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Non-rechargeable batteries: a review of primary battery technology and future trends

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Primary batteries, or non-rechargeable batteries, are crucial for powering a diverse range of low-drain applications, from household items to specialized devices in medical and aerospace industries. Despite the growth of rechargeable battery technologies, primary batteries offer distinct advantages, including cost-effectiveness, reliability, and long shelf life. This review examines the current state of primary battery technology, exploring the major types, including alkaline, zinc–carbon, lithium, and silver oxide batteries, and discussing their significance in both everyday and specialized applications. Key challenges, such as the environmental impact of battery disposal, limitations in energy density, and performance optimization, are highlighted as areas of ongoing research. Advances in nanotechnology, materials science, and novel chemistries, such as biodegradable materials and high-performance lithium-based systems, promise to improve energy density and sustainability in the future. The review also outlines future trends, including increased miniaturization for medical devices, the development of robust batteries for extreme environments, and new battery chemistries that can replace or enhance current primary battery technologies. Addressing these challenges and gaps is essential for ensuring that primary batteries remain a viable and sustainable energy storage solution in the future.

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Dr Peeyush Phogat completed his PhD in the Department of Physics at Netaji Subhas University of Technology. His current area of research is the synthesis and characterization of materials, focusing particularly on applications in solar energy and capacitors. Holding a master's degree with specialization in condensed matter physics, he is driven by the pursuit of uncovering novel materials and their distinct properties, meticulously tailored for effective solar energy capture and the design of efficient capacitors. His scholarly endeavors have resulted in significant contributions towards the development of new and advanced materials for solar applications, which are evidenced by his 35 publications in esteemed SCI/SCIE journals and authorship of 14 book chapters within the renowned book series. His expertise extends comprehensively into the domain of capacitors, where his research showcases a remarkable ability to engineer materials that optimize energy storage and discharge capabilities.

1. Introduction

Batteries are indispensable components of modern technology, facilitating the portability and operation of electronic devices by providing a steady, portable source of power. From common household devices like flashlights and remote controls to industrial and medical equipment, batteries are a central feature of our daily lives. The role of batteries has evolved in tandem with technological advancements, ensuring that electronic devices operate reliably, even when disconnected from mains electricity. A battery functions as an electrochemical energy storage device, converting chemical energy into electrical energy that can power an electronic circuit or a device. This process takes place within the battery's electrochemical cells, where chemical reactions occur at the electrodes and produce a flow of electrons, thus generating electricity.[1] Batteries, due to their versatility and ease of use, have emerged as a critical technology that supports both everyday needs and specialized functions. The need for batteries is driven by the ever-growing demand for portable power. In an increasingly mobile and digital world, where the use of wireless and portable technologies is ubiquitous, batteries enable continuous power supply in situations where connection to electrical grids is either impractical or impossible. Beyond everyday consumer products, batteries also play critical roles in sectors such as healthcare, transportation, space exploration, renewable energy storage, and emergency systems. For instance, medical devices like pacemakers and hearing aids rely on compact, reliable batteries for operation, while electric vehicles (eVs) depend on high-performance battery systems to store and deliver energy efficiently. The significance of batteries cannot be understated.[2] They have become a fundamental aspect of how modern societies function, enabling advances in technology and infrastructure that shape everyday life. As the demand for energy-efficient, sustainable, and reliable energy storage solutions continues to rise, battery technology remains an area of intensive research and development.

Batteries are classified into various types based on their characteristics and intended applications. Understanding these categories is essential for contextualizing the specific focus on primary batteries in this review. The major categories of batteries are as follows:

(a) Primary (non-rechargeable) batteries: primary batteries are single-use, non-rechargeable devices designed to be discarded once their energy has been fully depleted. They are widely used in low-power applications, such as household devices like remote controls, flashlights, and smoke detectors.[3] Examples of primary batteries include alkaline batteries, zinc–carbon batteries, lithium batteries, and silver oxide batteries. These batteries are generally inexpensive, widely available, and offer long shelf lives, making them ideal for low-drain applications where infrequent use or long-term storage is required.

(b) Secondary (rechargeable) batteries: unlike primary batteries, secondary batteries can be recharged and used for multiple times. These batteries are ideal for high-drain applications where long-term use is required, such as in eVs, smartphones and laptops.

Shreya

Dr Shreya Sharma is a physicist who earned her PhD in Physics from Netaji Subhas University of Technology, where her research was centered on the exploration of exceptional properties exhibited by nanomaterials and their potential contributions to advancing renewable energy technologies. Her primary focus lies in investigating the unique properties of 2D materials and their electrochemical study, specifically transition metal dichalcogenides, with the aim of applying these findings to enhance solar cells, supercapacitors, photodetectors, hydrogen production, and electrochemical sensing. Her dedication to leveraging advanced materials for sustainable energy solutions reflects her vision of contributing to societal progress through innovative technology. Currently, she is working to identify sustainable energy resources, with a specific focus on blue energy foresight. She is also the author and co-editor of multiple scientific books and papers in esteemed journals. Driven by a deep commitment to environmental sustainability, Dr Sharma's work embodies her passion for scientific advancement in service to future energy needs.

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Rechargeable battery types include nickel–metal hydride (NiMH) batteries, lithium-ion (Li-ion) batteries, and lead–acid batteries.[4] Secondary batteries are often more expensive initially but provide significant cost savings over time due to their reusability. They also play a crucial role in renewable energy storage systems, enabling the integration of solar and wind power into energy grids.

(c) Specialty batteries: specialty batteries are designed for high-performance or niche applications that demand specific characteristics, such as extreme energy density, temperature resilience, or durability.[5] These batteries are typically used in aerospace, medical devices, and military applications. Examples include zinc–bromine flow batteries, solid-state batteries and molten salt batteries. Specialty batteries are engineered to meet the unique requirements of these high-demand fields, where conventional battery technologies may not perform adequately.

(d) Fuel cells: although not technically classified as batteries, fuel cells generate electricity through chemical reactions rather than storing energy as traditional batteries do.[6] Fuel cells are increasingly used in applications requiring continuous power, such as eVs, backup power systems, and space exploration. Fuel cells offer high efficiency and can operate as long as they are supplied with fuel, typically hydrogen, making them a promising technology for both mobile and stationary applications.

(e) Emerging battery technologies: the field of the battery technology is continuously evolving, with ongoing research into novel battery chemistries and materials. Emerging technologies such as graphene-based batteries, silicon-anode batteries, and quantum batteries are currently being explored for their potential to offer significant improvements in the field of energy density, charging speed, efficiency, and sustainability. These next-generation batteries may help meet the growing global demand for energy storage while addressing environmental concerns and reducing reliance on limited resources. Fig. 1 illustrates the classification of these battery types and provides examples of batteries that fall under each category.

This review is centered on primary batteries, which, despite their single-use nature, remain an integral part of modern energy storage solutions. Primary batteries continue to dominate many applications due to their simplicity, reliability, and cost-effectiveness. They are indispensable in low-drain devices, such as smoke detectors, remote controls, clocks, and portable radios, where the long-term, consistent operation is more critical than the ability to recharge. The sustained relevance of primary batteries stems from their practical benefits. Primary batteries are typically inexpensive, widely available, and require little to no maintenance. They also have a long shelf life, making them ideal for devices that may sit unused for extended periods. Furthermore, primary batteries are often more reliable in extreme conditions, such as very cold or hot environments, where rechargeable batteries might struggle to maintain performance.[7] These advantages make primary batteries a critical technology in sectors such as military operations, emergency preparedness, and medical devices, where the ability to store power for long durations and provide instant, reliable energy is crucial.[8] Despite the ongoing development of rechargeable and emerging battery technologies, primary batteries retain their place in many essential applications. However, there are several key areas where research and innovation are needed to address the limitations of primary batteries and to ensure their future sustainability and efficiency.

While primary batteries have remained a staple in many applications, they are not without their challenges. As the world shifts towards more sustainable energy practices, the limitations of primary batteries, particularly in terms of environmental impact, have become a focal point of concern. Several research gaps need to be addressed to improve the performance, sustainability, and environmental impact of primary batteries. These gaps highlight the importance of continued research in this field.

One of the most pressing concerns surrounding primary batteries is their environmental impact. Since primary batteries are non-rechargeable, they must be discarded once their energy is depleted. This has led to a significant accumulation of battery waste, contributing to the broader problem of electronic waste (e-waste).[9] Improper disposal of primary batteries can lead to the release of harmful chemicals into the environment, including toxic heavy metals like mercury, cadmium, and lead.

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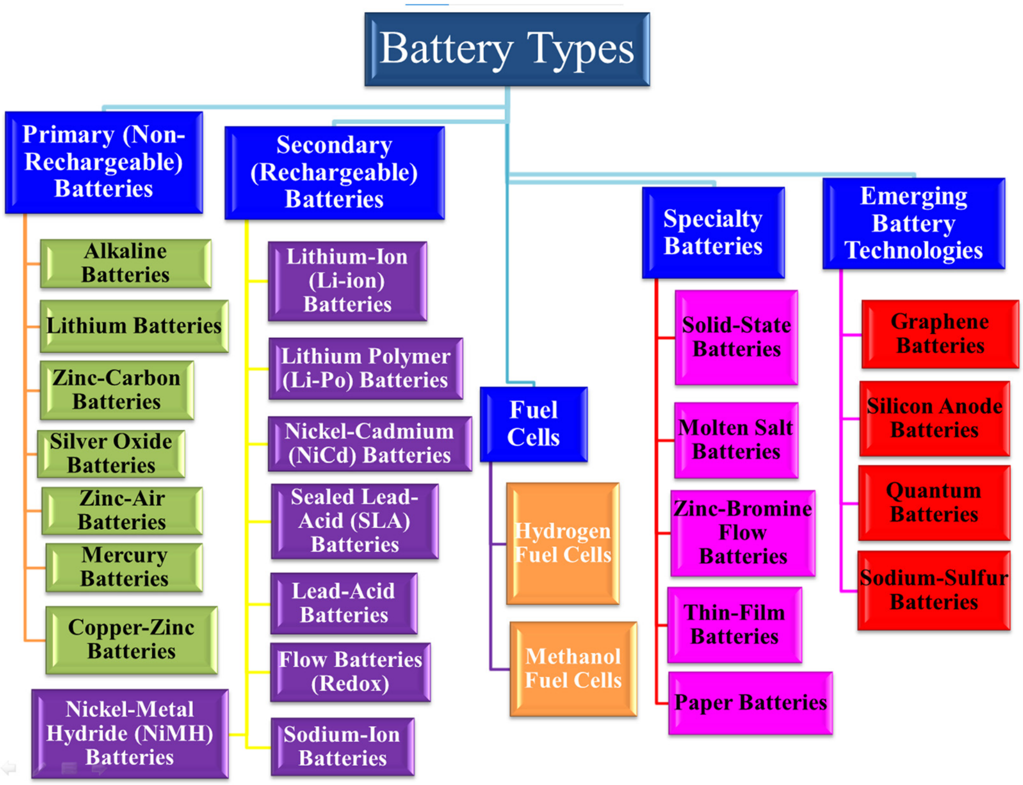

Fig. 1 A flow chart describing the types of batteries and their examples.

These substances pose serious risks to soil and water quality, as well as to human health. While some recycling programs exist for primary batteries, these programs are not as widespread or as efficient as those for secondary (rechargeable) batteries. Recycling primary batteries is often more challenging and less economically viable due to the relatively low material value extracted from them compared to rechargeable batteries. This creates a gap in current research and policy regarding how to improve the recyclability of primary batteries or develop alternatives that are more environmentally friendly. Research into the development of more sustainable primary batteries, such as those using non-toxic or biodegradable materials, is critical.[10] For example, there is growing interest in organic or bio-based battery chemistries that could potentially reduce the environmental footprint of battery disposal. Addressing the environmental challenges of primary battery use is essential for ensuring their continued viability in a world that is increasingly focused on sustainability.

Another major area of research for primary batteries is improving their performance, particularly in terms of energy density and efficiency. While primary batteries are generally reliable for low-drain applications, their energy density lags behind that of secondary batteries. This limits their use in high-drain or power-intensive applications.[11] As the demand for more powerful portable devices grows, primary batteries must evolve to meet these requirements. Improving the energy density of primary batteries would allow them to store more energy in the same physical space, making them more efficient and versatile. Advances in materials science, particularly in the development of new electrode and electrolyte materials, could play a key role in this. For instance, research into lithium-based chemistries for primary batteries has shown promise in increasing energy density while maintaining reliability. However, more work is needed to fully realize these benefits and make them commercially viable. Additionally, performance improvements in primary batteries could extend their shelf life and operational stability. This would make them even more attractive for applications like emergency systems and military operations, where reliability over long periods without maintenance is critical. Current research is exploring new materials and manufacturing techniques that could help enhance the stability and performance of primary batteries, making them more competitive in a range of applications.

Given the challenges and opportunities surrounding primary batteries, this review aims to provide a comprehensive analysis of recent advances, current research gaps, and future directions in the field. Specifically, the review will focus on the following key areas:

Advances in battery materials and chemistry: the review will explore recent developments in electrode and electrolyte materials for primary batteries, highlighting how these innovations are helping to improve energy density, efficiency, and environmental sustainability. Special attention will be given to emerging materials that could potentially address the limitations of current primary battery chemistries.

Environmental sustainability and recycling: this review will examine the environmental impact of primary batteries, including issues related to disposal and recycling. It will also explore the latest research into developing more sustainable battery technologies, such as biodegradable materials or batteries with non-toxic components. Additionally, the review will discuss potential policy changes and industry initiatives aimed at improving the recyclability of primary batteries.

Performance and safety improvements: the review will cover recent efforts to optimize the performance of primary batteries, focusing on energy density, shelf life, and operational stability. This section will also explore advancements in safety measures to prevent issues such as leakage, overheating, and explosion, particularly in high-stress or extreme environments.

Applications and emerging technologies: finally, the review will assess how primary batteries are being adapted for use in new and emerging applications, such as medical devices, space exploration, and other high-performance fields. Case studies and real-world examples will be presented to illustrate how primary batteries continue to play a vital role in modern technology.

