ hollow microboxes synthesized via a metal–organic framework (MOF) derivative approach. This system exhibited an initial capacity of approximately 406 mAh g^{-1} at a current density of 50 mA g^{-1} and still maintained a capacity of 135 mAh g^{-1} after 150 cycles. The voltage profile further confirmed that Fe serves as an electrochemically active redox center, while Mg functions as an inert structural host that maintains the mechanical stability of the anode [25]. Another study evaluated Sn- and Mg-doped $GeFe_2O_4$ spinels as potential anodes for sodium-ion batteries. In this system, Na^+ storage occurs mainly at Fe and Ge sites. Partial substitution of Ge^{4+} by Mg^{2+} does not directly boost capacity. However, it improves structural stability and helps suppress degradation during cycling. Although Mg-doped $GeFe_2O_4$ performs worse electrochemically than the Sn-doped version, Mg's role as a structural host is key to mitigating cyclic degradation [26].

These findings align with a recent study of SIB anodes, which highlights that transition-metal-based ferrites predominantly function via a conversion mechanism driven by the redox activity of the transition-metal core. Concurrently, secondary elements, such as Mg, remain electrochemically inactive and serve as structural hosts [3]. This comprehension strengthens the assertion that, in $MgFe_2O_4$-based composites, the electrochemical capacity predominantly originates from the Fe^{3+}/Fe^0 transition, whereas Mg fortifies the spinel structure and mitigates structural deterioration during successive cycling. Overall, these examples are more appropriately regarded as analogous evidence of how Mg can function as a structural host that stabilizes anode materials in Na^+ storage systems, rather than as direct demonstrations of anodes for Mg-RSBs. Accordingly, these findings provide an important conceptual foundation for the design of Mg-based anodes in RSBs, particularly by positioning Mg as a structural-stabilizing element while the primary electrochemical capacity remains provided by other active redox centers, such as transition metals or conductive carbon components.

3.3. Cathode Reaction

In the conceptual design of Mg-RSBs, the cathode is expected to operate in direct contact with seawater, where the ORR during discharge is strongly influenced by DO concentration and seawater chemistry. Compared with sodium-based RSB architectures, the development of Mg-RSBs is expected to face additional challenges. These challenges do not primarily indicate that the cathodic mechanism is fundamentally different, but rather that cathode performance must remain stable within an overall system that becomes more complex when coupled with a Mg anode, a solid separator, and a non-aqueous anolyte. In addition, the lack of a well-established cathode configuration for Mg-RSBs makes the study of cathode design, catalyst selection, and interfacial stability in seawater environments particularly important.

Furthermore, when viewed from the ORR during the discharging process, the system also experiences overpotential losses that limit the reaction rate and electron transfer efficiency. To overcome this obstacle, various studies have focused on catalytic materials—ranging from carbon-based structures to transition metal oxides, nitrides, and carbides—that can enhance ORR activity and reduce overpotential [27][28]. Catalyst selection is crucial for enhancing electrochemical reactivity, increasing cycle efficiency (round-trip efficiency), and minimizing side reactions in chloride-rich marine environments [12][29]-[34].

One of the main goals of cathode engineering is to develop bifunctional catalysts. These catalysts must efficiently facilitate the ORR during discharge and the OER during charge. At the same time, they should remain resistant to chloride-induced degradation and surface passivation [28]-[33]. In this context, cathode surface protection strategies do not regulate the transport of the primary ionic species between compartments. Instead, they preserve ORR/OER activity, suppress chloride-induced degradation, and maintain cathode surface stability during long-term cycling. Protective coatings that prevent aggressive species like Cl^- from being absorbed at the active cathode surface have demonstrated good potential. They also play a role in stabilizing the cathode during long-term operation [34]-[37]. When combined with electrolyte systems containing corrosion-inhibiting additives, these protective strategies also reduce parasitic side reactions and improve battery lifetime

[12][29][30][33][38][39].

Although most cathode-related studies in RSB research have focused on sodium-based configurations, the core challenges—such as sluggish oxygen reaction kinetics, catalyst degradation induced by chloride species, and the long-term stability of bifunctional catalysts—remain highly relevant to the development of Mg-RSBs. However, these findings are more appropriately regarded as sources of cathode design insight rather than as direct evidence that the same cathode configurations can be applied to Mg-RSBs without modification. In this context, studies on cathodes for rechargeable Mg batteries, including intercalation-type systems [40], conversion chemistries [41], and organic material platforms [23], can provide important guidance for material and system design. Therefore, cathode development for Mg-RSBs should focus on identifying configurations that maintain ORR/OER activity, resist chloride-rich marine environments, and remain compatible with the dual-electrolyte architecture characteristic of RSBs, rather than simply adopting cathode designs from other sodium - or Mg-based systems.

4. RECENT ADVANCES IN ANODE, CATHODE, AND ELECTROLYTE MATERIALS FOR RSBS

RSBs have been recognized as promising candidates for sustainable power storage systems, particularly in marine environments and off-grid applications. In Mg-RSBs, the overall cell performance is strongly governed by how the anode material is selected and engineered. Nevertheless, this battery concept is still at an exploratory stage, as further progress is hindered by severe Mg corrosion and the build-up of insulating surface films that block charge transport. In addition, using Mg as the active metal requires a rethinking of cathode and electrolyte design so that they remain stable in seawater while still being compatible with the non-aqueous anode compartment. Insights into cathode and electrolyte engineering from sodium-based RSB research are highly relevant to address these challenges in Mg-based architectures.

4.1. Advances in Anode Materials

Progressive work has contributed to the progress of Mg-RSBs, especially in the anode material field of Na-RSBs. Direct use, however, is difficult because of the different electrochemical nature of Mg^{2+} relative to Na^{+}, such as higher desolvation energy and strong surface passivation tendency. Accordingly, despite many of the approaches presented in this section being influenced by the study of Na-RSBs, adopters should carefully reconsider their use for Mg-RSB and possibly adapt them to meet the electrochemical demands of Mg. Anode is the most influential factor on battery performance in general, also in RSBs, for which they are crucial to energy density, cycle stability, and the overall electrochemical efficiency. Mg is

Table 1. Presents the standard seawater composition at a salinity level of 36,000 ppm (or 36 g/L) [21].

No.	Compound	Composition	Mass Percentage (%)	ppm
1.	Chloride	Cl^{-}	55.03	19810.8
2.	Sodium	Na^{+}	30.61	11019.6
3.	Sulfate	SO_4^{2-}	7.68	2764.8
4.	Magnesium	Mg^{2+}	3.69	1328.4
5.	Calcium	Ca^{2+}	1.16	417.6
6.	Potassium	K^{+}	1.16	417.6
7.	Carbonate	CO_3^{2-}	0.41	147.6
8.	Bromine	Br^{-}	0.19	68.4
9.	Boric Acid	H_3BO_3	0.07	25.2
10.	Strontium	Sr^{2+}	0.04	14.4
	Total		100	36000

one of the most attractive anode options because of its high volumetric capacity, low cost, and abundance in common resources. However, its practical application is yet limited due to problems with surface passivation, dendritic formation, and high corrosion rates in both aqueous/non-aqueous environments. In general, research on anode materials for Mg-RSB is inspired by that for Na-RSB. Although advances in materials design are necessary, targeted adaptation is still needed to overcome passivation, corrosion, and ion-transport limitations, as described in the following subsections.

4.1.1. Pure Magnesium and Commercial Alloys

Advancements in anode materials can be achieved through two principal approaches: optimizing the processing of pure Mg and developing Mg-based alloys. The Mg–Sn alloy system, has been extensively studied and commercially commercialized. The additional refinement of this technique, especially utilizing 14 wt% Sn has apparently resulted in substantial performance enhancements. This results from the development of a eutectic structure evenly dispersed between the α-Mg and Mg_2Sn phases [42]. In the context of anode development for Mg-RSBs, these findings indicate that modifying the alloy composition is a promising strategy to improve the microstructural stability and electrochemical behavior of Mg. Therefore, studies on pure Mg and commercial Mg-based alloys remain an important foundation for designing Mg anodes that are more stable and better suited for rechargeable seawater battery systems.

4.1.2. Mg-Based Binary and Ternary Alloys

The design of binary and ternary Mg-based alloys has emerged as an important approach to address the inherent weaknesses of pure Mg anodes, including rapid corrosion, dendrite growth, and passive layer formation that inhibit electrochemical behavior. The most investigated systems in literature include the Mg–Sn, Mg–Bi, Mg–Al, and Mg–Ca–In, as well as the Mg–Zn–Y; each of these shows a specific mechanism for engineered performance enhancement [42]-[44]. To our knowledge, research initiatives directly focused on RSB applications for Mg alloys are scarce. Therefore, the discussion in this section also draws on findings from MIBs and RMBs as relevant sources of comparative insight. MIB/RMB systems employ non-aqueous anolytes with physicochemical properties similar to those of the electrolytes used in the anode compartment of RSBs [45]. Similar to the design of Mg-RSBs, issues observed in MIB/RMB systems, such as passivation, interfacial degradation, and electrolyte compatibility, are also encountered [45]-[47]. Accordingly, Mg alloy materials and electrolyte systems reported in MIB/RMB studies may be regarded as useful conceptual references for the development of Mg-RSBs, although their performance still requires further evaluation within actual RSB architectures [46]-[48].

Among binary Mg-based alloys, Mg-Sn compositions are particularly leading candidates for tuning the anode characteristics of non-aqueous systems. When the Sn content is increased to 14 wt%, a eutectic microstructure is formed in excess of Mg_2Sn and α-Mg: α-Mg helps homogenize current distribution, while Mg_2Sn facilitates reduced local concentration gradients and suppresses dendrite formation during repeated electrochemical cycling [44]. The formation of these phases has been confirmed by XRD patterns and optical micrographs (Figure 4(a) – (c)), while SEM observations (Figure 4(d) – (e)) reveal a morphology that remains stable during prolonged cycling [44]. The Mg_2Sn phase reinforces the mechanical integrity of the alloy, increases the effective active surface area, and supports a more uniform distribution of charge transfer at the electrode–electrolyte interface [44]. These advantages are consistent with the general discussion of alloy-anode behavior in MIB/RMB systems, thereby supporting the consideration of Mg–Sn alloys as relevant candidates for further investigation in Mg-RSB designs [46][47].