Primary batteries remain an essential component of the energy storage landscape, providing reliable, cost-effective power for a wide range of applications. While they face challenges in terms of environmental sustainability and energy density, ongoing research is exploring ways to address these issues and improve the performance of primary batteries. By focusing on recent advances, challenges, and opportunities in the field, this review aims to provide a comprehensive overview of the current state of primary battery technology and its future potential.

2. Primary (non-rechargeable) batteries

2.1. Overview of primary batteries

Primary batteries, also known as non-rechargeable batteries, are a type of electrochemical energy storage that is designed for purpose of single-use applications. Once depleted or ruined, these batteries cannot be recharged, making them suitable for devices with low energy demands or infrequent use.[12] They are widely utilized in everyday household electronics such as remote controls, clocks, flashlights, and children's toys, where their relatively low cost, availability, and ease of use make them a preferred choice. The simplicity of their design and operation—typically requiring no maintenance—contributes to their widespread adoption.[13]

The chemistry of primary batteries is based on irreversible electrochemical reactions. This means that once the chemical reactants are exhausted, the battery can no longer generate power. While this limits the lifespan of primary batteries compared to rechargeable alternatives, their low self-discharge rate makes them ideal for long-term storage, ensuring they are ready to use even after extended periods without use.[14] Primary batteries are favored in applications where it is inconvenient or impractical to frequently replace or recharge batteries, such as in remote locations or emergency equipment like smoke detectors. A significant drawback of primary batteries is their environmental impact, as they must be discarded after use, contributing to electronic waste. Furthermore, some primary battery types, like mercury batteries, contain toxic heavy metals, although many countries have phased out such harmful chemistries. Primary batteries come in various types, each optimized for specific applications and performance characteristics. Let's discuss these types of primary batteries in detail.

Recent advancements in primary battery technologies, particularly in electrode materials and electrolytes, are focused on enhancing energy density, sustainability, and safety. Transition metal chalcogenides (TMCHs), such as $MoSe_2$ and WS_2, have garnered significant attention due to their high electrical conductivity, large surface area, and excellent electrochemical performance. These materials are being incorporated into both anodes and cathodes for primary batteries, enhancing energy storage and improving charge transport. Additionally, carbon-based nanomaterials, including graphene and carbon nanotubes, are being utilized to further enhance the performance of battery electrodes. These materials improve charge storage capacity, increase electron transfer efficiency, and contribute to the overall stability of the battery.[15] In metal–air batteries, optimization of air cathodes with bi-metallic catalysts, such as nickel–cobalt alloys, has shown promise in enhancing reaction kinetics and improving energy efficiency. Advancements in electrolytes have focused on improving the stability and performance of lithium-based primary batteries. The development of nonaqueous electrolytes incorporating ionic liquids and gel-based electrolytes has enabled higher voltage operation and reduced leakage risks, addressing many challenges associated with traditional electrolytes.[16] Additionally, solid-state electrolytes, particularly polymer- and ceramic-based, are being explored as alternatives to liquid systems to improve safety and energy density by reducing risks like leakage and flammability. The shift towards water-based electrolytes has gained momentum for applications requiring more environmentally friendly and cost-effective solutions, as these electrolytes offer a safer alternative with reduced environmental impact.

In existing reviews, the focus is often limited to specific types of primary batteries or particular performance parameters, leaving gaps in a comprehensive understanding of these technologies. For example, Kim *et al.* discuss the safety concerns of lithium-based batteries,[17] Zhang *et al.* explore the potential of magnesium anodes,[18] and Chen *et al.* highlight advances in lithium-fluorinated carbon batteries.[19] However, these studies focus on isolated aspects, such as material advancements or specific chemistries. The novelty of our manuscript lies in its holistic approach, providing an extensive review of all primary battery types, including their chemistries, voltage ranges, shelf life, capacity, environmental impact, leakage issues, temperature sensitivity, and size variants. This manuscript integrates these parameters into a comparative analysis that is not only descriptive but also evaluative, offering insights into their practical applications and limitations. Furthermore, the manuscript incorporates the latest advancements in electrode and electrolyte materials, demonstrating how they address key challenges like energy density and sustainability.

By combining a detailed comparative framework with recent technological developments, this work serves as both a comprehensive resource for researchers and a guide for future innovation in primary battery technologies.

2.2. Types of primary batteries

2.2.1. Alkaline batteries. Alkaline batteries have been a staple in modern society, powering everything from household devices to small electronics. Their chemistry, performance characteristics, and widespread availability have made them one of the most commonly used primary (non-rechargeable) batteries in the world.[20] This review will delve into various aspects of alkaline batteries, such as their chemistry, voltage, capacity, shelf life, usage, environmental impact, leakage, temperature sensitivity, and size variants.

Alkaline batteries derive their name from the alkaline electrolyte they use, which is typically potassium hydroxide (KOH) as depicted in Fig. 2(a). Unlike acidic electrolytes found in older battery technologies such as zinc–carbon batteries, the alkaline nature of KOH provides several advantages in terms of chemical stability and efficiency. The battery's primary chemical reaction involves the oxidation of zinc at the anode and the reduction of manganese dioxide at the cathode. During discharge, zinc is oxidized to form zinc oxide (ZnO), releasing electrons that travel through the external circuit to the cathode, where manganese dioxide (MnO_2) is reduced to Mn_2O_3. The electrolyte acts as an ionic conductor, allowing hydroxide ions to migrate between the electrodes.[21,22] The following electrochemical reactions take place in an alkaline battery:

$$\text{At the anode (oxidation): } Zn + 2OH^- \rightarrow ZnO + H_2O + 2e^-$$

$$\text{At the cathode (reduction): } 2MnO_2 + H_2O + 2e^- \rightarrow Mn_2O_3 + 2OH^-$$

The overall reaction can be summarized as:

$$Zn + 2MnO_2 \rightarrow ZnO + Mn_2O_3$$

The choice of zinc as the anode material and manganese dioxide as the cathode material offers a well-balanced combination of energy density, cost-effectiveness, and stability, making alkaline batteries particularly suited for consumer electronics. Moreover, the non-corrosive nature of the alkaline electrolyte enhances the battery's overall longevity and safety.

Fig. 2(b) illustrates the internal structure of an alkaline battery, highlighting its key components. At the center, the zinc anode serves as the negative electrode, surrounded by an ion conducting separator that prevents direct contact between the anode and the cathode while allowing ionic flow. The manganese oxide cathode, located on the outer layer, functions as the positive electrode. The current pick-up connects the electrodes to the external circuitry, ensuring proper electrical flow. The outer casing provides mechanical protection and houses the internal components. A pressure expansion seal is located near the base of the battery to accommodate gas

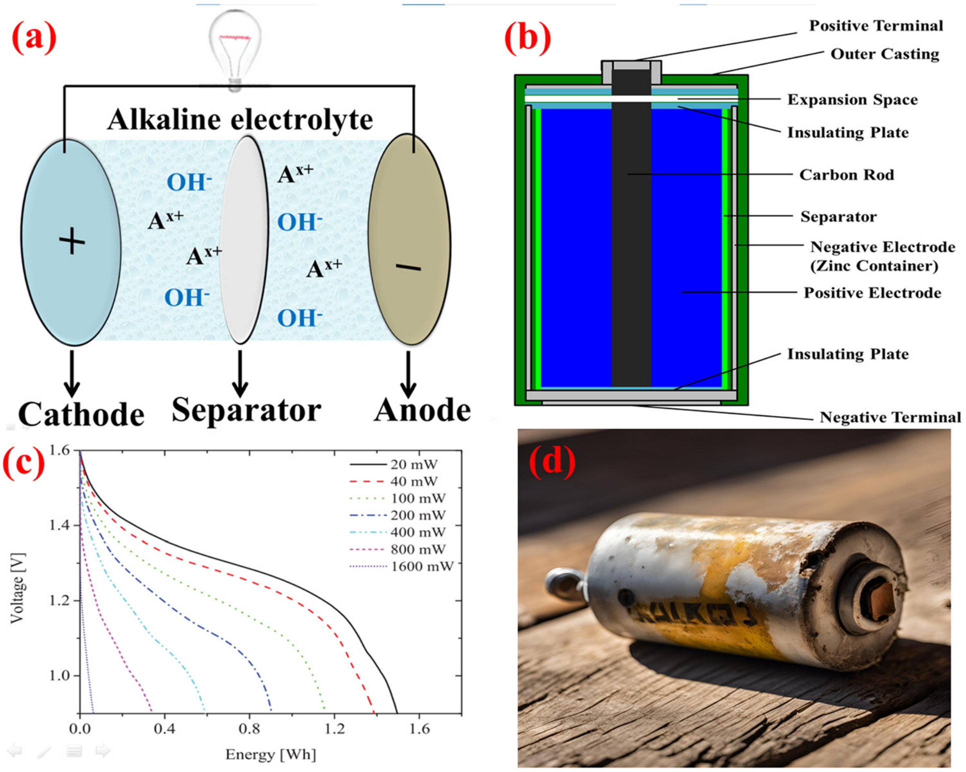

Fig. 2 (a) The schematic diagram for alkaline battery, (b) working diagram of a alkaline cell, (c) an alkaline battery's performance, power demands, and energy output reproduced from ref. 23 copyright Copyright © 2016 ACM, (d) a visualization of battery leakage produced from Lexica (AI).

buildup during discharge, preventing leakage. At the bottom, a protective cap safeguards the internal components, while the negative terminal ensures connection to the external circuit. The positive connection is at the top, completing the electrical circuit. This cross-sectional diagram in Fig. 2(b) provides a clear understanding of how the different components within an alkaline battery work together to generate and maintain electrical energy.

Alkaline batteries typically produce a nominal voltage of 1.5 volts per cell, which is slightly higher than the 1.2 volts provided by rechargeable NiMH and NiCd batteries.[24] This makes them more suitable for devices that require consistent and slightly higher voltage outputs. However, the voltage of alkaline batteries gradually decreases as the battery discharges, following a relatively smooth curve. This contrasts with other battery types, such as lithium-based batteries, which maintain their voltage levels for a longer duration before dropping sharply near the end of their cycle.[25] In multi-cell configurations, where several alkaline cells are combined in series (such as in 9 V batteries or D-cell batteries used in flashlights), the overall voltage can be multiplied to meet the requirements of the device. Despite their moderate voltage levels, alkaline batteries are favored for their predictable and steady discharge curve, which ensures reliable performance over extended use. Fig. 2(c) shows a set of discharge curves for an alkaline battery at different power loads (in mW), plotting voltage (V) on the *Y*-axis against energy (W h) on the *X*-axis. The graph represents how the battery's voltage changes as energy is drawn under various power loads. The voltage starts around 1.6 V and gradually decreases during discharge, while the energy represents the total watt-hours delivered by the battery. Different curves in the figure correspond to different power loads. The solid black line (20 mW) represents the lowest power load, where the battery discharges slowly, delivering more total energy, up to approximately 1.6 W h. As the power load increases, the voltage drops more quickly. For example, the dashed red line (40 mW) shows a steeper voltage decline compared to the 20 mW curve. Similarly, the dotted green line (100 mW), the dash-dotted blue line (200 mW), and the curves representing 400 mW, 800 mW, and 1600 mW illustrate progressively faster voltage drops, as the power demand increases. In general, the graph illustrates that higher power draws lead to quicker discharges, with the battery delivering less total energy before its voltage drops significantly. The lower the power consumption, the more efficiently the battery discharges, providing higher overall energy output. This visual representation in Fig. 2(c) helps to understand the relationship between an alkaline battery's performance, power demands, and energy output.

The capacity of an alkaline battery, measured in milliampere-hours (mA h), varies depending on the size of the battery and the specific application. On average, AA-sized alkaline batteries have a capacity ranging from 2400 to 2900 mA h,[26] while AAA batteries have a lower capacity, usually around 1000 to 1200 mA h.[27] Larger D-sized alkaline batteries can offer capacities exceeding 12 000 mA h,[28] making them ideal for high-drain devices like flashlights and portable radios. The capacity of alkaline batteries is closely tied to the current draw of the device they power. For low-drain devices like clocks or remote controls, alkaline batteries perform exceptionally well, providing long-lasting power. However, their capacity tends to decrease more rapidly under high-drain conditions, such as in digital cameras or motorized toys. In such cases, the internal resistance of the battery increases, causing heat generation and reducing the overall efficiency of the battery. Alkaline batteries also exhibit a "self-discharge" phenomenon, wherein the battery slowly loses capacity over time even when not in use. This self-discharge rate is relatively low in alkaline batteries compared to other chemistries, such as nickel-based rechargeable batteries, which means alkaline batteries retain their charge well over extended periods.

One of the key advantages of alkaline batteries is their long shelf life. Under ideal storage conditions—typically in a cool, dry environment—alkaline batteries can retain their charge for up to 5 to 10 years. This is due to the relatively slow self-discharge rate, which ranges from 1% to 2% per year.[29] Consequently, they are an excellent choice for emergency devices like flashlights, smoke detectors, and medical equipment, where reliability over long periods is critical. Manufacturers often label alkaline batteries with an expiration date to ensure consumers are aware of their storage potential. Even after prolonged storage, alkaline batteries can still retain a significant portion of their original capacity, making them suitable for devices that require sporadic or emergency use. However, storing alkaline batteries at extremely high temperatures can accelerate their self-discharge rate, reducing their overall shelf life.[30]

Alkaline batteries are used in a wide range of applications, making them one of the most versatile battery types on the market. They are commonly found in household devices such as remote controls, wall clocks, portable radios, flashlights, and toys. In addition, their relatively high energy density and consistent voltage output make them ideal for small consumer electronics like digital cameras, handheld gaming consoles, and wireless keyboards and mice. Alkaline batteries are favored for devices with both low and moderate power requirements.[31] However, in high-drain applications, such as digital cameras or motorized devices, their performance tends to diminish faster compared to rechargeable lithium-ion or NiMH batteries. In these cases, the internal resistance increases as the battery discharges, which can lead to voltage drops and decreased efficiency. Despite the growing popularity of rechargeable batteries, alkaline batteries remain the go-to choice for many consumer applications due to their convenience and widespread availability. Since they do not require any special charging equipment, they are often used in situations where ease of replacement and long shelf life are more important than rechargeability.

While alkaline batteries have numerous advantages in terms of performance, their environmental impact is a topic of concern. Being single-use, non-rechargeable batteries, alkaline cells contribute to the growing problem of electronic waste (e-waste). Millions of alkaline batteries are discarded annually, and improper disposal can lead to environmental contamination, particularly from the zinc and manganese compounds used in their construction. However, modern alkaline batteries contain no mercury or cadmium, substances that were once prevalent in older battery technologies and posed significant environmental hazards.[32] In recent years, manufacturers have made efforts to reduce the environmental footprint of alkaline batteries by designing them to be more recyclable. Some recycling programs accept alkaline batteries, although the process of recycling them is more complex and less economically viable than recycling other battery types like lead–acid or lithium-ion. As a result, many alkaline batteries still end up in landfills, where they can take decades to decompose. In response to these concerns, consumers are encouraged to switch to rechargeable batteries for frequently used devices. However, in applications where rechargeable batteries are impractical or too costly, alkaline batteries remain a practical option.[33] Continued development in battery recycling technologies may help mitigate the environmental impact of alkaline batteries in the future.

One of the common issues with alkaline batteries is the potential for leakage, especially as they near the end of their life or are left unused for extended periods. Alkaline batteries can leak KOH, a corrosive substance,[34] which can damage the device they are powering as shown in Fig. 2(d). Leakage typically occurs when the internal pressure builds up as the battery discharges, leading to the rupture of the outer casing. While leakage is less common in modern alkaline batteries compared to older models, it remains a concern, particularly for devices that are left in storage with batteries installed. To mitigate the risk of leakage, manufacturers often include safety features, such as pressure-release valves, to prevent internal pressure from reaching dangerous levels. Additionally, consumers are advised to remove alkaline batteries from devices that will not be used for extended periods, as this reduces the risk of leakage and prolongs the lifespan of the device.

Alkaline battery perform best at room temperature, but their performance can be affected by extreme temperatures. This is why devices powered by alkaline batteries tend to perform poorly in cold environments, such as during winter outdoor activities or in unheated areas. The increased heat accelerates the chemical reactions, which can cause the battery to discharge more quickly and increase the risk of leakage.[35] Prolonged exposure to high temperatures can also shorten the shelf life of alkaline batteries and reduce their overall performance. Manufacturers typically recommend storing alkaline batteries in a cool, dry place to maximize their shelf life and prevent performance degradation. The standardization of these sizes allows consumers to easily replace batteries in their devices, regardless of the brand or manufacturer. In addition to these common sizes, alkaline batteries are also available in specialized formats, such as button cells (used in watches, calculators, and hearing aids) and larger cylindrical cells for industrial applications. The versatility of alkaline batteries in terms of size and form factor makes them a highly adaptable energy source for a wide variety of devices.[36]

Alkaline batteries continue to play a critical role in modern society due to their affordability, availability, and reliable performance. While rechargeable batteries and other emerging technologies have gained popularity in recent years, alkaline batteries remain a practical and convenient choice for many applications. Their chemistry, voltage, capacity, and shelf life make them ideal for both low- and moderate-drain devices, although they may not perform as well in high-drain applications. However, the environmental impact of single-use alkaline batteries, particularly in terms of e-waste and disposal, remains a significant concern. Consumers are encouraged to recycle alkaline batteries whenever possible and consider switching to rechargeable alternatives for frequently used devices. Nevertheless, with their wide range of sizes and consistent performance, alkaline batteries will likely remain a staple in the consumer electronics market for the foreseeable future.

2.2.2. Zinc–carbon batteries.

Zinc–carbon batteries are among the oldest and most widely used types of batteries in the world, known for their simplicity, low cost, and widespread availability. First introduced in the late 19th century, they have historically been the dominant battery type for powering household devices. Despite the rise of more advanced battery technologies like alkaline and lithium-ion, zinc–carbon batteries remain in use due to their affordability and ease of manufacture. This review takes a critical look at zinc–carbon batteries, focusing on their chemistry, voltage, capacity, shelf life, usage, environmental impact, leakage, temperature sensitivity, and size variants.

At the anode, zinc undergoes oxidation, losing electrons to form zinc ions:

$$\text{Anode reaction (oxidation): } Zn \rightarrow Zn^{2+} + 2e^-$$

At the cathode, manganese dioxide is reduced as it gains electrons, reacting with the electrolyte:

$$\text{Cathode reaction (reduction): } 2MnO_2 + 2NH_4Cl + 2e^- \rightarrow Mn_2O_3 + 2NH_3 + H_2O + 2Cl^-$$

The zinc–carbon battery, often referred to as a dry cell, operates based on the chemical reactions between zinc and manganese dioxide (MnO_2) with an acidic electrolyte, usually ammonium chloride (NH_4Cl) or zinc chloride ($ZnCl_2$). The electrolyte in zinc–carbon batteries is acidic, which contrasts with the alkaline electrolyte used in more advanced battery chemistries like alkaline batteries. The acidic nature of the electrolyte makes zinc–carbon batteries more prone to corrosion and less efficient than other chemistries, particularly in terms of energy density and longevity.[37,38] This is one reason why zinc–carbon batteries have gradually been replaced by alkaline batteries in many applications.

Zinc–carbon batteries have a nominal voltage of 1.5 volts per cell, which is comparable to alkaline batteries.[39,40] However, their voltage tends to drop more rapidly during discharge due to the lower energy density and internal resistance of the zinc–carbon chemistry. This voltage drop occurs more noticeably in high-drain applications, where the demand for current is higher, leading to faster depletion of the battery's stored energy. In devices that require multiple cells in series, such as flashlights or portable radios, the combined voltage output can meet the necessary power requirements. However, the performance of zinc–carbon batteries in these configurations is often inferior to that of alkaline batteries, especially when powering high-drain devices. As the voltage drops below a certain threshold, the device may no longer function properly, even if the battery has some remaining capacity. The rapid voltage decline is a critical limitation of zinc–carbon batteries, making them less suitable for devices that require consistent power over extended periods.[41] This characteristic also contributes to their reputation as a ''disposable'' battery, intended for short-term or low-drain applications where cost is a primary concern.

The capacity of a zinc–carbon battery, measured in milliampere-hours (mA h), is generally lower than that of alkaline batteries. For example, an AA zinc–carbon battery typically has a capacity of around 400 to 600 mA h,[42] while its alkaline counterpart offers 2400 to 2900 mA h.[43] The capacity of zinc–carbon batteries varies based on the size and type of battery, with larger C and D cells offering higher capacities for more energy-demanding devices. Zinc–carbon batteries are best suited for low-drain applications such as clocks, remote controls, and basic flashlights. In high-drain devices like digital cameras or motorized toys, the limited capacity of zinc–carbon batteries is quickly exhausted, leading to shorter operating times and more frequent battery replacements.[44] Their relatively low capacity, combined with the voltage drop during discharge, makes zinc–carbon batteries less efficient for modern electronics that require sustained power. Despite their low capacity, zinc–carbon batteries remain popular in applications where the energy demand is minimal, and the cost of the battery is a primary consideration. For example, they are still widely used in inexpensive products like disposable flashlights, novelty items, and toys.

Fig. 3 compares various cathode materials for zinc-ion batteries (Zn-ion batteries) based on their specific capacity (in mA h g^{-1}) and their potential *versus* Zn^{2+}/Zn (in volts). The *x*-axis represents the specific capacity of different cathode materials, ranging from 0 to 500 mA h g^{-1}, while the *y*-axis shows the potential in volts, ranging from −0.5 V to 2.5 V. Additionally, the pH scale is indicated at the top of the graph, highlighting the electrochemical stability window of aqueous Zn-ion batteries in different pH conditions. Several cathode materials are grouped by their specific types and marked by different colors: Mn-based cathodes (blue), V-based cathodes (green), PBAs-based cathodes (Prussian Blue Analogue) (orange), organic-based cathodes (purple), other cathodes (red). The graph also includes two diagonal lines labeled as ''O_2 evolution'' and ''H_2 evolution,'' indicating the potential limits where water decomposition occurs, affecting the battery's operational window in aqueous electrolytes. These lines suggest that cathode materials operating within this window (between H_2 and O_2 evolution) are stable in water-based electrolytes. Some of the specific cathode materials mentioned include: Mn-based: MnO_2, Mn_3O_4, $ZnMn_2O_4$, V-based: VO_2, V_2O_5, $H_2V_3O_8$, PBAs-based: CuHCF, ZnHCF, FeHCF, organic-based: exTTF, PANF, other materials: MoS_2, Mo_6S_8, PTO, C4Q.

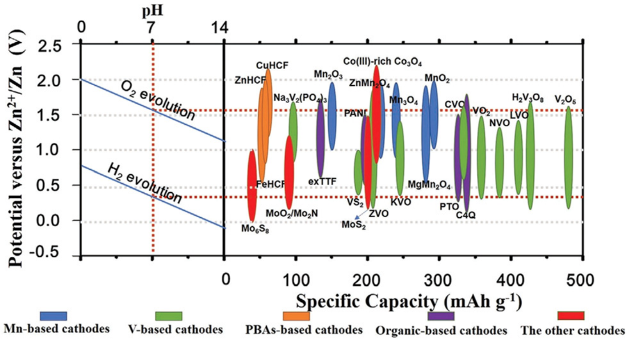

Fig. 3 Operating voltage *versus* specific capacity of various cathode materials for AZIBs reproduced from ref. 45 copyright © 2020 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim.

Each cathode material has a specific range for its potential and capacity, showing varying levels of performance in terms of energy storage (specific capacity) and voltage output. Some high-capacity materials (around 500 mA h g^{-1}) include V_2O_5 and $H_2V_3O_8$,[46] while materials like Mn_3O_4 and $ZnMn_2O_4$ have lower capacities but operate at safer potentials within the aqueous electrolyte stability window.[47] The graph highlights the trade-off between potential and specific capacity, helping to identify materials that are both electrochemically stable and capable of delivering high energy densities for Zn-ion batteries.

Hiralal *et al.*[48] presented a comprehensive study on the electrochemical properties of zinc–carbon batteries, particularly emphasizing their structure–performance relationship. The authors have successfully investigated the influence of different materials and structural modifications on the performance, utilizing a combination of experimental approaches and electrochemical characterizations. In Fig. 4(a) and (b), the structure and images of the battery are showcased, offering a clear representation of the structural composition. The data provided here demonstrates the effective integration of active materials, which plays a crucial role in the overall performance of the battery. Furthermore, Fig. 4(c)–(e) illustrates the electrochemical performance of the zinc–carbon battery under various conditions. The cyclic voltammetry (CV) and charge–discharge profiles show promising performance metrics, with the battery demonstrating stable electrochemical behavior over extended cycles. One of the key strengths of the study lies in its detailed analysis of the battery's discharge characteristics, particularly in varying environmental conditions. The authors have shown how the choice of materials directly influences the battery's durability and efficiency, which is critical for practical applications.

One of the major drawbacks of zinc–carbon batteries is their relatively short shelf life compared to other battery chemistries. Zinc–carbon batteries typically have a shelf life of 1 to 3 years, depending on storage conditions and the quality of the battery. This is significantly shorter than the shelf life of alkaline batteries, which can last up to 10 years under optimal conditions. The shorter shelf life of zinc–carbon batteries is due to the gradual degradation of the zinc anode over time. Even when

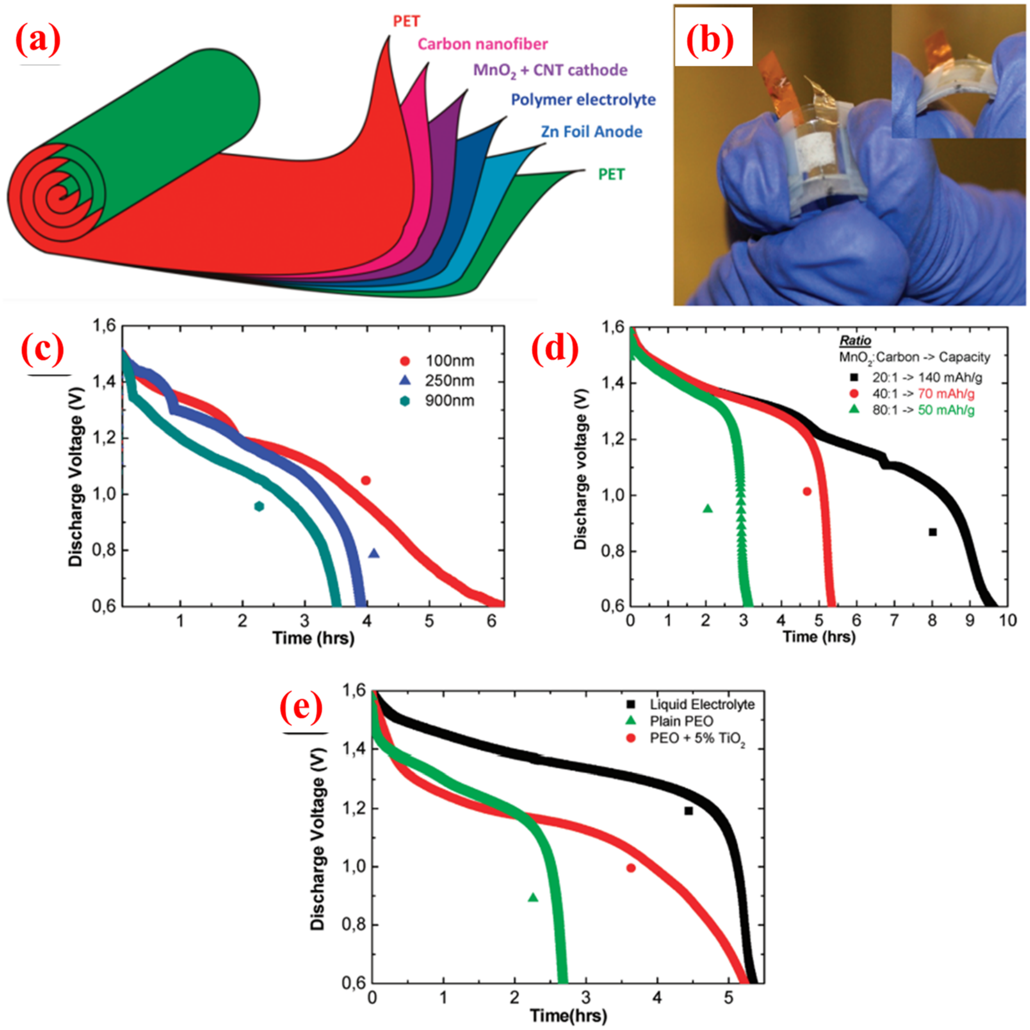

Fig. 4 (a) Image depicting the schematic image of zinc carbon battery, (b) the actual image of the produced flexible battery, (c)–(e) illustrates the electrochemical performance of the zinc–carbon battery under various conditions reproduced from ref. 48 copyright © 2010, American Chemical Society.

not in use, zinc–carbon batteries can undergo a self-discharge process, where the chemical reactions slowly consume the zinc, reducing the battery's overall capacity.[49] Additionally, the acidic electrolyte can corrode the internal components, leading to leakage and further reducing the battery's lifespan. To mitigate these issues, zinc–carbon batteries should be stored in a cool, dry environment to minimize self-discharge and corrosion. However, even under ideal storage conditions, zinc–carbon batteries will eventually lose their charge, making them less reliable for long-term storage or emergency use.