On the other hand, binary Mg–Bi alloys also show promise for improving interfacial stability. For example, a Bi–Sn@SnO_2 composite anode exhibited a reversible capacity of 148 mAh g^{-1} at 1 A g^{-1} after 300 cycles, along with a good rate performance of 297 mAh g^{-1} at 500 mA g^{-1} [43]. The Bi–Sn/SnO_2 nanostructured interface effectively reduced the voltage polarization to 0.065 V and lowered the charge-transfer resistance from

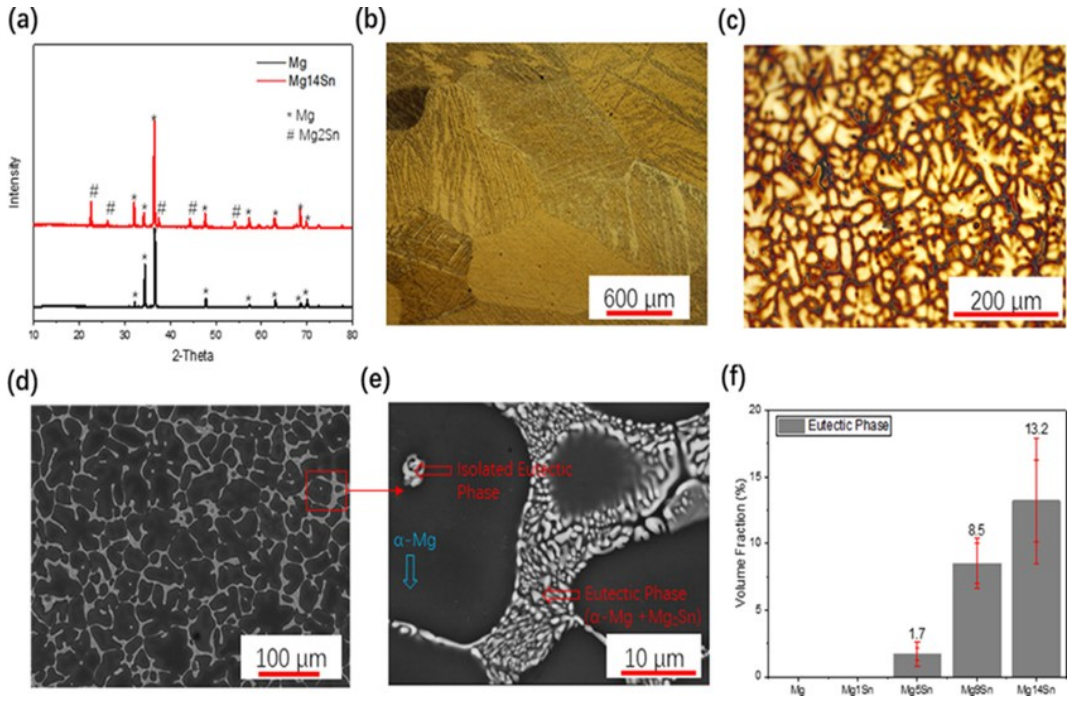

Figure 4. (a) X-ray diffraction (XRD) spectra comparing Mg and Mg–14 wt% Sn alloy, illustrating the phase composition. Optical micrograph depicting the surface morphology of (b) pure Mg and (c) magnesium–14 wt% tin alloy, highlighting the formation of a eutectic phase. Scanning electron microscopy (SEM) images presenting the (d) microstructural characteristics and (e) phase distribution within the Mg–14 wt% Sn alloy. (f) Quantitative analysis of the eutectic constituent fraction within Mg-Sn compositions, showing variations in volume fraction. Reproduced with permission from Chen et al. [44].

5989 to 22.15 Ω, indicating improved Mg^{2+} transport kinetics [43]. This improvement has been attributed to the in situ formation of nanoporous Bi and Mg_3Bi_2/Mg_2Sn intermetallic phases, which stabilize the solid–electrolyte interphase (SEI) and suppress passivation [43]. These findings are consistent with the general discussion on the importance of alloy-type anodes in mitigating interfacial limitations in RMB systems [46][47].

With regard to commercial binary alloys, Mg–Al alloys (e.g., AZ31 and AZ80) are probably the best known and easiest to process. However, when applied in environments containing 3.5 wt.% NaCl, these alloys tend to exhibit limited anodic utilization due to the formation of surface products that hinder further electrochemical reactions. In this regard, different improvement techniques like rare-earth doping and grain refinement have been reported to improve the discharge performance and anodic efficiency of Mg–Al alloys in chloride-containing systems [44]. These strategies align with the broader discussion on optimizing anode materials in rechargeable Mg battery systems, thereby providing an additional basis for considering their relevance to future Mg-RSB designs [46][47].

Turning to ternary alloys, systems based on Mg–Ca–In have a lot of promise for making Mg anodes work better, especially in electrolyte solutions. For example, the Mg–0.1Ca–0.2In alloy, developed through a synergistic microalloying approach, was reported to exhibit an anodic efficiency of 80.2% and an energy density of 2259 Wh kg^{-1} at a current density of 5 mA cm^{-2} [49]. Furthermore, SEM images and elemental mapping (Figure 5) confirmed a uniform phase distribution across the anode surface [49]. This enhanced electrochemical performance arises from the combined effects of calcium and indium: calcium stabilizes the Mg matrix and reduces the chunk effect, while indium undergoes redeposition during discharge, thereby inducing localized surface activation via microgalvanic interactions. Consequently, wasteful discharge can be suppressed, passive surface-film formation is reduced, and the negative difference effect (NDE) can be effectively mitigated [44][49].

Taken together, these findings provide a relevant basis for considering Mg–Ca–In alloys in the development of Mg-RSB anodes; however, further evaluation in actual RSB architectures is still required [47][48].

The Mg–Zn–Y alloys also exhibit improved electrochemical performance through grain-boundary engineering and the addition of rare-earth elements in ternary Mg-based alloys. The performance enhancement was obtained at 3.5 wt.% NaCl environment showing better corrosion resistance and discharge performance than some commercial Mg alloys, which was attributed to the formation of thermally stable phases and microstructural refinement that suppresses local galvanic corrosion [44]. Moreover, some characteristic phases within the Mg–Zn–Y system, including quasicrystalline phases or long-period stacking ordered (LPSO), were claimed to promote discharge reversibility and facilitate surface products desorption [44]. These findings provide a relevant basis for the design of corrosion-resistant alloys in seawater-like environments and may serve as an initial reference for the development of Mg-RSBs, although further evaluation in actual RSB architectures is still required [46][48].

4.1.3. Magnesium Anodes with Functional Protective Coatings

Several recent studies have investigated the use of functional protective coatings to improve performance parameters, such as coulombic efficiency, charge-transfer resistance, and cycling stability, and to suppress interfacial instability and corrosion in Mg-based anodes for related battery systems. In the context of this review, these strategies are considered relevant sources of design insight for the development of Mg-RSBs, although most available evidence still originates from non-RSB Mg battery systems. This approach has been tested on both pure Mg and several alloys, including Mg–Sn, Mg–Bi, and Mg–Ca–In. The reported coating materials include SnO_2, graphene, NaF, and various other inorganic fluorides and phosphates [44][50].

Recently, very important results were obtained in coating strategies using Bi–Sn@SnO_2 composites. The SnO_2 nanolayer serves as a protective interfacial layer, stabilizing the anode surface while suppressing parasitic side reactions. This configuration has been reported to reduce the overpotential by 27.4% and decrease the charge-transfer resistance from 5989 to 22.15 Ω. In addition, the composite anode exhibited a reversible capacity of 148 mAh g^{-1} at 1 A g^{-1} after 300 cycles, as well as a capacity of 297 mAh g^{-1} at 500 mA g^{-1} during rate testing [44]. This performance enhancement has been attributed to the formation of nanoporous Bi structures and Mg_3Bi_2/Mg_2Sn intermetallic phases, which help stabilize the interfacial layer and reduce the tendency toward passivation. In this context, the primary function of the coating is not merely to act as a passive barrier, but also to regulate the evolution of the surface structure during electrochemical cycling.

In addition to oxide-based coatings such as SnO_2, Li et al. [50] proposed other stable inorganic films, including MgF_2, $Mg(PO_3)_2$, and MgP_4O_{11}, as surface layers for non-aqueous systems. These materials are chemically stable, conduct ions well, and can allow Mg^{2+} to move through defects, all of which may help stabilize anode surfaces. These coatings block electrolyte damage and can guide Mg^{2+} movement through specific defect sites. For example, MgF_2 coatings have been shown to reduce resistance and help the anode maintain a steady voltage by stabilizing the surface layer. However, their suitability for Mg-RSBs still needs more study, especially since their performance could be affected by interactions with both the solid separator and the seawater catholyte in these batteries.

4.1.4. Magnesium Anodes with Nanostructured Surface and Grain Control

There is an increasing interest in microstructural engineering techniques for Mg-based anode candidates in RSB applications to enhance their electrochemical performance. These methods include controlling the crystallographic orientation, changing the surface topography, and applying nanocoating strategies to pure Mg, commercial alloys (like AZ80 and AP65), and ternary systems like Mg–Zn–Y and Mg–Bi [43][44][49][51][52]. One recent strategy is the application of a superhydrophobic Mg–Al LDH coating intercalated with MoO_4^{2-} and modified with lauric acid (LA). This coating provides excellent corrosion

protection, with the corrosion current density ($i_{(corr)}$) decreasing from approximately 15.29 $\mu A \cdot cm^{-2}$ in uncoated AZ31 alloy to ~1.7 × 10^{-3} $\mu A \cdot cm^{-2}$, as well as an increase in the charge transfer resistance (Rct) from 2.65 × 10^3 to 4.56 × 10^6 $\Omega \cdot cm^2$ in 3.5 wt.% NaCl solution [51]. This improvement is attributed to the synergistic effect between the Mg–Al LDH layered barrier and the ion exchange capability of MoO_4^{2-} that limits Cl^- penetration and promotes the formation of a more stable corrosion product layer. Although the results show a corrosion inhibition efficiency of up to ~99.99% against bare AZ31, this value is valid only for static tests in 3.5 wt.% NaCl solution and has not been tested in the RSB configuration. Furthermore, controlling the crystallographic texture can help reduce local corrosion and hydrogen evolution. The results of the examination using electron backscatter diffraction (EBSD) and scanning Kelvin probe force microscopy (SKPFM) showed that grains with the (0002) orientation are more resistant to corrosion than the (10–10)/(11–20) orientation [44][52]. Various microstructural and surface characterization techniques used to evaluate Mg-based anodes, including grain-size analysis, SEM, EBSD, TEM, three-dimensional surface reconstruction, XPS, and SKPFM, are summarized in Fig. 6.