Zinc–carbon batteries are primarily used in low-cost, low-drain applications where high performance and long battery life are not critical requirements. They are commonly found in devices such as: remote controls, clocks, flashlights, small toys and battery-operated radios. Their low price point makes them an attractive option for consumers who need an inexpensive power source for basic devices.[50] However, for high-drain or energy-hungry devices like digital cameras, smartphones, or motorized equipment, zinc–carbon batteries are not recommended due to their low capacity, short lifespan, and rapid voltage drop. In modern consumer electronics, zinc–carbon batteries have largely been replaced by more efficient and long-lasting battery types, such as alkaline and lithium-based batteries. Despite this, zinc–carbon batteries still have a place in certain markets, particularly in developing countries and low-cost products where the focus is on affordability rather than performance.

One of the most common problems associated with zinc–carbon batteries is leakage. As the battery discharges or ages, the acidic electrolyte inside the cell can corrode the zinc casing, leading to the release of ammonium chloride or zinc chloride. This leakage can damage the electronic devices that the battery powers, leading to costly repairs or replacements. Leakage is more likely to occur when zinc–carbon batteries are left in devices for extended periods, especially after they have been fully discharged. To prevent leakage, it is recommended to remove batteries from devices that will not be used for long periods and to check batteries regularly for signs of corrosion or damage. While modern zinc–carbon batteries are designed with better seals to reduce the risk of leakage, the problem still persists, particularly in cheaper or lower-quality brands.[51] Consumers are advised to dispose of old or corroded batteries promptly to prevent damage to their devices.

Zinc–carbon batteries are highly sensitive to temperature changes, which can significantly impact their performance. This makes zinc–carbon batteries unsuitable for use in cold environments, as devices powered by these batteries may experience performance issues or stop working altogether. At high temperatures, the opposite occurs. The increased heat accelerates the chemical reactions, leading to faster discharge rates and increased internal resistance. This can cause the battery to deplete more quickly, reducing its overall lifespan.[52]

Zinc–carbon batteries, while no longer the dominant battery technology, still play a role in powering low-cost, low-drain devices around the world. Their simple chemistry, low voltage, and limited capacity make them less suitable for high-performance applications, but their affordability ensures that they remain a viable option for many consumers. However, the environmental impact of zinc–carbon batteries, particularly in terms of disposal and leakage, is a growing concern. As more efficient and environmentally friendly battery technologies continue to emerge, zinc–carbon batteries may eventually be phased out in favor of more sustainable alternatives. Nonetheless, they have left an indelible mark on the history of battery technology, and their contributions to the development of portable power cannot be understated.

2.2.3. **Lithium batteries.**

Lithium batteries have revolutionized energy storage to understand the chemistry behind lithium batteries sheds light on why they have become indispensable in contemporary energy applications.

Lithium batteries come in two major types: lithium–metal batteries and lithium–ion batteries. While both utilize lithium as a key component, their internal chemistries and applications differ. Lithium–metal batteries were the first to utilize lithium, taking advantage of lithium's position as the lightest metal and one of the most electropositive elements. These batteries typically use metallic lithium as the anode and a non-aqueous electrolyte solution that enables the movement of lithium ions between the anode and cathode. The cathode is commonly composed of materials like manganese dioxide or carbon–fluorine compounds.[53] The electrochemical reaction for a lithium–metal battery follows the basic principle where lithium atoms at the anode release electrons to create lithium ions (Li^+). These ions migrate through the electrolyte and are stored at the cathode during the discharge cycle. When recharged, the process reverses, with lithium ions moving back to the anode. This cycle, however, presents challenges such as the formation of dendrites—needle-like structures of lithium that grow from the anode and can lead to short circuits or even cause the battery to catch fire.[54] Due to safety concerns, lithium–metal batteries are generally used in non-rechargeable applications like military devices, pacemakers, or other specialized technologies.

Lithium–ion batteries are by far the more popular and widely used version, mainly due to their rechargeability, safety improvements, and energy efficiency. In these batteries, lithium does not exist in its metallic state; instead, lithium ions move between two intercalated electrodes, typically made from compounds like lithium cobalt oxide ($LiCoO_2$) for the cathode and graphite for the anode. The core chemical process in a lithium-ion battery revolves around the intercalation and de-intercalation of lithium ions. During the discharge cycle, lithium ions are released from the anode and travel through the electrolyte (usually a lithium salt dissolved in an organic solvent) towards the cathode. As the ions are accepted by the cathode material, the battery releases electrical energy.[55] When the battery is recharged, an external current forces the lithium ions back to the anode, where they are stored within the layers of graphite.

In Fig. 5(a), the structural diagram of two types of lithium primary batteries is shown. On the left, we see a cylindrical lithium sulfur dioxide ($Li–SO_2$) primary battery, consisting of an anode (lithium metal), a cathode, and a liquid sulfur dioxide (SO_2) electrolyte. The structure includes insulating components such as a tube and ring to ensure separation of the electrodes, and a carbon catalyst to facilitate reactions at the cathode. The entire system is housed in a jacket and case for containment and protection. On the right, a cross-sectional view of a lithium manganese dioxide ($Li–MnO_2$) primary battery is displayed, showcasing a similar design with the lithium negative electrode and manganese dioxide (MnO_2) positive electrode, separated by a gasket and enclosed in a positive can. In Fig. 5(b), we see real-world examples of discarded lithium primary batteries ($Li–SO_2$) and lithium–ion (Li–ion) batteries being prepared for recycling or disposal. The left side shows a collection of Li-primary batteries, while the right side depicts a larger number of Li-ion batteries, emphasizing the importance of distinguishing between battery types in waste management.

Lithium batteries stand out because of their high voltage and energy density. A single lithium-ion cell produces a nominal voltage of around 3.6–3.7 volts, significantly higher than standard nickel–cadmium (NiCd) or NiMH batteries, which typically produce 1.2 volts per cell.[57] This higher voltage allows lithium batteries to deliver more power in a smaller package, making them ideal for portable electronics like smartphones, laptops, and cameras. Energy density is another key advantage. Lithium-ion batteries can achieve energy densities of 150–250 W h kg^{-1},[58] while advanced lithium–metal chemistries can go even higher. This high energy density is crucial for applications like EVs and renewable energy storage systems, where maximizing energy per unit of weight is essential for extending range or increasing efficiency.

Lithium-ion batteries generally have a much higher capacity than other rechargeable battery types, providing longer run times for devices. The battery's lifespan is typically measured in charge cycles—a full discharge and recharge cycle. On average, lithium-ion batteries can last between 300 to 500 cycles before they begin to lose significant capacity. With proper care, however, they can reach over 1000 cycles.[59] The long lifespan of lithium-ion batteries, coupled with their capacity to store large amounts of energy, makes them particularly appealing for consumer electronics, eVs, and energy storage systems.

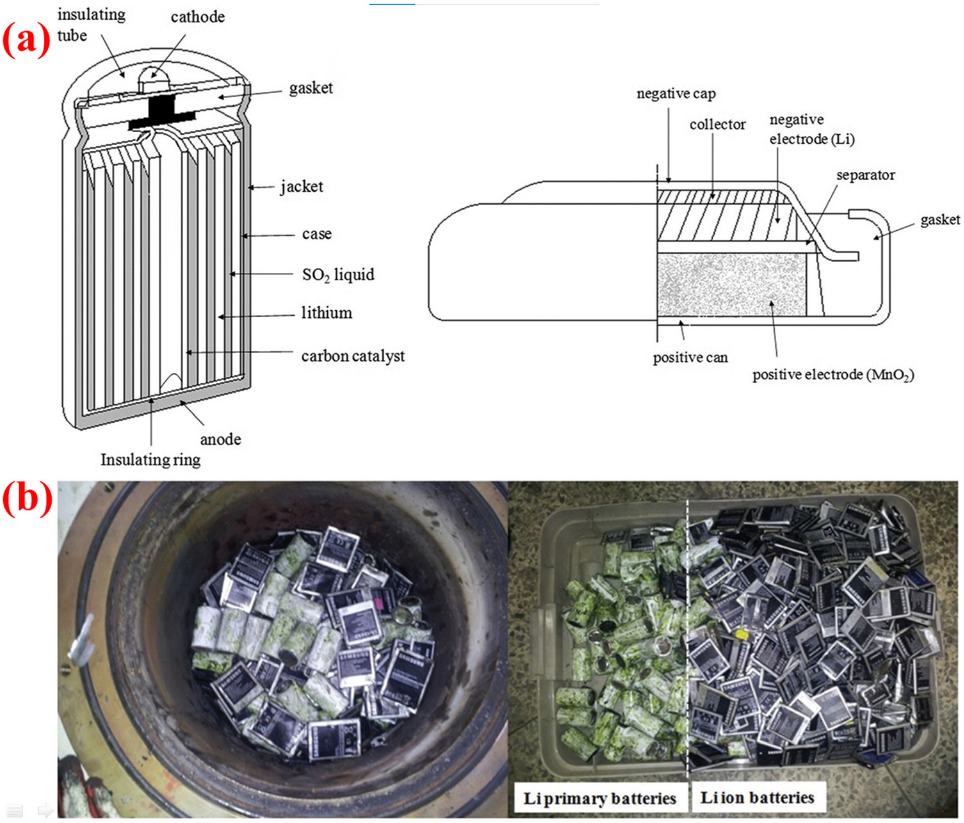

Fig. 5 (a) Schematic illustration of two types of lithium primary batteries: lithium sulfur dioxide (Li–SO_2) and lithium manganese dioxide (Li–MnO_2); (b) disposed lithium primary batteries (Li-primary) and lithium-ion (Li-ion) batteries in a recycling facility reproduced from ref. 56 copyright © IMechE 2015.

This advantage over traditional battery types, such as lead–acid or nickel-based chemistries, is a major reason for the widespread adoption of lithium batteries across industries.

Lithium batteries also benefit from an extended shelf life compared to other battery chemistries. When not in use, they exhibit low self-discharge rates, meaning they retain their charge for longer periods. A lithium-ion battery will typically lose only about 5–10% of its charge per month when stored, making them ideal for applications where batteries must be stored or remain idle for long durations, such as in emergency backup systems or infrequently used devices. The Fig. 6 displays the electrochemical performance of a solid-state lithium-ion battery utilizing a LiTFSI-60% hybrid electrolyte. Fig. 6(a) presents the charge and discharge profiles of the battery over multiple cycles at a constant C-rate of 0.1C. The specific capacity (in mA h g^{-1}) remains stable over different cycles, indicating good cyclic stability of the battery. The voltage range during cycling is between 2.6 V and 4.2 V, with slight deviations as the number of cycles increases. Fig. 6(b) shows the charge and discharge curves at varying C-rates, ranging from 0.1C to 1C. As the C-rate increases, the specific capacity decreases, which is typical due to increased polarization at

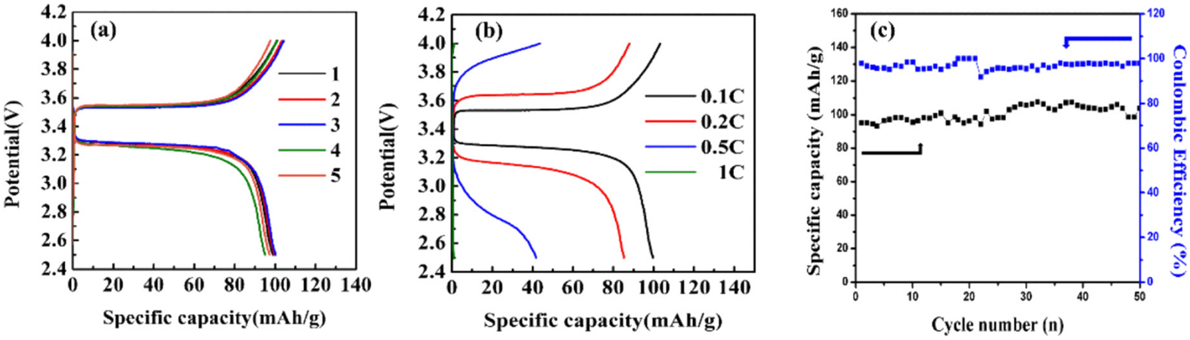

Fig. 6 Electrochemical performance of the solid-state lithium-ion battery with LiTFSI-60% hybrid electrolyte: (a) charge and discharge profiles at 0.1C over multiple cycles, (b) charge and discharge curves at varying C-rates of 0.1C, 0.2C, 0.5C, and 1C, and (c) cycling performance and coulombic efficiency at 0.1C over 50 cycles reproduced from ref. 60 copyright © 2022 by the authors. Licensee MDPI, Basel, Switzerland.

higher current densities. The curve at 0.1C offers the highest specific capacity, while 1C results in lower capacity due to rapid charge/discharge. Fig. 6(c) illustrates the cycling performance and coulombic efficiency of the battery over 50 cycles at a 0.1C rate. The specific capacity remains relatively constant, while the coulombic efficiency stays above 90%, demonstrating the battery's efficient charge storage and discharge over extended cycles.

While lithium batteries offer numerous advantages, one of their key vulnerabilities is temperature sensitivity. Extreme temperatures, both high and low, can adversely affect the performance and lifespan of lithium-ion batteries. At low temperatures, the movement of lithium ions slows down, reducing the battery's ability to deliver power. This is why devices powered by lithium-ion batteries may exhibit diminished performance in cold environments.

Conversely, high temperatures can lead to the degradation of the electrolyte and the electrodes, accelerating the aging process of the battery. Prolonged exposure to heat can also increase the risk of thermal runaway—a scenario where the battery's internal temperature rises uncontrollably, potentially leading to combustion.[61] Modern lithium-ion batteries are equipped with safety features like temperature sensors, venting mechanisms, and battery management systems to mitigate these risks, but managing temperature remains a challenge in high-performance applications like eVs.

Lithium batteries versatility lies in their wide-ranging applications, from small electronics to large energy storage systems, making them essential across industries. Their adaptability stems from high energy density, lightweight design, and rechargeability, allowing them to power devices for extended periods without significant capacity loss.[62] This scalability has led to widespread use in portable electronics, renewable grids, eVs, and critical medical devices. Their unique ability to meet diverse energy demands efficiently positions lithium batteries as a leading technology in modern energy solutions while also aligning with environmental considerations by offering rechargeable, long-lasting power.

In the realm of portable electronics, lithium-ion batteries have become the preferred power source due to their lightweight yet high-energy nature. Devices like smartphones, tablets, laptops, cameras, and wearable technology depend on these batteries for their compact form and reliable energy output. Unlike traditional batteries, lithium-ion cells can be recharged repeatedly without substantial loss of capacity, making them essential in tech devices that require frequent charging. Their reliable performance and efficiency have solidified lithium-ion batteries as the standard choice for manufacturers striving to meet the needs of today's tech-savvy, mobile users. Lithium-ion batteries have also become a driving force behind the development of eVs,[63] thanks to their substantial energy density and ability to power electric motors over considerable distances. Their capacity to store significant energy in a compact form factor makes them especially suitable for EVs, where maximizing efficiency and driving range is crucial. As EV manufacturers continuously improve lithium-ion technology to extend range, decrease charging time, and lengthen battery lifespan, lithium-ion batteries remain at the forefront of sustainable transportation, making eVs increasingly practical and appealing to a broader market.

The need for efficient and effective energy storage solutions is also essential as the renewable energy sources, such as wind and solar, gain popularity. Li-ion batteries are widely used in residential and grid-scale energy storage systems to capture and store excess energy produced during peak periods. This stored energy can be dispatched when production dips or demand rises, ensuring a steady energy supply. Their reliability and adaptability in storing renewable energy make lithium-ion batteries the top choice for supporting sustainable power grids, thus promoting the global shift towards more extensive renewable energy adoption. Lithium batteries are also crucial in medical devices where reliability, longevity, and low maintenance are priorities. Devices like pacemakers, defibrillators, and hearing aids rely on lithium batteries for stable, long-lasting power to ensure patient safety. Their extended lifespan reduces the need for frequent replacements, offering both convenience and safety for users. With their dependable, compact design and high energy output, lithium batteries are indispensable in healthcare, where consistent power is essential for patient health and the functioning of vital medical technologies.

2.2.4. Silver oxide batteries.

Silver oxide batteries are a type of primary, non-rechargeable battery that has garnered significant attention for their use in small electronic devices. Known for their high energy density, stable voltage output, and long shelf life, these batteries are commonly found in devices such as wristwatches, hearing aids, calculators, and other small-scale electronics. Silver oxide batteries belong to the zinc–silver battery family, leveraging silver's unique electrochemical properties to deliver consistent and reliable performance. This review examines the chemistry, characteristics, and various applications of silver oxide batteries, offering insight into their strengths and limitations.

At the heart of silver oxide batteries lies a simple but effective chemical composition. These batteries operate based on the electrochemical reaction between silver oxide (Ag_2O) and zinc, which serves as the anode and cathode, respectively. The electrolyte used in silver oxide batteries is typically a highly alkaline solution, often KOH or sodium hydroxide (NaOH).[64] This strong electrolyte enables efficient ion transport, facilitating the chemical reactions that generate electricity.

The overall cell reaction in a silver oxide battery can be expressed as:

$$\text{At the anode (oxidation): } Zn \rightarrow Zn^{2+} + 2e^-$$

$$\text{At the cathode (reduction): } Ag_2O + H_2O + 2e^- \rightarrow 2Ag + 2OH^-$$

The combination of these two half-reactions results in the following overall reaction: $Zn + Ag_2O \rightarrow ZnO + 2Ag$

In this reaction, zinc undergoes oxidation, losing electrons, while silver oxide is reduced, gaining electrons and forming metallic silver. The energy released during this process is harnessed as electrical power, allowing the battery to provide a stable and sustained voltage output. Silver oxide batteries are designed to have a high energy density due to the significant electrochemical potential difference between zinc and silver oxide.[65] Silver is a highly conductive material, allowing the battery to maintain a stable voltage throughout its discharge cycle, even under varying loads. This characteristic makes silver oxide batteries ideal for precision electronic devices that require consistent performance over long periods.

The Fig. 7 represents the structure of a typical zinc–silver oxide (Zn–AgO) cell, illustrating its three main regions: the positive electrode, the separator, and the negative electrode. Region 1: positive electrode ($x = 0$): this region contains silver (Ag) and silver oxide (AgO) particles immersed in a KOH electrolyte. During discharge, AgO is reduced to Ag, releasing electrons and contributing to the cell's overall electrochemical reaction. Region 2: separator: the central region consists of a porous separator that physically separates the two electrodes while allowing ionic conductivity through the KOH electrolyte. It prevents the direct contact of the electrodes, avoiding a short circuit. Region 3: negative electrode ($x = l$): the negative electrode contains zinc and ZnO particles, also in contact with the KOH electrolyte. During discharge, zinc is oxidized to ZnO, releasing electrons to the external circuit.

The nominal voltage of silver oxide batteries is typically 1.55 volts per cell.[67] This voltage remains relatively stable during the discharge cycle, a notable advantage over other battery chemistries that experience a gradual voltage drop as they deplete. The stable voltage output ensures that devices powered by silver oxide batteries maintain consistent performance until the battery is nearly exhausted. This stable voltage is particularly beneficial for precision instruments such as digital watches and medical devices like hearing aids, where a sudden drop in voltage could result in malfunction or inaccuracy. The ability of silver oxide batteries to provide steady voltage makes them highly reliable for long-term use in such applications.

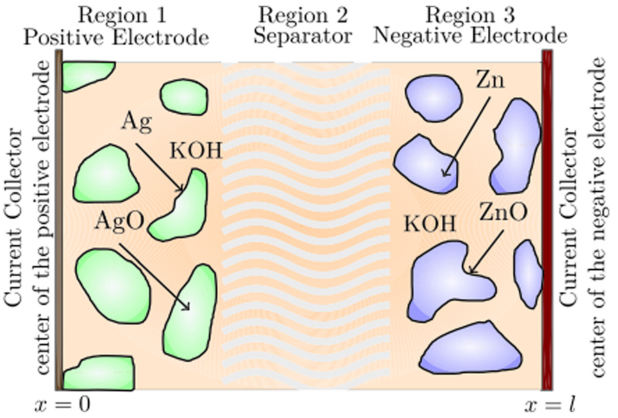

Fig. 7 A typical zinc–silver oxide (Zn–AgO) cell showing the positive electrode (Ag/AgO), the separator, and the negative electrode (Zn/ZnO) with KOH as the electrolyte reproduced from ref. 66 copyright Copyright © 2020 Elsevier.

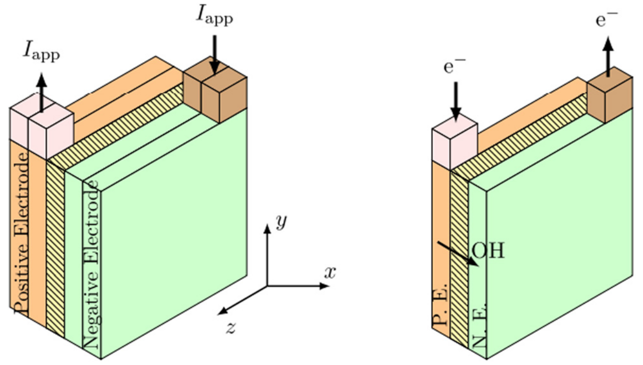

Fig. 8 Schematic of a typical cell sandwich structure and its operation: (left) physical arrangement of the positive electrode, separator, and negative electrode, and (right) direction of electron (e^-) and hydroxide ion (OH^-) movement during operation reproduced from ref. 66 copyright Copyright © 2020 Elsevier.

Silver oxide batteries have a higher capacity compared to other small form-factor batteries, such as alkaline or zinc–carbon button cells. The exact capacity of the battery depends on its size and application, but silver oxide batteries generally outperform their competitors in terms of energy density.[68] For example, in small button cell formats, silver oxide batteries can offer up to 50% more capacity than comparable alkaline button cells, allowing them to power devices for longer periods.[69] One of the standout features of silver oxide batteries is their impressive shelf life. When stored under optimal conditions (typically at room temperature and low humidity), silver oxide batteries can retain their charge for up to five years or more. This long shelf life makes silver oxide batteries particularly suitable for emergency devices, medical equipment, and backup power applications where batteries may remain dormant for extended periods before use.[70] Additionally, the minimal loss of capacity during storage provides users with confidence in the reliability and readiness of their devices.

The Fig. 8 shows a schematic of a typical battery cell structure, referred to as a "cell sandwich," depicting both the physical arrangement and the movement of ions and electrons during operation. Fig. 7(a) The left diagram provides a 3D view of a typical cell sandwich, consisting of a positive electrode (P.E.), negative electrode (N.E.), and a separator layer in between. The external circuit connections at both ends allow for an applied current (I_{app}) to flow during charging or discharging cycles. Fig. 7(b) The right diagram illustrates the electron (e^-) and ion (OH^-) movement. Electrons flow from the N.E. to the P.E. through an external circuit, while hydroxide ions (OH^-) migrate within the cell from the negative to the P.E. through the electrolyte. This flow of ions and electrons enables the redox reactions, facilitating the battery's charge/discharge process.

One of the key environmental concerns associated with silver oxide batteries is the use of silver, a precious metal. The extraction and processing of silver involve energy-intensive mining operations that can have significant environmental impacts, including habitat destruction, soil contamination, and the release of toxic substances. Moreover, improper disposal of silver oxide batteries can result in the release of silver and other harmful substances into the environment, contributing to pollution. Despite these concerns, silver oxide batteries are considered less environmentally harmful than some other battery chemistries, such as those containing mercury or cadmium. Many silver oxide batteries are now manufactured to be mercury-free, reducing their toxicity and making them safer for disposal. Additionally, the recyclable nature of silver makes it possible to recover and reuse the metal, mitigating some of the environmental impact associated with silver extraction. To minimize environmental harm, users are encouraged to recycle silver oxide batteries through proper battery recycling programs. These programs help recover valuable materials like silver and zinc, reducing the need for further mining and preventing the harmful chemicals from entering the waste stream.

Silver oxide batteries, like many other batteries, exhibit some sensitivity to temperature. Extreme cold can slow down the chemical reactions inside the battery, reducing its output and capacity. Conversely, extreme heat can accelerate the reactions, leading to faster discharge rates and potentially reducing the overall lifespan of the battery.[71,72] However, silver oxide batteries are generally more resilient to temperature fluctuations compared to some other battery types, such as zinc–carbon batteries. In typical usage conditions—room temperature or slightly above—silver oxide batteries perform reliably, delivering consistent voltage and capacity. However, it is still advisable to avoid exposing them to extreme temperatures for prolonged periods to maximize their performance and longevity.

Silver oxide batteries are available in a wide range of sizes, making them suitable for various applications. The most common size is the button cell format, which is widely used in small devices such as watches, hearing aids, and calculators. These batteries come in standard sizes, including SR44, SR41, SR43, and SR626, among others, allowing them to fit into different devices with specific power requirements.[73] The compact size of silver oxide batteries, combined with their high energy density, makes them ideal for the application of portable electronics where space is limited, and power demands are low to moderate. Their versatility in terms of size ensures that they can be used in a broad range of applications, from tiny hearing aids to larger photographic equipment.

2.2.5. Zinc–air batteries.

A zinc–air battery generates electrical energy through the chemical reaction between zinc and oxygen from the air. The image (Fig. 9) depicts the internal structure and operation of a zinc–air battery, which consists of two main electrodes: the zinc electrode (anode) and the porous air electrode (cathode), separated by an electrolyte.

Anode (zinc electrode): at the anode (right side of Fig. 9), zinc undergoes oxidation, reacting with OH^- to form zincate ions ($Zn(OH)_4^{2-}$), which then decompose to produce ZnO and release electrons: $Zn + 4OH^- \rightarrow Zn(OH)_4^{2-} + 2e^-$

Cathode (air electrode): at the porous air electrode (left side of Fig. 9), oxygen (O_2) from the surrounding air is reduced. Oxygen combines with water and electrons (from the external circuit) to form OH^-: $O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$

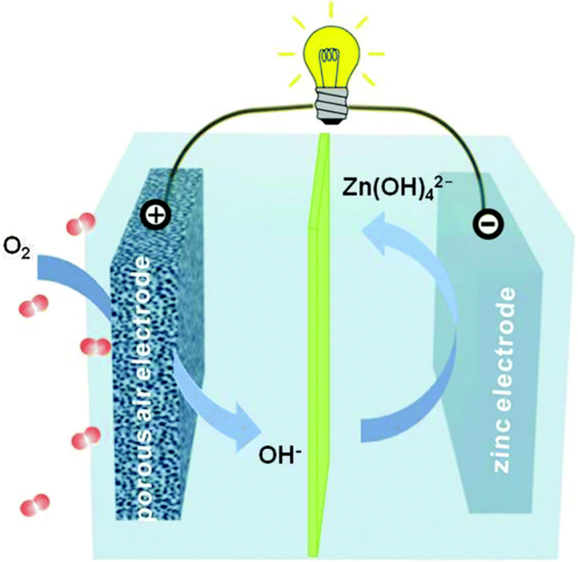

Fig. 9 The figure illustrates the working principle of a zinc–air battery, showing the zinc electrode on the right and the porous air electrode on the left, along with the flow of OH^- and O_2 reproduced from ref. 74 copyright © The Royal Society of Chemistry 2014.