4.1.5. Alternative Anode Candidates

Mg and its alloys remain widely studied as promising anode candidates for seawater-based RSB designs due to their abundance and high volumetric capacity. Therefore, improvements are needed, particularly regarding interfacial stability, dendrite growth suppression, and compatibility with seawater-based electrolytes. Recently, one of the widely studied Sn-based anode systems in Mg batteries, and potentially providing design inspiration for RSB anode candidates, is the Bi–Sn@SnO_2 composite anode, which integrates the Bi–Sn intermetallic phase with a nanostructured SnO_2 surface layer. The electrochemical test findings indicated a reversible capacity of 314 $mAh \cdot g^{-1}$ at 50 $mA \cdot g^{-1}$, an exceptional rate performance of 297 $mAh \cdot g^{-1}$ at 500 $mA \cdot g^{-1}$, and significant cycle

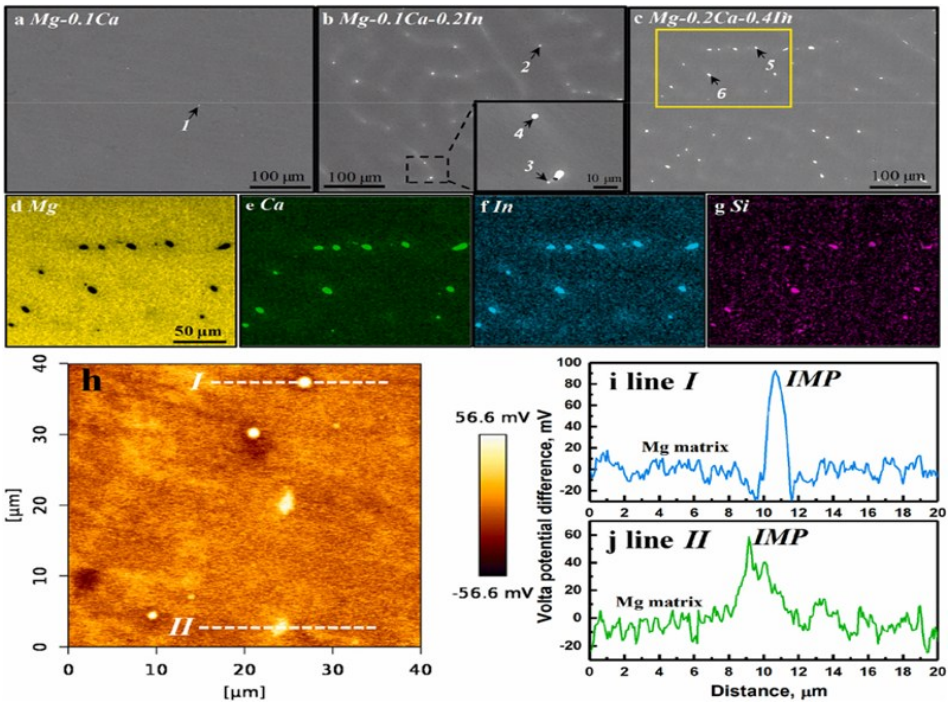

Figure 5. SEM images illustrating three different Mg alloys, where images (a–c) display their distinct microstructures. Elemental mapping results for the highlighted region in image (c) of the Mg–0.2Ca–0.4In (wt%) alloy are presented in images (d–g). Image (h) provides the Volta potential distribution for the Mg–0.1Ca–0.2In (wt%) alloy, as obtained via the SKPFM technique. Meanwhile, images (i) and (j) illustrate the Volta potential variations measured along lines I and II, respectively. Reproduced with permission from Deng et al. [49].

stability with a capacity of 148 mAh·g^{-1} at 1 A·g^{-1} after 300 cycles [43]. This system also exhibited a 27.4% reduction in overpotential and a substantial decrease in charge-transfer resistance, from 5.989 to 22.15 Ω, confirming a significant improvement in Mg^{2+} transport kinetics and interfacial conductivity. Similar interfacial advantages in Bi- and Sn-based alloy systems have been observed in research on non-aqueous Mg batteries, where nanostructuring and intermetallic phase engineering have accelerated Mg^{2+} diffusion [45][47]. These investigations demonstrate that advanced interface engineering techniques, like oxide coatings, intermetallic phase design, or heteroatom-doped carbon matrices, can significantly enhance the electrochemical performance of seawater-utilizing devices. Although ionic incompatibility and manufacturing scale remain challenges for non-Mg systems, research on RSBs and Mg batteries more generally provides valuable insights into producing hybrid or multifunctional anodes with appropriate interfacial properties.

4.2. Advances in Cathode Materials

Cathode materials for Na-RSB have undergone extensive development to enhance ORR, improve round-trip efficiency, and reduce degradation in chloride-rich seawater environments. These studies offer significant design foundations for the ongoing development of Mg-RSB designs; however, their direct application necessitates further considerations—specifically to ensure the compatibility of the two-electrolyte system, avert galvanic coupling between the Mg anode and cathode when exposed to seawater, and tackle variations in interfacial chemistry and operational potential ranges.

In the context of Mg-RSB development, the cathode is expected to play a crucial role in system performance and lifetime, as it must efficiently catalyze ORR during discharge and OER during charging in chloride-rich seawater [53][54]. A major problem in cathode engineering is the large overpotential difference between ORR and OER. This not only reduces the effectiveness of cycling but also wears down the electrodes more quickly. For example, ordinary carbon-based current collectors usually have overpotentials of more than 1.4 V, which can produce parasitic reactions and make cycling behavior hard to predict.

Many efforts in the last few years have tried to close this gap and make catalytic durability better. One noteworthy example is the development of a bifunctional Pt–Co alloy catalyst utilizing the carbothermal shock (CTS) approach, which achieved an overpotential gap of only 1.02 V and sustained steady operation for over 500 h in genuine seawater at a current density of 0.25 mA cm^{-2}. This performance was due to the optimized oxygen adsorption energy (ΔG^*_o = 2.34 eV) and the uniform dispersion of nanoparticles over a scalable electrode surface (up to 16.5 × 12 cm²). These results demonstrate the strong practical potential of the catalyst for seawater-based energy storage systems [53]. Simultaneously, density functional theory (DFT) modeling has identified Mg-based spinel sulfides (MgB_2S_4, where B = Sc, Y, or Lu) with a broad electrochemical stability range (up to 1.8 V vs. Mg/Mg^{2+}) and minimal Mg^{2+} migration barriers (<0.45 eV). Consequently, these materials are regarded as promising candidates for cathode materials in forthcoming hybrid and fully solid-state Mg-RSB designs [54]. Overall, cathode design development for Mg-RSBs demands materials capable of maintaining bifunctional catalytic activity, resisting chloride-induced degradation, and maintaining a stable interface in a two-electrolyte configuration. The following subsections classify recent cathode developments into several categories, namely structured carbon, transition metal oxides, nitrides, sulfides, conductive polymers, perovskites, and MOFs, highlighting their performance metrics, durability, and associated challenges.

4.2.1. Carbon-Based Cathodes

As the corrosion resistance, high specific surface area and good redox activity of carbon based material in seawater electrolyte, carbon materials were a competitive cathode for RSBs [55]-[57]. The latest publications disclosed their catalytic activity, chloride anion tolerance and long cycling stability. Tubular carbon frameworks doped with nitrogen have exhibited strong ORR efficiency, obtaining the current density of −5.48 mA·cm^{-2}at −0.33 V vs. RHE, following a nearly ideal four-electron route [55]. However, the long-term electrochemical stability of this material still needs to be

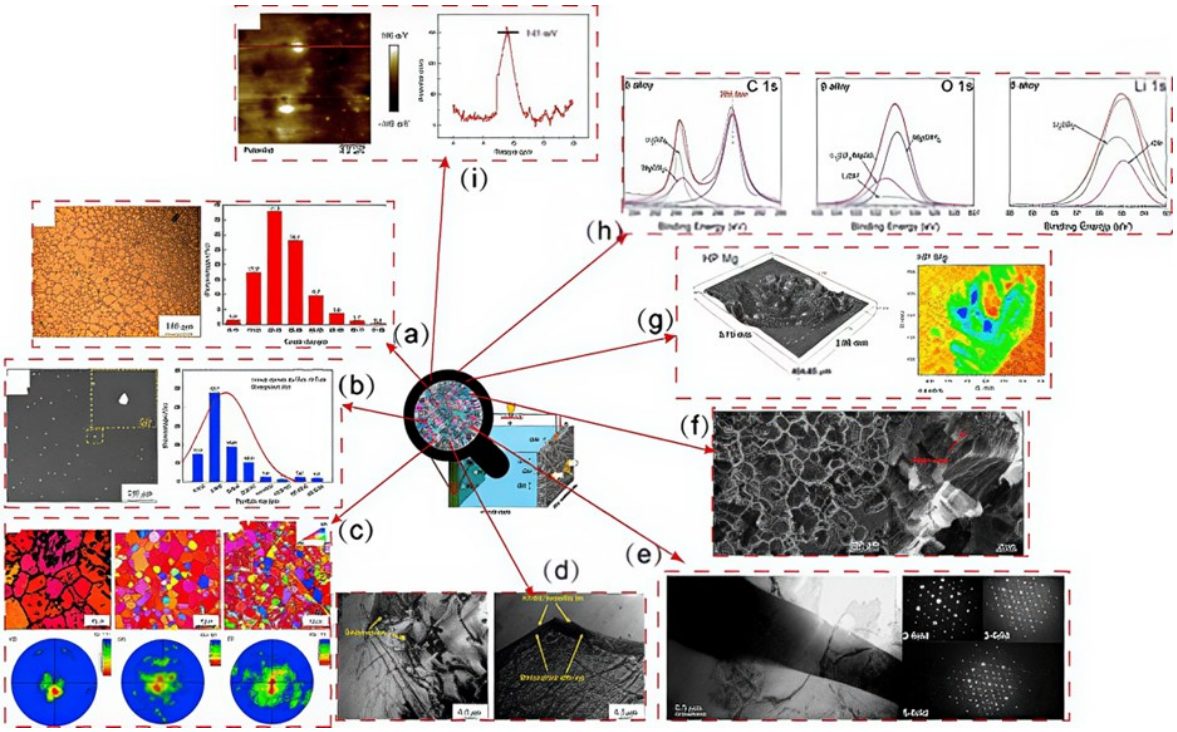

Figure 6. Various microstructural and surface characterization techniques applied to Mg anodes: (a) grain-size distribution of a rolled AP65 anode; (b) SEM image showing the particle morphology and size variation of an extruded AP65-RE anode; (c) EBSD and inverse pole figure (IPF) maps of Mg–Hg–Ga, showing texture evolution under different deformation processes; (d) TEM image of an extruded AP65-RE anode, showing grain boundaries and dislocations; (e) TEM image showing quasicrystal phases in a Mg–Zn –Y anode, accompanied by the corresponding selected-area electron diffraction (SAED) pattern; (f) surface morphology of an AZ80 anode after discharge and removal of the discharge products; (g) three-dimensional reconstruction showing the topographical features and depth distribution of a high-purity magnesium (HP Mg) anode after discharge; (h) XPS analysis showing the layered discharge products formed on a Mg–11% Li alloy anode; and (i) SKPFM map showing the surface-potential distribution measured along the red line on an extruded Mg–1% Bi anode. Adapted from the referenced studies and reprinted with permission from Elsevier [44].

investigated [58].