Flow of electrons and ions: the electrons released from zinc travel through the external circuit, powering a device (symbolized by the light bulb), and return to the cathode. Meanwhile, OH^- ions generated at the cathode flow through the electrolyte to the anode, continuing the electrochemical reaction.

Zinc–air batteries are a unique class of electrochemical cells that use oxygen from the air as the active material at the cathode, while zinc serves as the anode. The chemistry of these batteries is based on the oxidation of zinc in the presence of air. The battery operates through a reaction where Zn is oxidized to ZnO, and oxygen from the air is reduced at the cathode to form hydroxide ions. The use of oxygen as the active material at the cathode eliminates the need to store it within the battery, significantly reducing the size and weight compared to other chemistries.[75] This external oxygen source provides a higher energy density, which makes zinc–air batteries particularly appealing for applications where lightweight and high energy output are important.

The nominal voltage of zinc–air batteries is around 1.4 to 1.45 volts per cell, slightly lower than some other primary battery types like alkaline or silver oxide batteries.[76] Despite this, zinc–air cells maintain a stable output voltage throughout their discharge cycle. This stable voltage is essential for devices that require consistent power for extended periods, such as hearing aids and medical devices. However, the voltage can drop rapidly once the battery is nearing the end of its life due to the depletion of zinc or the reduced availability of oxygen at the cathode. Since these batteries rely on air, they need an openair supply, which makes them vulnerable to performance degradation if the air intake is blocked or limited.

Zinc–air batteries are known for their exceptionally high energy density compared to other battery types of similar size.

This high capacity is largely due to the fact that oxygen, a key reactant in the battery's chemical process, is sourced from the surrounding air rather than being stored internally. As a result, zinc–air batteries can store more energy per unit of weight than many other primary batteries.[77] For example, the energy density of zinc–air batteries is often several times greater than that of alkaline or Li-ion batteries in the same form factor. The actual capacity of a zinc–air battery depends on its size and the specific application it is used for. In small button cell formats used in hearing aids, the capacity is optimized for long-term, low-power use. These batteries can last much longer than other types in similar applications, providing steady power for extended periods.

Fig. 10 presents a comprehensive comparison of the electrochemical performance and behavior of Zn plating/stripping using different electrolytes: 2 M $ZnSO_4$ in water, 2 M $Zn(BF_4)_2$ in water, and an ionic liquid-based zinc electrolyte (ILZE). Fig. 10(a): the electrochemical window of water and ionic liquid ($EMIMBF_4$) shows cyclic voltammetry (CV) curves for Zn plating/stripping in various electrolytes. The plot demonstrates hydrogen evolution reaction (HER) and electrolyte decomposition regions. ILZE displays a more stable window with suppressed hydrogen evolution compared to aqueous electrolytes. Fig. 10(b): the plot of hydrogen evolution during the Zn plating/stripping process shows that ILZE (red curve) exhibits zero

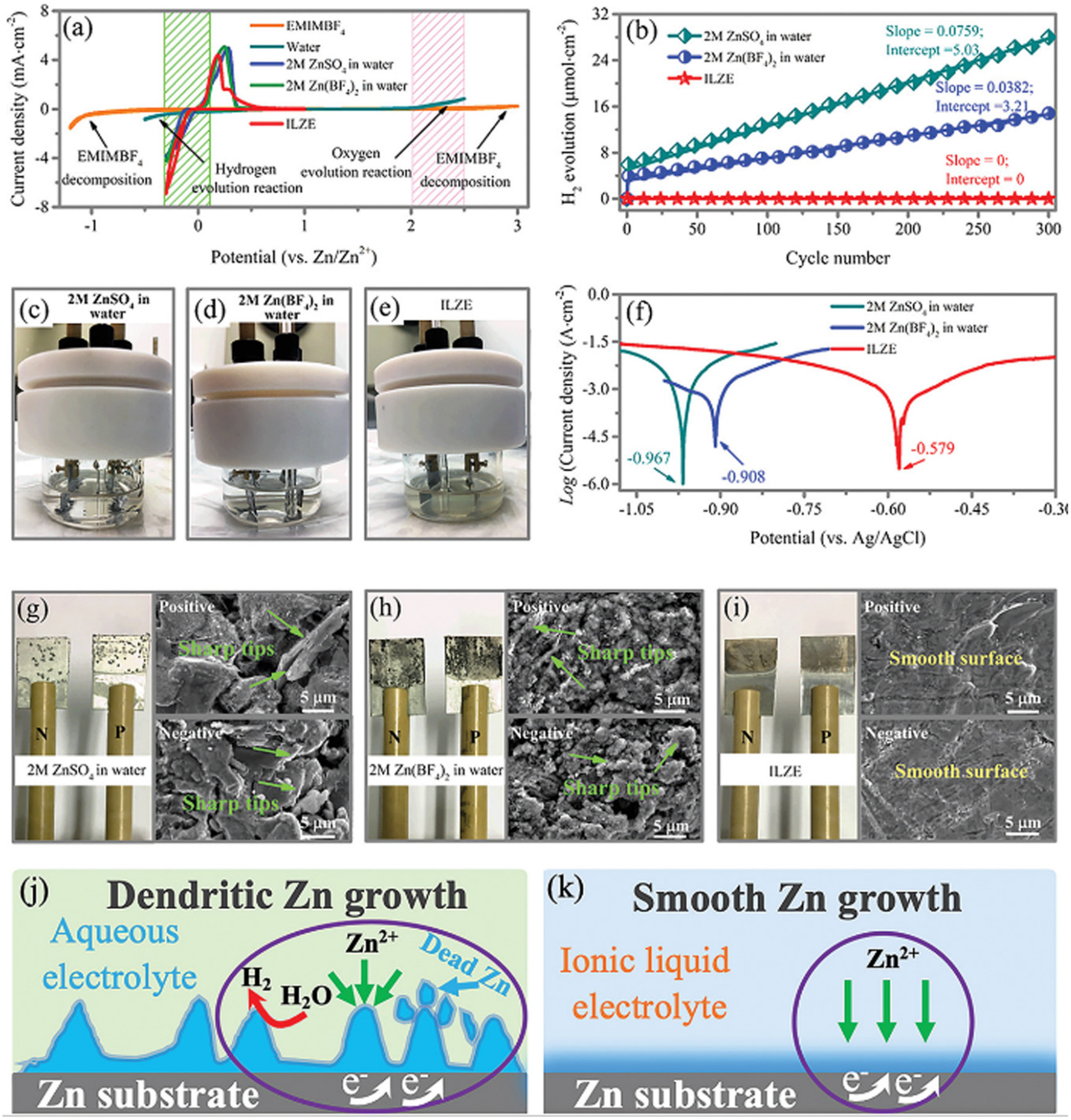

Fig. 10 Comparison of electrochemical performance and Zn morphology in different electrolytes (a) CV curves showing Zn plating/stripping behavior in water-based and ionic liquid electrolytes. (b) Hydrogen evolution during Zn plating/stripping at 0.5 mA cm^{-2}. (c)–(e) Symmetrical Zn cells after 300 cycles in different electrolytes. (f) Polarization curves showing corrosion on metallic Zn. (g)–(i) SEM images of Zn foils after 300 cycles. (j) and (k) Schematic illustrations of dendritic *vs.* smooth Zn growth in aqueous and ionic liquid electrolytes, respectively reproduced from ref. 78 copyright © 2020 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim.

hydrogen evolution, indicating a higher stability and efficiency compared to aqueous electrolytes (blue and green curves), which show increasing hydrogen production with cycling. Fig. 10(c)–(e): photographs of symmetrical Zn cells assembled with 2 M $ZnSO_4$, 2 M $Zn(BF_4)_2$ aqueous electrolytes, and ILZE after 300 cycles at a current density of 0.5 mA cm^{-2}. Cells with aqueous electrolytes (c and d) show noticeable gas formation (hydrogen evolution), while ILZE (e) remains visually stable without gas formation. Fig. 10(f): potentiodynamic polarization curves indicate the corrosion behavior of metallic Zn in different electrolytes. The aqueous electrolytes (blue and green curves) show more negative corrosion potentials (−0.967 V and −0.908 V) than ILZE (−0.579 V), suggesting that ILZE offers better corrosion resistance. Fig. 10(g)–(i): scanning electron microscopy (SEM) images of Zn foil surfaces after 300 cycles at 0.5 mA cm^{-2}: with 2 M $ZnSO_4$ (g), dendritic Zn growth with sharp tips is visible, which can lead to short circuits. With 2 M $Zn(BF_4)_2$ (h), the Zn surface also shows sharp tips, though less pronounced than with $ZnSO_4$. With ILZE (i), the Zn surface remains smooth and free from dendrites, indicating better plating behavior. Fig. 10(j)–(k): schematic illustrations comparing Zn growth behavior in aqueous and ionic liquid electrolytes: in aqueous electrolytes (j), dendritic Zn growth occurs due to the reaction between Zn^{2+} ions and water, leading to the formation of "dead" Zn and hydrogen gas. In ionic liquid electrolytes (k), smooth Zn growth is achieved, with better ion distribution and no gas formation.

Zinc–air batteries have a relatively long shelf life in their sealed, inactive state. However, once the battery is exposed to air by removing the protective seal, its lifespan begins to decline. The battery starts reacting with oxygen immediately, and even when not in active use, the ongoing chemical reaction will eventually deplete the battery. Typically, once activated, zinc–air batteries have a lifespan of a few weeks to a few months, depending on usage. The shelf life before activation is generally between three and four years. The seal is critical to preserving the battery's stored energy, and the quality of the seal directly influences the battery's shelf life. Storing these batteries in a cool, dry place can extend their shelf life somewhat, but once activated, the deterioration due to air exposure is inevitable.

Zinc–air batteries are most commonly used in hearing aids and other small, portable medical devices where long battery life and consistent power are critical. They are also used in other devices such as pagers, wireless communication devices, and, more recently, in larger formats for renewable energy storage.[79] Their high energy density and compact size make them ideal for applications where space is limited, and extended use is required. In the context of renewable energy, larger zinc–air batteries are being developed for grid storage applications, where their ability to provide high-capacity, long-duration energy storage could play a crucial role in balancing supply and demand in renewable energy systems as depicted in Fig. 11.

Zinc–air batteries have a relatively lower environmental impact compared to many other battery chemistries. Zinc is an abundant and non-toxic metal, and the environmental hazards associated with its extraction and disposal are less

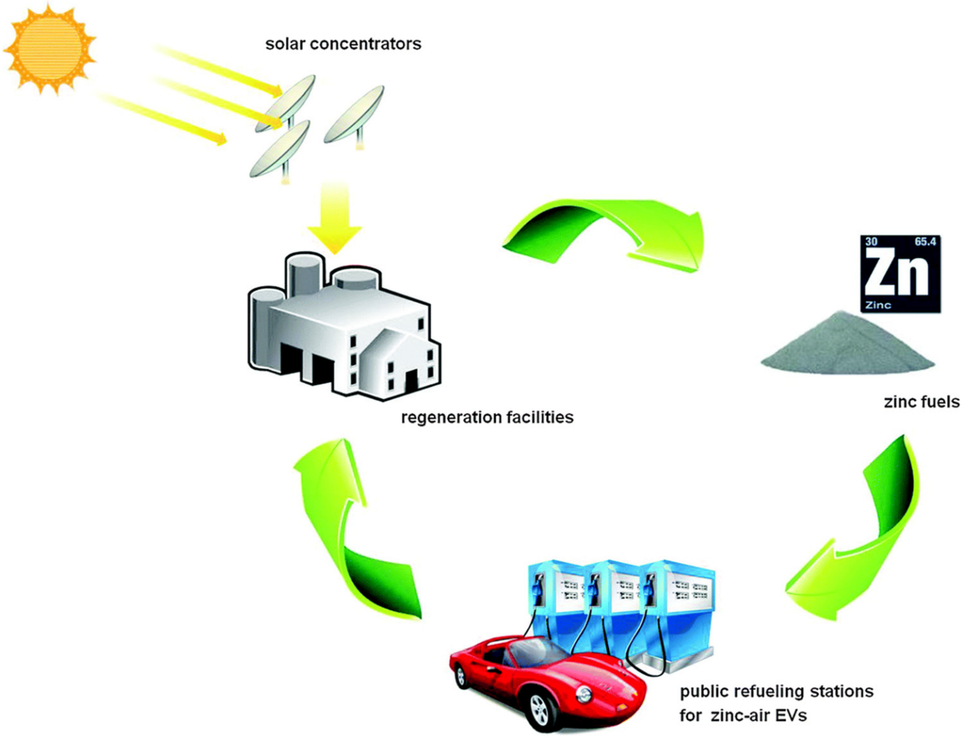

Fig. 11 Re-usage of zinc–air battery reproduced from ref. 74 copyright © The Royal Society of Chemistry 2014.

severe than those related to heavy metals such as lead, cadmium, or mercury, which are found in other battery types. The use of air as a key reactant also reduces the overall material consumption, which is a notable environmental benefit. However, as with all batteries, proper recycling and disposal are important to minimize environmental harm. Zinc can be recycled, and many programs exist to recover valuable materials from spent batteries, further reducing their environmental footprint.

Zinc–air batteries offer a unique combination of high energy density, stable voltage, and relatively low environmental impact, making them a valuable choice for applications that require long-lasting, reliable power in compact devices.[80] However, their reliance on air intake makes them sensitive to environmental factors such as humidity and temperature, and their performance can degrade once activated. Despite these limitations, zinc–air batteries are a highly effective solution for hearing aids and other medical devices, and ongoing research could expand their use in larger energy storage applications.

2.2.6. Mercury batteries. Mercury batteries, also known as mercury oxide (HgO) batteries, were once highly favored due to their stable voltage output and long shelf life. However, their environmental impact has largely curtailed their widespread use. This review critically evaluates mercury batteries in terms of their chemistry, voltage, capacity, shelf life, usage, environmental impact, leakage, temperature sensitivity, and size variants.

Mercury batteries, operate on the redox reaction between HgO and zinc or cadmium as the anode material. The typical construction of a mercury battery includes a zinc or cadmium anode that reacts with the electrolyte, while the cathode is made of HgO. The electrolyte is usually NaOH or KOH, which facilitates the movement of ions between the electrodes. A separator soaked in electrolyte prevents direct contact between the anode and cathode, ensuring safe operation. The entire structure is encased in a steel can that serves as the positive terminal, while a steel cap at the top functions as the negative terminal.[81]

Fig. 12 shows a typical cross-section of a HgO battery, which consists of multiple key components that facilitate its electrochemical reactions. The positive electrode (shown in red) is made from a steel can that houses the internal parts of the battery. The zinc or cadmium anode is placed near the center of the structure, which serves as the primary source of electrons when the battery is in use. Opposite the anode is the HgO cathode (illustrated in blue), which participates in the redox reactions that generate electrical current. Between the anode and cathode is an electrolyte-saturated separator (in dark blue), which prevents direct contact between the electrodes while allowing ionic movement essential for battery operation. The negative electrode is capped with a steel cap at the top, which, along with the steel can, helps maintain the integrity of the battery structure. A seal is included around the structure to prevent leakage of the electrolyte and to ensure a longer battery life. This layered design enables mercury batteries to maintain a stable voltage and provide high energy density, ideal for small electronic devices.[82]

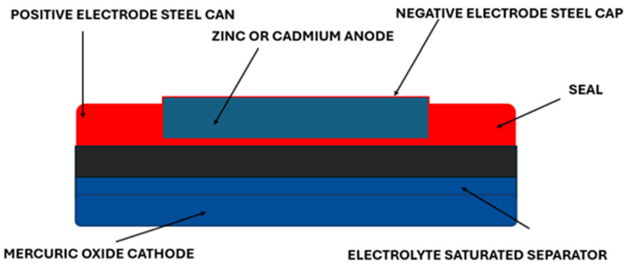

Fig. 12 Cross-sectional view of a HgO battery, illustrating the zinc or cadmium anode, HgO cathode, steel casing, and electrolyte-saturated separator.

Mercury batteries, rely on HgO as the cathode and Zn as the anode, with an alkaline electrolyte, typically KOH or NaOH. The overall electrochemical reaction that occurs during discharge involves the reduction of HgO and the oxidation of zinc.[83] The stable and highly efficient reactions make mercury batteries reliable power sources, especially in applications requiring consistent, low-power output. The primary reaction can be represented as:

$$\text{Anode reaction: } Zn + 2OH^- \rightarrow ZnO + H_2O + 2e^-$$

$$\text{Cathode reaction: } HgO + H_2O + 2e^- \rightarrow Hg + 2OH^-$$

One of the most notable features of mercury batteries is their remarkably stable voltage output. The nominal voltage of a mercury battery is typically 1.35 volts per cell,[84] which remains consistent throughout most of the battery's discharge cycle. This stability is in stark contrast to the other battery chemistries, which are zinc–carbon or alkaline batteries, where voltage tends to gradually decrease as the battery discharges. The consistent 1.35 V output is a result of the efficient chemical reactions at both the anode and cathode, which proceed steadily without major drops in potential. The releasing electrons from the zinc anode oxidizes, while the HgO at the cathode reduces to mercury metal, producing a smooth, constant flow of current. This high stability of voltage is also what allowed mercury batteries to outperform other battery types in specific applications, even though they have a lower overall energy capacity.

The performance of HgO batteries is significantly influenced by external pressure. This relationship between pressure and battery voltage is illustrated in the experimental data (Fig. 13), where the battery was subjected to increasing and decreasing pressures while current was passed. As pressure increases, the voltage exhibits substantial jumps, which is about ten times larger than the difference observed in open circuit conditions. However, an important observation is that when pressure is increased, the voltage does not immediately stabilize at a new value. Instead, it overshoots and gradually drifts back to a steady-state value over time. This ''overshoot'' behavior suggests a dynamic interaction between pressure and electrochemical processes within the battery, causing temporary fluctuations before the system re-stabilizes.

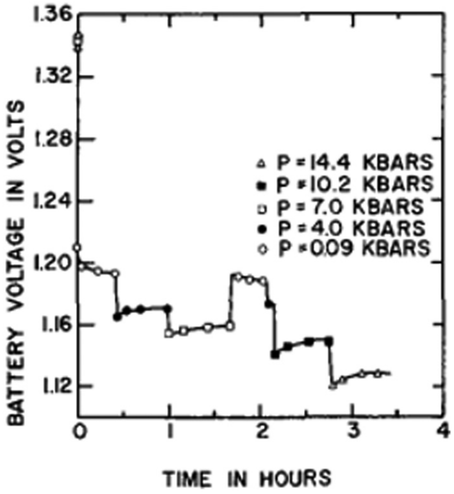

Fig. 13 The pressure dependence of the HgO battery voltage under a load of 1065 ohms. The battery voltage is plotted as a function of time for pressures ranging from 0.09 kbars to 14.4 kbars. The voltage shows significant overshoot behavior and fluctuation before stabilizing, indicating a strong response to pressure variations from ref. 85 copyright © The Electrochemical Society 1969.

Mercury batteries have a relatively low capacity compared to modern battery technologies such as lithium-ion and alkaline batteries. However, their capacity was considered sufficient for the low-drain applications for which they were predominantly used. The energy density of mercury batteries is around 130 W h kg^{-1},[86] which, although lower than that of Li-ion batteries, provided a stable and reliable energy supply for devices requiring consistent, low-power consumption. The relatively low capacity of mercury batteries did not significantly limit their usage in these low-drain applications, as their chemical stability and low internal resistance ensured that the available energy was used efficiently. Moreover, mercury batteries were particularly effective in environments where long battery life and minimal maintenance were priorities.

One of the defining characteristics of mercury batteries is their long shelf life. These batteries could last up to 10 years or more when stored under proper conditions, such as in cool, dry environments. The long shelf life is primarily due to the chemical stability of HgO, which does not readily react with other battery components or degrade over time in the absence of an external circuit.[87] Even after several years of storage, mercury batteries often performed nearly as well as they did when first manufactured, with little to no significant loss of capacity or voltage output. This was a significant advantage over other battery chemistries, such as zinc–carbon, which tend to degrade faster over time.

Mercury batteries were widely used throughout the 20th century in a variety of industries due to their stable performance and long-lasting power. Some of the key applications of mercury batteries included:

1. Medical devices: mercury batteries were used in hearing aids and other medical instruments where stable voltage output was crucial for consistent operation. Their long shelf life also ensured that these devices remained functional for extended periods without needing frequent battery replacements.[88]

2. Watches: analog watches, particularly those requiring a constant and stable voltage to maintain accurate timekeeping, commonly used mercury batteries.

3. Photographic equipment: precision instruments like light meters in cameras benefited from the steady voltage output of mercury batteries, ensuring reliable performance in capturing accurate exposures.

4. Military equipment: the durability and long shelf life of mercury batteries made them well-suited for use in military applications, where reliable power under various environmental conditions was essential.

5. Portable electronic devices: early portable electronic devices such as calculators also utilized mercury batteries for their small size and reliable, long-lasting power.

Although mercury batteries were widely used, their environmental impact led to a decline in their popularity. Regulations in many countries have restricted their use, and they have largely been replaced by alternative battery technologies like zinc–air, alkaline, and lithium-based batteries.

The most significant drawback of mercury batteries is their environmental impact. Mercury is highly toxic, and its improper disposal can lead to mercury contamination in the soil and water, where it can be absorbed by plants and animals, eventually entering the human food chain. Mercury poisoning can cause severe neurological damage, particularly in young children and pregnant women, as well as long-lasting ecological harm.[89]

Due to these dangers, many countries have implemented strict regulations on the production and disposal of mercury batteries. For example, the United States passed the Mercury-Containing and Rechargeable Battery Management Act in 1996, effectively banning the sale of most mercury batteries. The European Union, Japan, and other countries have introduced similar restrictions, greatly reducing the presence of mercury batteries in consumer markets.

Mercury batteries are relatively resistant to leakage compared to other battery types such as zinc–carbon or alkaline batteries. This is primarily due to the alkaline or neutral electrolytes used in mercury batteries, which are less corrosive than acidic electrolytes found in other batteries.[90] Additionally, the robust construction of mercury batteries helps prevent leaks during regular use. However, like all batteries, mercury batteries can still leak if damaged, over-discharged, or exposed to extreme conditions. The consequences of leakage are more severe in mercury batteries due to the toxic nature of mercury. If a mercury battery leaks, it can release mercury into the environment, posing significant health and ecological risks. As such, proper disposal and handling of mercury batteries are essential to prevent mercury contamination.

Mercury batteries are known for their relatively stable performance across a wide range of temperatures. They typically operate most efficiently at room temperature, but their chemical reactions remain stable in both cold and moderately high temperatures. This stability made mercury batteries suitable for use in diverse environments, including military and aerospace applications where temperature extremes were common.[91] In cold environments, mercury batteries often outperform other types of batteries, such as zinc–carbon, which experience significant performance drops at low temperatures. While there is some degradation in performance at extremely cold temperatures, mercury batteries generally maintain a higher level of functionality compared to other chemistries. At high temperatures, mercury batteries can experience accelerated degradation of their internal components, leading to reduced capacity and shortened lifespan. However, they are still less susceptible to leakage or capacity loss than some other battery types, such as alkaline batteries, which are more prone to these issues at elevated temperatures

Mercury batteries were manufactured in a wide range of sizes to the accommodation of various applications. The most common sizes included:

1. Button cells: small button-shaped mercury batteries were widely used for the purposes of watches, hearing aids, and other small electronic devices where compact size and reliable performance were critical.[92]

2. Cylindrical cells: larger cylindrical mercury batteries were used in industrial and military applications that required more power and capacity over a longer duration. These batteries provided steady output for devices that needed reliable, long-lasting power.[93]

3. Custom sizes: mercury batteries were also produced in custom sizes for specialized applications, particularly in military and aerospace sectors where unique power requirements necessitated specific battery configurations.[94]

The versatility of mercury batteries in terms of size made them suitable for a wide range of applications, from small portable electronics to more robust industrial devices. As more environmentally friendly alternatives became available, however, mercury batteries were gradually phased out.

Today, mercury batteries are largely obsolete in consumer electronics, replaced by more environmentally friendly alternatives such as alkaline, zinc–air, and lithium-ion batteries. While they still find limited use in some specialized applications, strict regulations on the production and disposal of mercury batteries have largely curtailed their widespread availability. The legacy of mercury batteries, however, is a reminder of the trade-offs between performance and environmental sustainability in battery technology. As the world moves toward greener energy solutions, the lessons learned from mercury batteries continue to inform the development of safer and more sustainable energy storage systems.

2.2.7. **Copper–zinc batteries.** Copper–zinc batteries, originally based on the Daniell cell,[95] have a long history in electrochemical technology. They were among the first widely used battery types, but their prominence diminished with the advent of higher energy-density batteries such as lithium-ion. Despite this, copper–zinc batteries have garnered renewed interest due to their sustainable, low-cost nature and environmentally friendly materials. Copper and zinc are abundant, non-toxic, and recyclable, making these batteries appealing in an era focused on green energy solutions. This review takes a critical look at zinc–carbon batteries, focusing on their chemistry, voltage, capacity, shelf life, usage, environmental impact, leakage, temperature sensitivity, and size variants.

The first configuration (Fig. 14), labeled Type I, features a simple design where a zinc anode and a copper cathode are immersed in sulfuric acid (H_2SO_4) as the electrolyte. Zinc at the anode undergoes oxidation, releasing two electrons and forming Zn^{2+} ions. These electrons flow through the external circuit, generating an electric current. Meanwhile, at the cathode, hydrogen ions (H^+) from the sulfuric acid gain electrons, resulting in the release of hydrogen gas (H_2). This type of battery represents a basic form of electrochemical power generation and follows the reaction: $Zn + 2H^+ \rightarrow Zn^{2+} + H_2$.

The second configuration (Fig. 14), labeled Type II, presents a more refined setup, utilizing two separate solutions, zinc sulfate ($ZnSO_4$) for the anode and copper sulfate ($CuSO_4$) for the

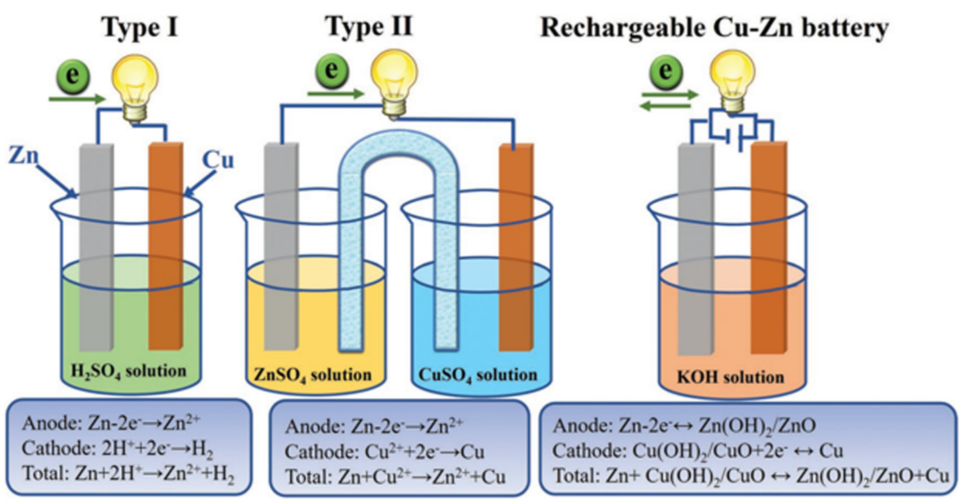

Fig. 14 Depiction of Cu–Zn battery types: Type I (H_2SO_4 solution), Type II ($ZnSO_4$ and $CuSO_4$ solutions with a salt bridge), and rechargeable Cu–Zn battery (KOH solution), showcasing their electrochemical processes and reactions from ref. 96 copyright © Wiley Online Library 2019.

cathode. A salt bridge connects the two solutions, allowing ion exchange while preventing the solutions from mixing. In this system, zinc again oxidizes at the anode to form Zn^{2+} ions, while at the cathode, Cu^{2+} ions from the $CuSO_4$ solution gain electrons, leading to the deposition of metallic copper. The overall reaction in this case is $Zn + Cu^{2+} \rightarrow Zn^{2+} + Cu$. The salt bridge ensures charge neutrality by balancing the flow of ions between the two compartments, making it more efficient than Type I.