In addition, carbon-based substrates of commercial nature, such as carbon felt (CF), activated carbon cloth (ACC), and carbon paper (CP), have been widely used due to their mechanical robustness and good conductivity. The pyridinic-N was determined to be the major active site produced at 700 °C via XPS characterization, and in this case, nitrogen-doped ACC reached an overpotential of as low as 0.84 V and a power density of 9.66 mW cm² at 0.25 mA cm² in the simulated seawater electrolyte [59]. The same material showed a stable discharge voltage of around 1.3 V vs. Mg/Mg^{2+} for more than 30 cycles, with little drift [60]. In contrast, the CF presents a higher current density and better voltage stability than CP or Ni foam at ambient conditions in NaCl for ORR, due to its interconnected porosity and excellent wettability [61]. Bifunctional action of lignin- and biomass-feedstock-based porous carbon has also been shown to be successful. A hierarchically porous carbon showed an OER overpotential of 480 mV at 10 mA cm², with durability tested for more than 100 h [56]. The carbon-tuning channel structure was demonstrated to improve ion transport and enable fast redox kinetics in a saline environment [57].

More recently, sophisticated electronic modulation strategies, including heteroatom doping and electrical double-layer (EDL) engineering, have been reported to further enhance redox kinetics. N, S-doped carbon nanospheres derived from

melanosome-like structures showed improved activity towards ORR/OER with enhanced active site density and favourable charge distribution [62]. The integrated EDL-enabled effects and ORR/OER catalysis in the doped carbon fabrics decreased the potential gap to 0.49 V and raised EE to 86% in seawater electrolyte [63]. Carbon–metal hybrids have also been successfully pursued to improve bifunctional performance. A sulfur-doped rGO composite with CNTs and cobalt (S–rGO–CNT–Co) shows excellent voltage efficiency and cycle life in seawater [16]. Co–N/S/rGO hybrid catalyst realised 870 mV of half-wave potential for ORR, 320 mV of OER overpotential at 10 mA cm^{-2} with a peak power density of 67 mW cm^{-2} [64]. In the N-GC/Co@CoO/rGO system, the onset potential was 0.99 V, and it showed a better ORR durability than Pt/C [65]. In the spectrum of such hybrid forms, the resistance to chloride attack is also also relevant. Functional groups present on the carbon not only influence the electrochemical oxidation of chloride, but also affect its adsorption and corrosion. These materials exhibit good stability in NaCl-based electrolytes and in real seawater, without loss of redox activity or surface morphology upon cycling [66].

4.2.2. Transition Metal Oxides

To date, transition metal oxides, e.g., MnO_2 and Co_3O_4, have attracted significant attention as cathode materials for RSB due to their intrinsic bifunctional catalytic activity toward oxygen redox reactions and relatively stable performance in chloride-containing electrolytes. MnO_2 is extensively studied because it possesses abundant polymorphic forms (e.g., α-, β-, γ-, and δ-phases) with different tunnel or layered structures for Mg^{2+} insertion (Figure 7). An α-MnO_2, which has 1D diffusion channels (ca. ~5 Å), the electrochemical measurements of which suggest that for Mg^{2+} storage, its performance is also affected by the surface area rather than only the crystal phase [50]. Additional DFT studies indicated that the main Mg^{2+} intercalation behavior adopts a conversion-type reaction, and not through the Mg_xMnO_2 intercalation phase, attributable to strong binding between O^{2-} ions and Mg^{2+} cations [50]. Nevertheless, excavations into these deep magnesia levels often result in tunnel collapse and amorphization, which are detrimental to long-term structural stability. Theoretically, MnO_2 has recently shown the ORR onset potential of 0.82 vs RHE and the OER current density of 10 mA·cm^{-2} at an overpotential of 420 mV in seawater-based electrolyte, which further proves its bifunctional catalytic activity [16]. The RCA also increases the initial capacity, which means that surface area scaling is important [50].

On the other hand, Co_3O_4 also exhibits attractive ORR/OER catalytic performance, it is prone to degradation in chloride-rich solutions. The OER activity decreased by 23% after 100 cycles in 0.6 M NaCl solution, predominantly due to surface detachment and particle aggregation [22]. Repeating the cycling process causes severe morphological damage and deformation, and, over time, a drop in catalytic stability owing to insufficient substrate support and a lack of interfacial enhancement. Related work also indicates that such oxides need to be structurally stabilized to approach suitability for marine operating conditions [63]. Additionally, to sustain improvements in performance, emerging engineering strategies have been employed: nanosheet morphology, mesoporous structure, and hybridization with conductive carbon scaffolds [16]. What's more, increase of electroactive surface area, decrease of Mg^{2+} diffusion distance and mitigation of volume expansion during the redox process are arose from these combination. Among others, co-doping with V_2O_5 or NiO into MnO_2 has been found to alleviate the redox heterogeneity and retard capacity fade at high cycles [50].

4.2.3. Transition Metal-Based Catalysts and Prussian Blue Analogues (PBAs)

To address the limitations of carbon cathodes regarding performance and durability, alternative materials such as Prussian Blue Analogs (PBAs), Ag/AgCl-based electrodes, and transition metal-based catalysts have been developed to enhance redox kinetics and expand the accessible electrochemical potential range while ensuring stability in marine environments [67]-[70]. Nickel hexacyanoferrate (NiHCF) is a very promising PBA because it has an open framework, can take in and release Na^+ ions without changing its structure too much, and is stable in saltwater. In the seawater

battery with a Mg anode, for example, NiHCF delivers an output voltage of ~2.09 V and a peak power density of 161.2 mW cm^{-2}, serving as a key design guidepost for future rechargeable battery systems [67]. In the three-electrode cells, a high optimal value and relatively stable power density were shown during the temperature range of 0–40 ° C for NiHCF electrodes' capacity results, maintaining more than about 1000 and showing weak degradation, similar to others' NiHCF seawater battery performance over 1000 cycles.

The carbon felt-supported AgCl/Ag composite electrode (AgCl/Ag/CF) also had better initial activity. This cathode showed a specific capacity of 179 mAh g^{-1} and a discharge voltage plateau at 1.42 V, which are higher than the performance observed in pure AgCl, as compared to the AgCl/CF system [70]. Electrochemical impedance spectroscopy (EIS) measurements revealed that R_2 could reach as low as 0.26 Ω, much lower than that of the AgCl-based system alone (~1.2 Ω), thereby boosting conductivity and redox kinetics. These properties indicate the bifunctionality of AgCl/Ag/CF for ORR and OER in seawater batteries. Nevertheless, Ag/AgCl is not suitable for practical application owing to the high cost, low scaling-up ability, and structural breakdown during long-term cycling. Damage in the structure and depletion of Ag^+ during successive applications result in a diminished capacity retention and electrode instability [70]. Other non-poor metal frameworks, including PBAs and diverse TMOx/TMSy, have been intensively studied, which has eventually resulted in the low-cost preparation, modifiable ionic pathway, as well as high resistance to seawater electrolyte [67][69].

4.2.4. Nitrides and Sulfides

Metal nitrides and sulfides are increasingly used as alternative cathode materials in RSBs. This is mainly because they are highly conductive, corrosion-resistant, and can act as catalysts in environments with high chloride levels [16][22][50]. Researchers have extensively investigated metal nitrides, particularly Ni-based systems such as NiMoN@NiFeN, due to their exceptional stability and favorable ORR/OER kinetics in chloride-rich environments [66]. Moreover, as synthesized by Jia Yu et al. [71], the MOF exhibited substantial ORR activity with a stable response potential in alkaline conditions. An organomagnesium complex in a binary ionic liquid electrolyte system also had a coulombic efficiency of about 90% for Mg deposition/dissolution over 100 cycles. This demonstrates its high stability in ion-rich environments.

Layered metal sulfides, especially molybdenum disulfide (MoS_2), have a very polarizable S^{2-} anion framework that can be designed at the interlayer scale to speed up Mg^{2+} diffusion. This makes them

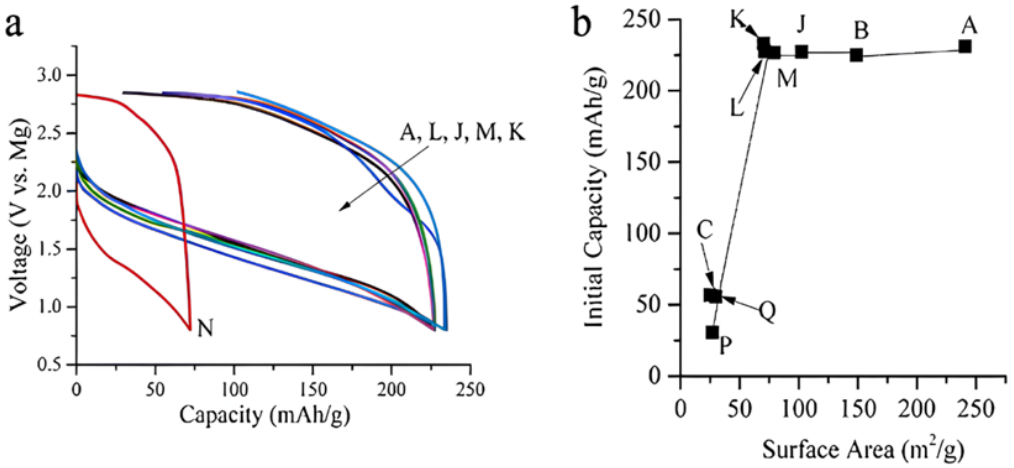

Figure 7. (a) Illustrates the different polymorphic structures of MnO_2 and their ability to store magnesium ions, which enhances their stability in magnesium battery systems. (b) Shows the correlation between MnO_2 surface area and the initial magnesium insertion capacity, highlighting that a larger surface area improves ion storage efficiency. The capital letters represent different MnO_2 structures. Adapted from Zhang et al. [24].

a good model for designing cathodes for Mg-based rechargeable seawater batteries (Mg-RSBs). When the interlayer distance of MoS_2 is increased from about 0.62 nm to about 1.45 nm, the activation energy for the diffusion of Mg^{2+} drops sharply. This changes the MoS_2 from being almost inactive to being a stable Mg cathode [72]. Another study also said that the sulfide framework in thiospinels like Ti_2S_4 and Mn_2S_4 is easy to polarize and has three-dimensional diffusion pathways, which means that Mg^{2+} can move through them easily, they have a lot of capacity, and they don't take up too much space [50]. These results suggest that sulfide materials are promising candidates for Mg cathodes suitable for incorporation into future Mg-redox flow battery designs.

4.2.5. Bifunctional Catalysts

RSB needs bifunctional catalysts to promote the OER in charging thus the ORR during discharging process. This dual role of plating helps close voltage polarization gaps and promotes high energy efficiency in addition to maintaining the long-term cycling stability, albeit its presence, also in marine electrolytes (high Cl^-). The voltage gap was decreased to 0.95 V, the voltage efficiency was increased to 76% and a maximum power density of 5.9 mW cm^{-2} with $Co_3V_2O_8$ catalyst was obtained. More than 400 h electrochemical durability was witnessed in the cell, which verified its bifunctional stability under seawater environment [73]. In a different study, the spinel Co_2VO_4 catalyst showed high ORR and OER activities with a half-wave potential of 0.83 V vs. RHE, a Tafel slope of 59 mV dec^{-1}, a specific activity of 37.27 μA cm^{-2}, and a mass activity of 5.2 A g^{-1}. When used in a zinc–air battery setup, Co_2VO_4 reached a peak power density of 380 mW·cm^{-2}, which was higher than that of the commercial Pt/C catalyst [74].

Cobalt-manganese oxides (CMO) from PBAs are another type of bifunctional catalyst. These materials have high energy efficiency and can easily switch between oxidation and reduction. When combined with hard carbon, CMO exhibits a voltage gap of about 0.53 V and a specific capacity of about 190 mAh g^{-1}. This system had a coulombic efficiency of over 96% and an energy efficiency of 74–79% over the first 100 cycles. This indicates its potential efficacy in marine environments [75]. Carbon-based composite materials have also been shown to exhibit bifunctional ORR/OER activity, similar to metal oxides. Carbon materials co-doped with nitrogen and oxygen exhibited an ORR onset potential of 0.97 V and a half-wave potential of 0.84 V, alongside an ORR–OER polarization gap of approximately 0.79 V, while sustaining high catalytic activity for over 5000 cycles [57]. Likewise, N-GC/Co@CoO/rGO hybrids demonstrated an ORR onset potential of 0.99 V and a half-wave potential that surpassed those of Pt/C catalysts. At the same time, their electrode architecture maintained structural stability during extended charge-discharge cycles [56].

Hybrid composites further demonstrate that combining conductive carbon with transition-metal particles benefits both components. An integrated energy storage system based on S–rGO–CNT–Co finds its way towards seawater in addition and it is stable with high electrochemical stability [16]. This hybrid setup accelerates charge transfer and reduces surface damage caused by aggressive marine ions. Sodium cobalt-manganese oxide ($Na_{0,5}Co_{0,5}Mn_{0,5}O_2$) has also been proposed as a bifunctional catalyst owing to its low overpotential and facile switching between oxidation and reduction. Its layered structure facilitates oxygen-mediated reactions, and it is compatible with seawater-based catholytes [22].

4.2.6. Conductive Polymers and Organic Materials

Conductive polymers such as polyaniline (PANI) and polypyrrole (PPy) have emerged as attractive cathode material candidates for RSBs. This is due to their reversible ion storage capabilities and ease of synthesis [16][22][76]. Of these systems, a binderless hybrid electrode made of PPy and Co_3O_4 on carbon cloth (PPy/Co_3O_4@CF) showed competitive bifunctional electrocatalytic activity when compared to systems based on noble metals [76]. This electrode exhibited an OER overpotential of 1.4 V vs. RHE at a current density of 10 mA·cm^{-2} in alkaline electrolyte, was able to maintain continuous operation for more than 300 h, and achieved performance equivalent to the commercial catalyst Pt/C + IrO_2, while completely eliminating the use of precious metals [76]. Conductive polymers have been used to improve the performance of sensors due to their properties;

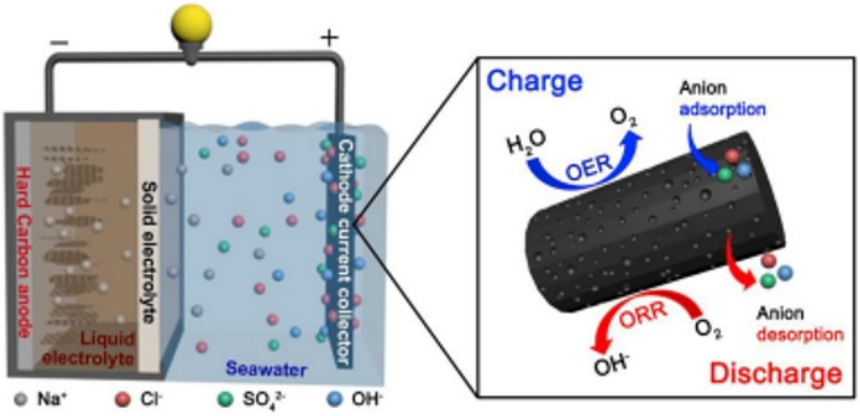

Figure 8. A practical example of a RSB configuration using a carbon-based cathode, demonstrating ion transport and ORR/OER mechanisms in seawater electrolyte. Figure is adapted from Park et al. [63].

however, they are limited in seawater detection because of their backbone sensitivity in chloride ions. This degradation usually contributes to reduced electronic conductivity and destruction of structure in the long-term cycle. Furthermore, organic cathode materials more broadly suffer from high solubility in organic electrolytes, low intrinsic conductivity, and structural durability—especially in ether- or carbonate-based media [77].

To address these issues, biomass-based carbon materials, such as starch-based biochar and bamboo charcoal, have been explored as alternative cathode materials. A biochar cathode made from these two materials demonstrated a reversible capacity of 110 mAh g^{-1} at 800 mA g^{-1} for 1000 cycles, with a coulombic efficiency of 99.8%. This system also produced a specific energy of 507 Wh kg^{-1} and a power density of 2961 W kg^{-1} in a seawater-based electrolyte [68]. On the other hand, a polytriphenylamine (PTPAn)-based carbon material demonstrated a capacity of 90 mAh g^{-1} at 50 mA g^{-1}, retained 88% of its capacity after 5000 cycles, and remained stable at temperatures below –10 °C [69].

4.2.7. Emerging Frontier Materials

The latest developments in cathodes for RSBs increasingly centre on emerging materials – mainly oxide perovskites and MOFs with high degrees of structural tunability and excellent catalytic potential in chloridic environments. Oxide perovskites like $La_{1-x}Sr_xCoO_{3-\delta}$ demonstrate good OER activity due to the presence of lattice oxygen vacancies and strong covalency of Co–O bonds. OER at these sites can be dominated by the lattice oxygen mechanism (LOM), in which O atoms from certain crystal lattices are directly involved in the redox reaction, thereby enhancing kinetics and reducing the energy barrier to overcome [78]. In addition to improving electronic conductivity, substituting La^{3+} with Sr^{2+} also increases the electrochemical stability window. Interestingly, $SrCoO_{2.7}$ features a much lower Tafel slope of 31 mV·dec^{-1}, specific activity of 28.4 mA·cm^{-2}, and mass activity of 1020 mA·mg^{-1} at the same potential vs. RHE, exceeding those records for both commercial IrO_2 and $LaCoO_3$ in alkaline environment [78].

In addition, the MOFs themselves possess a large surface area and a tunable pore structure with well-dispersed catalytically active sites. During thermal chemical treatment, ZIF-67 and Co-MOF can undergo structural transformation into conductive carbons with an architectural resemblance to their parent MOFs. One such Co-MOF-adapted electrode displayed stable operation for more than 300 h with a peak power density of 1.6 mW cm^{-2} in a zinc–air battery and exhibited enhanced charge-transfer kinetics and excellent resistance to Cl^- corrosion [79]. These features would endow MOF-derived materials with good potential as bifunctional ORR and OER electrocatalysts for marine applications.

A contemporary RSB system with a carbon cathode—depicted in Figure 8—is modified from Park et al. and demonstrates the ion transport channels and ORR/OER mechanisms at the seawater-based electrode–electrolyte interface [63]. For comparison, Figure 9 presents the same quantities as derived from He et al., which describe

the organic cathode reaction mechanism (in particular conductive polymers), the role of redox-active functional groups, and the complications associated with stability in chloride-rich environments [77]. The majority of perovskite and MOF systems remain at the proof-of-concept stage; however, they exhibit high intrinsic charge-transport capability. Structural flexibility and chloride tolerance further underscore their promise as next-generation RSB cathodes. Achieving their practical utilization will require synergistic design, compatible electrolytes, and anodes to achieve full-cell efficiency and long-term cycle life.

4.3. Advances in Electrolyte Materials

Further in the discussion on electrolyte hurdles, it should be argued that, unlike Na-RSBs, which have successfully optimized NASICON-type conductors, Mg-RSBs' development is at an early stage, and no solid electrolytes truly selective for Mg^{2+} ions exist to date. Current research is directed toward developing the aforementioned ceramic- or polymer-based membranes that can transport Mg^{2+} while blocking the passage of Cl^- and H_2O. Newer strategies include solid–liquid hybrid systems, ionic liquid incorporation, and special polymer blends to stabilize the Mg interface for potential Mg-RSB designs. Comprehensive comparison studies of Mg $(TFSI)_2$/glyme, $MgCl_2$–$AlCl_3$/THF, organoborate, and $Mg(BH_4)_2$ systems also reveal the intrinsic trade-offs between ionic conductivity, stability, and compatibility. Therefore, electrolyte and separator co-design could be a more promising development direction for the unexplored future candidate Mg-RSB system, which has yet to cross from laboratory -scale electrolyte studies to a real marine prototype.

The electrolyte systems for the Na-RSBs have been extensively studied and optimized to balance between ionic conductivity, chemical stability, and anode-cathode interfacial compatibility. However, replicating these designs in Mg-RSBs poses new challenges, including ensuring that Mg^{2+} transport through a solid or hybrid separator is facilitated while preventing water from permeating into the anode compartment. The greater reactivity of Mg to aqueous conditions requires a very precise control over the electrolyte composition and free moisture. In the RSB two-compartment configuration, "electrolyte" applies to both (seawater-based catholyte) and non-aqueous anolyte. Now, in Mg-RSBs, this region focuses only on the anolyte, since no direct interaction between seawater catholyte and the Mg anode has been deemed feasible. However, the strong passivation, parasitic hydrogen evolution, and accelerated corrosion of Mg anodes in a high-chloride environment remain major technical challenges for the lab-scale integration of seawater catholyte with Mg-RSB.

Over the past few years, attention has shifted to the development of water-free anolytes that should enable reversible Mg^{2+} electrochemistry without compromising interfacial stability or suppressing side reactions. Electrolyte design has a substantial impact on voltage efficiency, electrochemical reversibility, and long-term stability—all of which are important parameters for the application of Mg-RSBs in open seaboard conditions. In general, the design of anolyte systems for Mg-RSBs should meet all targeted requirements, including high ionic conductivity, corrosion resistance, and good interfacial compatibility. These advances are summarized in the subsequent subsections by electrolyte type and implementation strategies, including novel configurations (i.e., solid–liquid hybrids) that may benefit future Mg-RSB applications.

4.3.1. Liquid Non-Aqueous Electrolytes for Mg-RSBs

For future applications of Mg RSBs, it is critical to develop water-free liquid electrolytes to enable stable and efficient Mg^{2+} ion transport within the anode electrochemical system. Compared to the fragile electrochemical environment for Mg in aqueous systems owing to its intrinsic strong reactivity toward water, leading to undesirable hydrogen gas evolution through side reactions [47] [80], organic electrolytes offer a more stable potential window and are thus considered ideal electrolytes for Mg batteries. In this view, among the several electrolyte candidates explored so far, Mg bis(trifluoromethanesulfonyl)imide ($Mg(TFSI)_2$) dissolved into linear ether solvents such as monoglyme (G1), diglyme (G2), triglyme (G3), and tetraglyme (G4), has been of the most interest. The ionic conductivity of $Mg(TFSI)_2$/G2 is 10^{-3} S/cm at RT, and the electrochemical window is up to 3.5 V vs. Mg/Mg^{2+} [47]. The imidazolium chemical

environment in $Mg(TFSI)_2$/glyme can largely suppress the formation of a passivated layer, thereby blocking plating/stripping, for underh CE/ lowoverpotential conditions [80][81].

In addition, another investigated electrolyte is $MgCl_2$–$AlCl_3$ in tetrahydrofuran (THF), in which $[MgCl]^+$ and $[AlCl_4]^-$ complexes can be generated to facilitate reversible plating/dissolution of Mg^{2+} [57][82]. This can provide high coulombic efficiency; however, the volatility of THF and its insufficient long-term stability are challenging problems. Similar dual-salt strategies, in which Mg $(TFSI)_2$ is added to different organic salts with ether solvents, have been shown to improve anode interfacial stability and increase the operating voltage window [57][83]. HyD + $Mg(TFSI)_2$ in tetraglyme, with ionic liquid addition, in a single hybrid electrolyte study, resulted in a more uniform morphology of Mg deposition, higher capacity (similar to 79% retention over 250 cycles), and better thermal stability [57]. Due to higher Mg^{2+} solubility and low overpotential, organoborate and magnesium borohydride ($Mg(BH_4)_2$) complexes have also been recently examined [47][83]. However, their high synthetic complexity and inherent chemical instability usually disqualify them for direct use in RSB systems. The optimal non-aqueous liquid electrolyte requires compatibility with metallic Mg, as well as sufficiently high solubility and mobility of Mg^{2+} , together with great oxidative stability at the carbon -based cathode in seawater. The most promising types of electrolyte are those containing $Mg(TFSI)_2$/ glyme, $MgCl_2$–$AlCl_3$/THF, double-salt derivatives, and hybrid ones with ionic liquids. Additionally, the combination of hybrid configurations and additive incorporation is expected to enhance ion migration efficiency, suppress corrosion, and expand ESW operation in open seawater systems [47][57][80] [83].

5. CONCLUSIONS

Rechargeable seawater batteries (RSBs) have attracted increasing attention as a sustainable, large-scale energy storage platform that combines a seawater-based catholyte with either a non-aqueous or a solid-state anolyte in a dual-electrolyte configuration. In sodium-based systems, ion-selective solid electrolytes such as NASICON have enabled selective Na^+ transport, minimized chloride -ion crossover, and suppressed side reactions, thereby providing a crucial conceptual foundation for the development of Mg-RSBs. However, Mg-RSBs are still in an early stage of development and face several fundamental challenges, including the

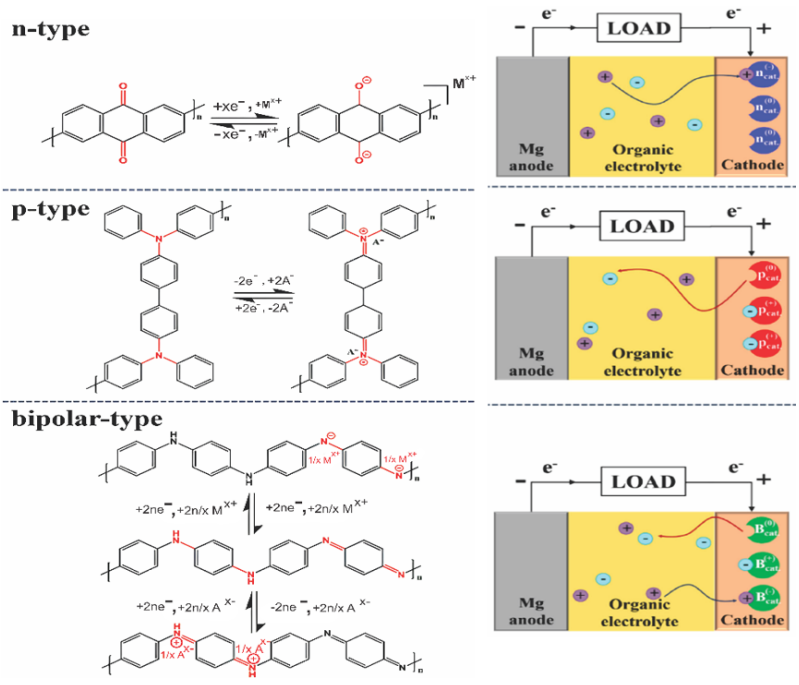

Figure 9. The reaction mechanisms and cell architectures related to the discharge process in n-type, p-type, and bipolar cathodes within magnesium-organic batteries. Adapted from He et al. [77].

instability and passivation of magnesium anodes, a lack of Mg^{2+}-selective solid electrolytes, electrolyte –separator incompatibility, corrosion caused by chloride-rich catholytes, and sluggish cathodic reaction kinetics. These restrictions further emphasize the need for a system-level approach to design instead of individual material optimization. Currently, Mg-RSBs have not reached practical application, and major progress in both materials and system integration must be pursued for their implementation in real-world applications. In this regard, this review emphasizes that magnesium is not a direct replacement for sodium but represents a distinct host system, thus necessitating dedicated electrochemical and materials design strategies. Future advances are critical and must be accomplished through integrated strategies, including electrolyte–separator co-design, advanced mitigation strategies of corrosion alongside chloride -tolerant bifunctional cathode catalysts, and stable magnesium electrodes with a hybrid membrane architecture. Against this backdrop, knowledge gathered from Na-RSBs and developments of magnesium-ion and rechargeable magnesium batteries serve as guidelines for the generation of Mg-specific design policies. With continued advances in materials innovation and interfacial engineering, Mg-RSBs have the potential to leverage magnesium's high volumetric capacity, natural abundance, and low material cost, thereby paving the way for durable, cost-effective, and environmentally sustainable energy storage solutions for marine, renewable, and off-grid applications.

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Conflicts of Interest

The authors declare no conflict of interest.

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DECLARATION OF GENERATIVE AI

Not applicable.

REFERENCES

[1] Z. Yang, J. Zhang, M. C. W. Kintner-Meyer, X. Lu, D. Choi, J. P. Lemmon, and J. Liu. (2011). "Electrochemical Energy Storage for Green Grid". *Chemical Reviews.* **111** : 3577-3613. 10.1021/cr100290v.

[2] O. Schmidt, A. Hawkes, A. Gambhir, and I. Staffell. (2017). "The Future Cost of Electrical Energy Storage Based on Experience Rates". *Nature Energy.* **2** : 17110. 10.1038/nenergy.2017.110.

[3] T. Perveen, M. Siddiq, N. Shahzad, R. Ihsan,

A. Ahmad, and M. I. Shahzad. (2020). "Prospects in Anode Materials for Sodium Ion Batteries: A Review". *Renewable and Sustainable Energy Reviews.* **119** : 109549. 10.1016/j.rser.2019.109549.

[4] D. H. Nam, M. A. Lumley, and K. S. Choi. (2021). "A Seawater Battery with Desalination Capabilities Enabling a Dual-Purpose Aqueous Energy Storage System". *Energy Storage Materials.* **37** : 556-566. 10.1016/j.ensm.2021.02.037.

[5] F. Liu, T. Wang, X. Liu, and L. Fan. (2021). "Challenges and Recent Progress on Key Materials for Rechargeable Magnesium Batteries". *Advanced Energy Materials.* **11** : 2000787. 10.1002/aenm.202000787.

[6] R. Mohtadi, O. Tutusaus, T. S. Arthur, Z. Zhao-Karger, and M. Fichtner. (2021). "The Metamorphosis of Rechargeable Magnesium Batteries". *Joule.* **5** : 581-617. 10.1016/j.joule.2020.12.021.

[7] X. Luo, A. Shen, B. Liu, J. Wu, M. Fan, N. Yang, G. Zhang, X. Chen, and Q. Dai. (2025). "The Interfacial Reactions of Mg Battery Anodes". *Journal of Magnesium and Alloys.* **13** : 1915-1938. 10.1016/j.jma.2025.04.031.

[8] X. Wu, Y. Dou, R. Lian, Y. Wang, and Y. Wei. (2022). "Understanding Rechargeable Magnesium Ion Batteries via First-Principles Computations: A Comprehensive Review". *Energy Storage Materials.* **48** : 344-355. 10.1016/j.ensm.2022.03.039.

[9] S. Abdessameud, M. Mezbahul-Islam, and M. Medraj. (2014). "Thermodynamic Modeling of Hydrogen Storage Capacity in Mg-Na Alloys". *The Scientific World Journal.* **2014** : 190320. 10.1155/2014/190320.

[10] Y. Kim, A. Varzi, A. Mariani, G. T. Kim, Y. Kim, and S. Passerini. (2021). "Redox-Mediated Red-Phosphorous Semi-Liquid Anode Enabling Metal-Free Rechargeable Na-Seawater Batteries with High Energy Density". *Advanced Energy Materials.* **11** : 2102061. 10.1002/aenm.202102061.

[11] P. W. Jaschin, Y. Gao, Y. Li, and S. H. Bo. (2020). "A Materials Perspective on Magnesium-Ion-Based Solid-State Electrolytes". *Journal of Materials Chemistry A.* **8** : 2875-2897. 10.1039/C9TA11729F.

[12] Z. Wang, R. Deng, Y. Wang, and F. Pan. (2024). "Comparison of Construction Strategies of Solid Electrolyte Interface (SEI) in Li Battery and Mg Battery: A Review". *Molecules.* **29** : 4761. 10.3390/molecules29194761.

[13] W. Zhang, B. Feng, L. Huang, Y. Liang, J. Chen, X. Li, Z. Shi, and N. Wang. (2024). "Fe/Cu Diatomic Sites Dispersed on Nitrogen-Doped Mesoporous Carbon for the Boosted Oxygen Reduction Reaction in Mg-Air and Zn-Air Batteries". *Applied Catalysis B: Environment and Energy.* **358** : 124450. 10.1016/j.apcatb.2024.124450.

[14] W. Zhang, X. Li, S. Guo, X. Wu, Y. Tang, Z. Wan, L. Huang, Z. Shi, and N. Wang. (2025). "Long-Range Electronic Modulation of Fe Atomic Sites via Third Coordination Layer Selenium Anchoring for Enhanced Oxygen Reduction Reaction in Zn-Air and Mg-Air Batteries". *Chemical Engineering Journal.* **521** : 167173. 10.1016/j.cej.2025.167173.

[15] J. Liu, H. Hu, T. Wu, J. Chen, X. Yang, N. Wang, and Z. Shi. (2024). "Tailoring the Microstructure of Mg-Al-Sn-RE Alloy via Friction Stir Processing and the Impact on Its Electrochemical Discharge Behaviour as the Anode for Mg-Air Battery". *Journal of Magnesium and Alloys.* **12** : 1554-1565. 10.1016/j.jma.2022.07.016.

[16] S. T. Senthilkumar, W. Go, J. Han, L. Pham Thi Thuy, K. Kishor, Y. Kim, and Y. Kim. (2019). "Emergence of Rechargeable Seawater Batteries". *Journal of Materials Chemistry A.* **7** : 22803-22825. 10.1039/C9TA08321A.

[17] S. M. Hwang, J. Park, Y. Kim, W. Go, J. Han, Y. Kim, and Y. Kim. (2019). "Rechargeable Seawater Batteries: From Concept to Applications". *Advanced Materials.* **31** : 1804936. 10.1002/adma.201804936.

[18] M. Guo, C. Yuan, T. Zhang, and X. Yu. (2022). "Solid-State Electrolytes for Rechargeable Magnesium-Ion Batteries: From Structure to Mechanism". *Small.* **18** : 2106981. 10.1002/smll.202106981.

[19] J. Chen, W. Xu, X. Wang, S. Yang, and C. Xiong. (2023). "Progress and Applications of Seawater-Activated Batteries". *Sustainability.* **15** : 1635. 10.3390/su15021635.

[20] C. Wu, X. Meng, and W. Wang. (2020). "High-Performance Mg-Al-Bi Alloy Anode for Seawater Batteries and Related Mechanisms". *Processes.* **8** : 1362. 10.3390/pr8111362.

[21] H. T. El-Dessouky and H. M. Ettouney. (2002)."Fundamentals of Salt Water Desalination". Elsevier Science, Amsterdam.

[22] Y. Jia, B. Q. Li, C. X. Zhang, and Q. Zhang. (2020). "Seawater Electrolyte-Based Metal-Air Batteries: From Strategies to Applications". *Energy & Environmental Science.* **13** : 3253-3268. 10.1039/D0EE01617A.

[23] M. Kotobuki, B. Yan, and L. Lu. (2023). "Recent Progress on Cathode Materials for Rechargeable Magnesium Batteries". *Energy Storage Materials.* **54** : 227-253. 10.1016/j.ensm.2022.10.034.

[24] X. Zhang, T. Chen, D. Yan, W. Qin, B. Hu, Z. Sun, and L. Pan. (2015). "MgFe2O4/Reduced Graphene Oxide Composites as High-Performance Anode Materials for Sodium Ion Batteries". *Electrochimica Acta.* **180** : 616-621. 10.1016/j.electacta.2015.09.002.

[25] Y. Guo, Y. Zhu, C. Yuan, and C. Wang. (2017). "MgFe2O4 Hollow Microboxes Derived from Metal-Organic Frameworks as Anode Material for Sodium-Ion Batteries". *Materials Letters.* **199** : 101-104. 10.1016/j.matlet.2017.04.069.

[26] M. Ambrosetti, I. Quinzeni, A. Girella, V. Berbenni, B. Albini, P. Galinetto, M. Sturini, and M. Bini. (2024). "Pure and (Sn or Mg) Doped GeFe2O4 as Anodes for Sodium-Ion Batteries". *Batteries.* **10** : 134. 10.3390/batteries10040134.

[27] Y. Cao, W. Li, F. Wang, X. Hao, and J. Tan. (2023). "Experimental Study of Discharging Magnesium-Dissolved Oxygen Seawater Batteries with Various Binder Ratios". *Applied Sciences.* **13** : 12996. 10.3390/app132412996.

[28] T. Zhang, Z. Tao, and J. Chen. (2014). "Magnesium-Air Batteries: From Principle to Application". *Materials Horizons.* **1** : 196-206. 10.1039/C3MH00059A.

[29] A. I. Ikeuba, P. C. Iwuji, I. I. E. Nabuk, O. E. Obono, D. Charlie, A. A. Etim, B. I. Nwabueze, and J. Amajama. (2024). "Advances on Lithium, Magnesium, Zinc, and Iron-Air Batteries as Energy Delivery Devices: A Critical Review". *Journal of Solid State Electrochemistry.* **28** : 2999-3025. 10.1007/s10008-024-05866-x.

[30] J. Ma, P. Hu, X. Jia, C. Zhang, and G. Wang. (2021). "Organic/Inorganic Double Solutions for Magnesium-Air Batteries". *RSC Advances.* **11** : 7502-7510. 10.1039/D0RA10528G.

[31] M. A. Osipenko, A. A. Kasach, J. Adamiec, M. Zimowska, I. I. Kurilo, and D. S. Kharytonau. (2023). "Corrosion Inhibition of Magnesium Alloy AZ31 in Chloride-Containing Solutions by Aqueous Permanganate". *Journal of Solid State Electrochemistry.* **27** : 1847-1860. 10.1007/s10008-023-05472-3.

[32] S. Abbasi, M. Aliofkhazraei, H. Mojiri, M. Amini, M. Ahmadzadeh, and M. Shourgeshty. (2017). "Corrosion Behavior of Pure Mg and AZ31 Magnesium Alloy". *Protection of Metals and Physical Chemistry of Surfaces.* **53** : 573-578. 10.1134/S2070205117030029.

[33] X. Wei, Z. Li, P. Liu, S. Li, X. Peng, R. Deng, and Q. Zhao. (2020). "Improvement in Corrosion Resistance and Biocompatibility of AZ31 Magnesium Alloy by NH2+ Ions". *Journal of Alloys and Compounds.* **813** : 153832. 10.1016/j.jallcom.2020.153832.

[34] T. Chen, G. Ceder, G. S. Gautam, and P. Canepa. (2019). "Evaluation of Mg Compounds as Coating Materials in Mg Batteries". *Frontiers in Chemistry.* **7** : 24. 10.3389/fchem.2019.00024.

[35] W. Lee, J. Park, J. Park, S. J. Kang, Y. Choi, and Y. Kim. (2020). "Identifying the Mechanism and Impact of Parasitic Reactions Occurring in Carbonaceous Seawater Battery Cathodes". *Journal of Materials Chemistry A.* **8** : 9185-9193. 10.1039/D0TA02913K.

[36] H. Parangusan, J. Bhadra, and N. A. Al-

Thani. (2021). "A Review of Passivity Breakdown on Metal Surfaces: Influence of Chloride- and Sulfide-Ion Concentrations, Temperature, and pH". *Emergent Materials.* **4** : 1187-1203. 10.1007/s42247-021-00194-6.

[37] G. Williams, H. A. L. Dafydd, R. Subramanian, and H. N. McMurray. (2017). "The Influence of Chloride Ion Concentration on Passivity Breakdown in Magnesium". *Corrosion.* **73** : 471-481. 10.5006/2328.

[38] S. Khalifeh and T. D. Burleigh. (2017). "Effect of Anodizing Parameters on Corrosion Resistance of Coated Purified Magnesium". *arXiv Preprint*. 10.48550/arXiv.1706.09547.

[39] C. Carré, A. Zanibellato, M. Jeannin, R. Sabot, P. Gunkel-Grillon, and A. Serres. (2020). "Electrochemical Calcareous Deposition in Seawater: A Review". *Environmental Chemistry Letters.* **18** : 1193-1208. 10.1007/s10311-020-01002-z.

[40] J. J. Pryke, R. M. Kennard, and S. A. Cussen. (2022). "Cathodes for Mg Batteries: A Condensed Review". *Energy Reports.* **8** 83-88. 10.1016/j.egyr.2022.07.124.

[41] M. Javed, A. Shah, J. Nisar, S. Shahzad, A. Haleem, and I. Shah. (2024). "Nanostructured Design Cathode Materials for Magnesium-Ion Batteries". *ACS Omega.* **9** : 4229-4245. 10.1021/acsomega.3c06576.

[42] X. Chen, S. Wei, F. Tong, M. P. Taylor, and P. Cao. (2021). "Electrochemical Performance of Mg-Sn Alloy Anodes for Magnesium Rechargeable Battery". *Electrochimica Acta.* **398** : 139336. 10.1016/j.electacta.2021.139336.

[43] D. Gu, Y. Yuan, X. Peng, D. Li, L. Wu, G. Huang, J. Wang, and F. Pan. (2024). "Realizing High-Stability Anodes for Rechargeable Magnesium Batteries via In Situ-Formed Nanoporous Bi and Nanosized Sn". *Journal of Materials Chemistry A.* **12** : 26890-26901. 10.1039/D4TA04998E.

[44] X. Chen, X. Liu, M. Zhang, M. Liu, and A. Atrens. (2021). "A Comprehensive Review of the Development of the Magnesium Anode for Primary Batteries". *Journal of Materials Chemistry A.* **9** : 12367-12399. 10.1039/D1TA01471D.

[45] R. Deivanayagam, B. J. Ingram, and R. Shahbazian-Yassar. (2019). "Progress in Development of Electrolytes for Magnesium Batteries". *Energy Storage Materials.* **21** : 136-153. 10.1016/j.ensm.2019.05.028.

[46] D. Li, Y. Yuan, J. Liu, M. Fichtner, and F. Pan. (2020). "A Review on Current Anode Materials for Rechargeable Mg Batteries". *Journal of Magnesium and Alloys.* **8** : 963-979. 10.1016/j.jma.2020.09.017.

[47] R. Yang, W. Yao, B. Tang, F. Zhang, X. Lei, C. S. Lee, and Y. Tang. (2021). "Development and Challenges of Electrode Materials for Rechargeable Mg Batteries". *Energy Storage Materials.* **42** : 687-704. 10.1016/j.ensm.2021.08.019.

[48] G. Wang, Z. Wang, H. Shi, A. Du, M. Sun, and G. Cui. (2024). "Progress and Perspective on Rechargeable Magnesium-Ion Batteries". *Science China Chemistry.* **67** : 214-246. 10.1007/s11426-022-1454-0.

[49] M. Deng, L. Wang, D. Höche, S. V. Lamaka, P. Jiang, D. Snihirova, N. Scharnagl, and M. L. Zheludkevich. (2020). "Ca/In Micro-Alloying as a Novel Strategy to Simultaneously Enhance Power and Energy Density of Primary Mg-Air Batteries from Anode Aspect". *Journal of Power Sources.* **472** : 228528. 10.1016/j.jpowsour.2020.228528.

[50] Z. Li, J. Häcker, M. Fichtner, and Z. Zhao-Karger. (2023). "Cathode Materials and Chemistries for Magnesium Batteries: Challenges and Opportunities". *Advanced Energy Materials.* **13** : 2300682. 10.1002/aenm.202300682.

[51] X. Wang, C. Jing, Y. Chen, X. Wang, G. Zhao, X. Zhang, L. Wu, X. Liu, B. Dong, and Y. Zhang. (2020). "Active Corrosion Protection of Super-Hydrophobic Corrosion Inhibitor Intercalated Mg-Al Layered Double Hydroxide Coating on AZ31 Magnesium Alloy". *Journal of Magnesium and Alloys.* **8** : 291-300. 10.1016/j.jma.2019.11.011.

[52] D. H. Kim, H. Choi, D. Y. Hwang, J. Park, K. S. Kim, S. Ahn, Y. Kim, S. K. Kwak, Y. Yu, and S. J. Kang. (2018). "Reliable Seawater Battery Anode: Controlled Sodium Nucleation via Deactivation of Current

Collector Surface". *Journal of Materials Chemistry A.* **6** : 1-8. 10.1039/C8TA07610C.

[53] J. H. Ryu, J. Park, J. Park, J. Mun, E. Im, H. Lee, S. Y. Hong, K. An, G. Lee, Y. Kim, P. S. Jo, and S. J. Kang. (2022). "Carbothermal Shock-Induced Bifunctional Pt-Co Alloy Electrocatalysts for High-Performance Seawater Batteries". *Energy Storage Materials.* **45** : 281-290. 10.1016/j.ensm.2021.11.036.

[54] M. Sotoudeh and A. Groß. (2022). "Stability of Magnesium Binary and Ternary Compounds for Batteries Determined from First Principles". *The Journal of Physical Chemistry Letters.* **13** : 10092-10100. 10.1021/acs.jpclett.2c02316.

[55] P. Manikandan, K. Kishor, J. Han, and Y. Kim. (2018). "Advanced Perspective on Synchronized Bifunctional Activities of P2-Type Material to Implement Interconnected Voltage Profile for Seawater Battery". *Journal of Materials Chemistry A.* **6** : 1-10. 10.1039/C8TA02667J.

[56] L. Lin, N. Miao, G. G. Wallace, J. Chen, and D. A. Allwood. (2021). "Engineering Carbon Materials for Electrochemical Oxygen Reduction Reactions". *Advanced Energy Materials.* **11** : 2100695. 10.1002/aenm.202100695.

[57] R. Ma, G. Lin, Y. Zhou, Q. Liu, T. Zhang, G. Shan, M. Yang, and J. Wang. (2019). "A Review of Oxygen Reduction Mechanisms for Metal-Free Carbon-Based Electrocatalysts". *npj Computational Materials.* **5** : 78. 10.1038/s41524-019-0210-3.

[58] W. Jiao, Y. Fan, C. Huang, and Sanglin. (2018). "Effect of Modified Polyacrylonitrile -Based Carbon Fiber on the Oxygen Reduction Reactions in Seawater Batteries". *Ionics.* **24** : 285-296. 10.1007/s11581-017-2197-4.

[59] N. D. K. Tu, S. O. Park, J. Park, Y. Kim, S. K. Kwak, and S. J. Kang. (2020). "Pyridinic-Nitrogen-Containing Carbon Cathode: Efficient Electrocatalyst for Seawater Batteries". *ACS Applied Energy Materials.* **3** : 1602-1608. 10.1021/acsaem.9b02087.

[60] M. M. Huie, D. C. Bock, E. S. Takeuchi, A. C. Marschilok, and K. J. Takeuchi. (2015). "Cathode Materials for Magnesium and Magnesium-Ion Based Batteries". *Coordination Chemistry Reviews.* **287** : 15-27. 10.1016/j.ccr.2014.11.005.

[61] H. Kobayashi. (2024). "Development of Oxide-Type Cathode Materials Towards Room-Temperature Magnesium Rechargeable Batteries". *Electrochemistry.* **92** : 101004. 10.5796/electrochemistry.24-00068.

[62] Z. Khan, S. O. Park, J. Yang, S. Park, R. Shanker, H. K. Song, Y. Kim, S. K. Kwak, and H. Ko. (2018). "Binary N,S-Doped Carbon Nanospheres from Bio-Inspired Artificial Melanosomes: A Route to Efficient Air Electrodes for Seawater Batteries". *Journal of Materials Chemistry A.* **6** : 24459-24467. 10.1039/C8TA10327E.

[63] J. Park, J. S. Park, S. T. Senthilkumar, and Y. Kim. (2020). "Hybridization of Cathode Electrochemistry in a Rechargeable Seawater Battery: Toward Performance Enhancement". *Journal of Power Sources.* **450** : 227600. 10.1016/j.jpowsour.2019.227600.

[64] L. Gu, X. L. Sun, J. Zhao, B. Q. Gong, Z. L. Bao, H. L. Jia, M. Y. Guan, and S. S. Ma. (2021). "A Highly Efficient Bifunctional Electrocatalyst (ORR/OER) Derived from GO Functionalized with Carbonyl, Hydroxyl and Epoxy Groups for Rechargeable Zinc-Air Batteries". *New Journal of Chemistry.* **45** : 6535-6542. 10.1039/D1NJ00837D.

[65] M. Li, C. Bao, Y. Liu, J. Meng, X. Liu, Y. Cai, D. Wuu, Y. Zong, T. P. Loh, and Z. Wang. (2019). "Reduced Graphene Oxide-Supported Cobalt Oxide Decorated N-Doped Graphitic Carbon for Efficient Bifunctional Oxygen Electrocatalysis". *RSC Advances.* **9** : 16534-16540. 10.1039/C9RA02389E.

[66] W. Wei, J. Xu, W. Chen, L. Mi, and J. Zhang. (2022). "A review of sodium chloride -based electrolytes and materials for electrochemical energy technology". *Journal of Materials Chemistry A.* **10** (6): 2637-2671. 10.1039/d1ta09371a.

[67] Z. Le, W. Li, Q. Dang, C. Jing, W. Zhang, J. Chu, L. Tang, and M. Hu. (2021). "A High-Power Seawater Battery Working in a Wide

Temperature Range Enabled by an Ultra-Stable Prussian Blue Analogue Cathode". *Journal of Materials Chemistry A.* **9** : 8685-8691. 10.1039/D0TA12052A.

[68] J. Xie, W. Chen, G. Long, W. Gao, Z. J. Xu, M. Liu, and Q. Zhang. (2018). "Boosting the Performance of Organic Cathodes Through Structure Tuning". *Journal of Materials Chemistry A.* **6** : 12985-12991. 10.1039/C8TA03857K.

[69] D. Lu, H. Liu, T. Huang, Z. Xu, L. Ma, P. Yang, P. Qiang, F. Zhang, and D. Wu. (2018). "Magnesium Ions Based Organic Secondary Battery". *Journal of Materials Chemistry A.* **6** : 17297-17302. 10.1039/C8TA05230A.

[70] M. Kong, L. Bu, and W. Wang. (2021). "Investigations on the Discharge/Charge Process of a Novel AgCl/Ag/Carbon Felt Composite Electrode Used for Seawater Batteries". *Journal of Power Sources.* **506** : 230210. 10.1016/j.jpowsour.2021.230210.

[71] T. Kakibe, J. Hishii, N. Yoshimoto, M. Egashira, and M. Morita. (2012). "Binary Ionic Liquid Electrolytes Containing Organo-Magnesium Complex for Rechargeable Magnesium Batteries". *Journal of Power Sources.* **203** : 195-200. 10.1016/j.jpowsour.2011.10.127.

[72] Y. Liang, H. D. Yoo, Y. Li, J. Shuai, H. A. Calderon, F. C. R. Hernandez, L. C. Grabow, and Y. Yao. (2015). "Interlayer-Expanded Molybdenum Disulfide Nanocomposites for Electrochemical Magnesium Storage". *Nano Letters.* **15** : 2194-2202. 10.1021/acs.nanolett.5b00388.

[73] K. H. Shin, J. Park, S. K. Park, P. Nakhanivej, S. M. Hwang, Y. Kim, and H. S. Park. (2019). "Cobalt Vanadate Nanoparticles as Bifunctional Oxygen Electrocatalysts for Rechargeable Seawater Batteries". *Journal of Industrial and Engineering Chemistry.* **72** : 250-254. 10.1016/j.jiec.2018.12.025.

[74] C. Mu, J. Mao, J. Guo, Q. Guo, Z. Li, W. Qin, Z. Hu, K. Davey, T. Ling, and S. Z. Qiao. (2020). "Rational Design of Spinel Cobalt Vanadate Oxide Co2VO4 for Superior Electrocatalysis". *Advanced Materials.* **32** (10): 1907168. 10.1002/adma.201907168.

[75] M. Abirami, S. M. Hwang, J. Yang, S. T. Senthilkumar, J. Kim, W. S. Go, B. Senthilkumar, H. K. Song, and Y. Kim. (2016). "A Metal-Organic Framework-Derived Porous Cobalt Manganese Oxide Bifunctional Electrocatalyst for Hybrid Na-Air/Seawater Batteries". *ACS Applied Materials & Interfaces.* **8** : 32778-32787. 10.1021/acsami.6b10082.

[76] C. Kim, S. Kim, O. Kwon, J. Kim, and G. Kim. (2019). "Polypyrrole-Assisted Co3O4 Anchored Carbon Fiber as a Binder-Free Electrode for Seawater Batteries". *ChemElectroChem.* **6** : 1-10. 10.1002/celc.201801219.

[77] X. He, R. Cheng, X. Sun, H. Xu, Z. Li, F. Sun, Y. Zhan, J. Zou, and R. M. Laine. (2023). "Organic Cathode Materials for Rechargeable Magnesium-Ion Batteries: Fundamentals, Recent Advances, and Approaches to Optimization". *Journal of Magnesium and Alloys.* **11** : 4359-4389. 10.1016/j.jma.2023.11.008.

[78] J. T. Mefford, X. Rong, A. M. Abakumov, W. G. Hardin, S. Dai, A. M. Kolpak, K. P. Johnston, and K. J. Stevenson. (2016). "Water Electrolysis on La1-xSrxCoO3-d Perovskite Electrocatalysts". *Nature Communications.* **7** : 11053. 10.1038/ncomms11053.

[79] J. Lee, I. Choi, E. Kim, J. Park, and K. W. Nam. (2024). "Metal-Organic Frameworks for High-Performance Cathodes in Batteries". *iScience.* **27** : 110211. 10.1016/j.isci.2024.110211.

[80] Z. Yu, T. R. Juran, X. Liu, K. S. Han, H. Wang, K. T. Mueller, L. Ma, K. Xu, T. Li, L. A. Curtiss, and L. Cheng. (2021). "Solvation Structure and Dynamics of Mg(TFSI)2 Aqueous Electrolyte". *Energy & Environmental Materials.* **4** : 761-772. 10.1002/eem2.12174.

[81] Y. He, Q. Li, L. Yang, C. Yang, and D. Xu. (2019). "Electrochemical Conditioning-Free and Water-Resistance of the Hybrid AlCl3/MgCl2/Mg(TFSI)2 Electrolytes for Rechargeable Mg Batteries". *Angewandte Chemie International Edition.* **58** : 11978-

11982. 10.1002/anie.201812824.

[82] Z. Ma, M. Kar, C. Xiao, M. Forsyth, and D. R. MacFarlane. (2017). "Electrochemical Cycling of Mg in Mg[TFSI]2/Tetraglyme Electrolytes". *Electrochemistry Communications.* **78** : 29-32. 10.1016/j.elecom.2017.03.018.

[83] R. Jay, A. W. Tomich, J. Zhang, Y. Zhao, A. De Gorostiza, V. Lavallo, and J. Guo. (2019). "A Comparative Study of Mg(CB11H12)2 and Mg(TFSI)2 at the Magnesium/ Electrolyte Interface". *ACS Applied Materials & Interfaces.* **11** : 11414-11422. 10.1021/acsami.9b00037.