The final configuration (Fig. 14) in the image shows a Rechargeable Cu–Zn Battery, a modern variation using KOH as the electrolyte. The rechargeable design is more advanced, allowing the battery to be reused. In this system, zinc undergoes oxidation at the anode, forming zinc hydroxide ($Zn(OH)_2$) or ZnO, while at the cathode, copper hydroxide ($Cu(OH)_2$) or copper oxide (CuO) is reduced to metallic copper (Cu). The battery can be recharged by reversing the chemical reactions, making it a sustainable solution for repeated use.

Fig. 15 shows, the voltage output of Cu–Zn batteries is influenced by the electrochemical potential difference between copper and zinc, two metals with distinct reduction potentials. Zinc, being a more reactive metal, acts as the anode and undergoes oxidation, releasing electrons, while copper, which is less reactive, serves as the cathode and undergoes reduction, gaining electrons. The standard reduction potential of zinc (Zn^{2+}/Zn) is -0.76 V, while copper (Cu^{2+}/Cu) has a standard reduction potential of +0.34 V. This difference in potential creates a voltage output of approximately 1.1 volts under standard conditions.

The voltage stability of a Cu–Zn battery, as demonstrated in the image, shows consistent voltage profiles across multiple cycles. The first graph (Fig. 15) illustrates the voltage *versus* capacity at a current density of 1 mA cm^{-2} over the 1st, 50th, and 135th cycles. It highlights that the voltage remains stable, starting slightly above 1.2 V and maintaining a similar profile through extended cycling, with minimal voltage drop as the capacity increases up to 5 mA h cm^{-2}. This indicates excellent cycling stability, suggesting that the Cu–Zn battery retains its performance even after repeated charge and discharge cycles. The second graph (Fig. 15) presents the relationship between voltage and capacity at various current densities, ranging from 0.2 mA cm^{-2} to 2 mA cm^{-2}. Across these current densities, the voltage remains steady around 1.2 V, even as the current density increases. This stable performance across different charge rates indicates that Cu–Zn batteries exhibit reliable voltage retention under varying operational conditions, which is crucial for applications requiring consistent power delivery over time.

In practice, the actual voltage of a Cu–Zn battery can be affected by various factors, including the concentration of the electrolytes, the temperature of the mentioned system, and the internal resistance of the battery. As the battery discharges, the concentration of Zn^{2+} ions in the electrolyte increases, and the Cu^{2+} ions at the cathode decrease, which can lead to a gradual drop in the voltage. The presence of an internal resistance, caused by factors such as electrode degradation or inefficient ion transfer in the electrolyte, can also reduce the effective voltage output. In rechargeable Cu–Zn batteries, the voltage can be maintained for a longer period due to the reversibility of the reactions at the electrodes. In these batteries, KOH is often used as an electrolyte, providing more stable performance and making it easier to recharge the battery by reversing the electrochemical reactions. The voltage in these systems can remain close to 1.1 V during the discharge phase, though with some variance due to the cycling processes.[98]

The capacity of a Cu–Zn battery refers to the amount of charges, it can be stored or delivered over time, typically measurement is taken in ampere-hours (A h). It depends on several important factors, including the surface area of the electrodes, the concentration of the electrolyte, and the efficiency of the electrochemical reactions occurring between copper and zinc.[99] Zinc, being the anode, undergoes oxidation and provides a significant contribution to the battery's overall capacity, as it has a high specific energy. In typical Cu–Zn cells, the theoretical capacity of the battery is largely influenced by the amount of zinc available to undergo the oxidation reaction,

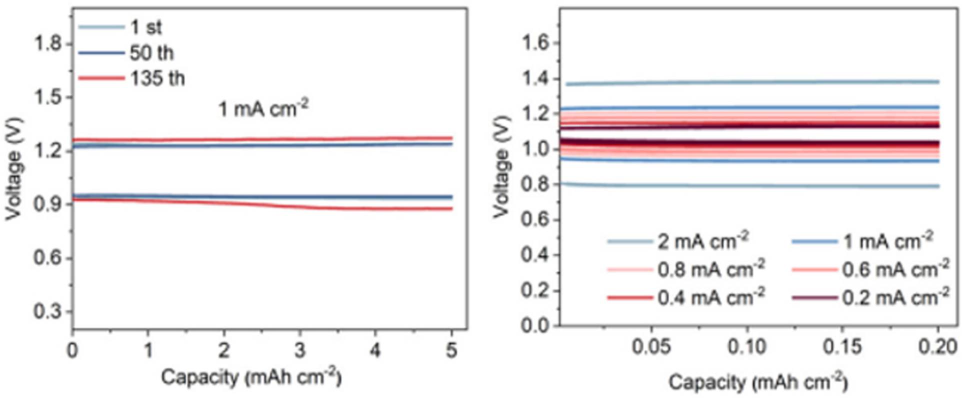

Fig. 15 Voltage-capacity profiles of Cu–Zn batteries. The first graph shows stable voltage during cycling at 1 mA cm^{-2} over 135 cycles, while the second graph presents voltage stability across different current densities, highlighting the battery's consistent performance across varying operational conditions from ref. 97 copyright © The Royal Society of Chemistry 2023.

which produces electrons that travel to the copper cathode, driving the circuit. However, real-world capacities are often lower than theoretical values due to inefficiencies such as side reactions, electrode degradation, and internal resistance.

Rechargeable Cu–Zn batteries, using alkaline electrolytes like KOH, exhibit improved cycling stability and capacity retention compared to non-rechargeable versions. In these systems, a balance between charge storage and reversibility of reactions is crucial for maintaining consistent capacity across charge–discharge cycles. The capacity can range from small-scale applications, such as in low-power electronics, to higher capacities when designed for energy storage or other more demanding uses.

The graph (Fig. 16) illustrates the specific capacity of Cu–Zn batteries over a series of charge and discharge cycles in two different electrolytes: $ZnSO_4$ and KOH. Initially, in a 1 M $ZnSO_4$ solution, the battery displays a high specific capacity of approximately 500 mA h g^{-1} during the first charge. However, this value sharply drops to below 100 mA h g^{-1} after only a few cycles, indicating significant degradation and poor cycling stability in $ZnSO_4$. In contrast, when using a 1 M KOH solution as the electrolyte, the Cu–Zn battery shows a more stable performance, with the specific capacity remaining around 250–300 mA h g^{-1} for over 180 cycles. The superior cycling performance in KOH highlights the better electrochemical stability and longevity of Cu–Zn batteries when operated in alkaline conditions compared to acidic electrolytes like $ZnSO_4$.

For Cu–Zn batteries, the shelf life is influenced by factors such as chemical stability, the quality of materials used, and environmental conditions. Unlike lithium-based or alkaline batteries, the shelf life of Cu–Zn batteries tends to be shorter due to the susceptibility of zinc to corrosion and the self-discharge process.[100] Over time, zinc anodes can undergo degradation even when the battery is not in use, leading to the formation of zinc dendrites. These dendrites can create internal short circuits, reducing the battery's capacity and shelf life.

In addition to zinc degradation, the electrolyte's stability is crucial for shelf life. In conventional Cu–Zn batteries, if the electrolyte solution is not well-contained or experiences evaporation, the internal components may become less efficient over time, further shortening the battery's shelf life.[101] To improve the shelf life of Cu–Zn batteries, efforts are made to use more stable electrolyte formulations or to add inhibitors that prevent the growth of zinc dendrites. Modern advancements in sealing technology have also enhanced the shelf life by minimizing exposure to air and moisture, which are known to accelerate corrosion. Temperature and storage conditions also play a significant role in the shelf life of these batteries. Storing them in cool, dry environments typically slows the degradation process, while high temperatures can lead to faster self-discharge and electrolyte degradation. Although Cu–Zn batteries generally have a shorter shelf life than other chemistries,[102] improvements in materials science and storage techniques are helping to mitigate these issues and extend their practical usability in various applications.

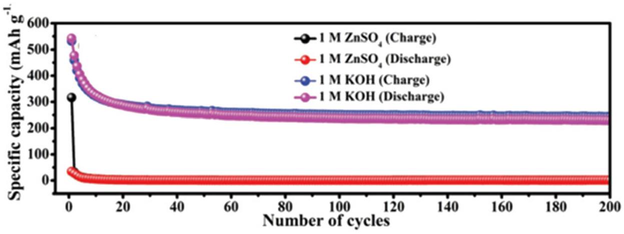

Fig. 16 Specific capacity of Cu–Zn batteries in $ZnSO_4$ and KOH electrolytes over 200 cycles, showing initial degradation in $ZnSO_4$ and stable performance in KOH from ref. 96 copyright © Wiley Online Library 2019.

Historically, copper–zinc batteries played a pivotal role in the early experiments of electrical science and engineering. Their simplicity in design and ease of construction made them a staple for pioneering researchers, particularly in the realm of telegraphy, where reliable power sources were essential. The Daniell cell was favored due to its relatively stable voltage and availability of materials, making it an accessible option for early electrical applications.

In contemporary settings, however, the use of copper–zinc batteries has become more niche, primarily relegated to educational demonstrations and low-power devices. While they are excellent for teaching the fundamentals of electrochemistry, their practical applications have dwindled as more efficient and higher-capacity batteries have emerged.[103] Nevertheless, recent advancements in battery technology have sparked renewed interest in the potential of copper–zinc batteries, especially concerning their rechargeability and capacity enhancements. As sustainability becomes increasingly important, copper–zinc batteries offer several advantages, including low environmental impact and cost-effectiveness. Their relatively simple manufacturing process can be a significant benefit in reducing production costs and resource consumption. While the energy density of copper–zinc batteries remains lower compared to modern lithium-ion alternatives, this limitation might not hinder their applicability in smaller-scale or stationary energy storage solutions.

The left side of the image (Fig. 17), labeled (a), presents a Ragone plot, which compares the performance of various previously reported Zn-based batteries to the newly developed rechargeable Cu–Zn battery. The graph showcases specific capacity *versus* current density for different metal–oxide-based batteries, including Mn-based oxides, V-based oxides, and Prussian Blue analogs. Notably, the Cu–Zn battery developed in this work demonstrates a higher specific capacity, especially at lower current densities, achieving values close to 750 mA h g^{-1}. This suggests that the Cu–Zn battery offers superior energy storage performance compared to other Zn-based batteries, making it highly competitive for practical applications that demand both energy density and power efficiency.

The right side of the image (Fig. 17), labeled (b), features an experimental setup where two Cu–Zn batteries are connected in series to power a set of 36 LED lights. These lights are arranged to spell "Cu–Zn," illustrating the effectiveness of the battery in delivering consistent power for small-scale electronic devices. This setup visually confirms the practical utility of Cu–Zn

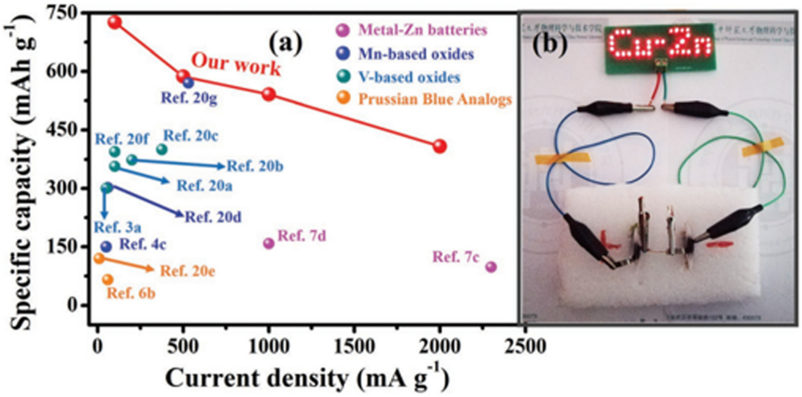

Fig. 17 (a) Ragone plots comparing the performance of previously reported Zn-based batteries with the newly developed rechargeable Cu–Zn battery, which exhibits superior specific capacity at lower current densities. (b) Demonstration of two Cu–Zn batteries in series, successfully powering 36 LED lights arranged to spell "Cu–Zn," highlighting the practical applicability of Cu–Zn batteries in low-power electronic devices from ref. 96 copyright © Wiley Online Library 2019.

batteries in real-world applications, emphasizing their potential in powering low-energy devices like LEDs.

One of the most significant advantages of Cu–Zn batteries is their environmental friendliness. Both copper and zinc are abundant, non-toxic metals that are widely used and highly recyclable. In contrast to lithium-ion batteries, which often rely on more scarce and environmentally harmful materials like cobalt and nickel, Cu–Zn batteries present a much lower environmental footprint. This accessibility not only reduces the ecological impact of mining but also contributes to resource sustainability.[104] Moreover, the recycling processes for copper and zinc are well-established, making it easier to recover these materials at the end of a battery's life cycle. This enhances the overall sustainability of Cu–Zn batteries, as valuable resources can be reclaimed and reused, minimizing waste and reducing the need for new raw materials.

Additionally, the use of aqueous electrolytes in copper–zinc batteries further supports their eco-friendly profile. Aqueous electrolytes are less flammable and hazardous than the organic solvents typically employed in other battery technologies. This significantly reduces safety risks associated with battery use and storage. However, it is essential to manage any potential leakage or proper disposal of used electrolytes to maintain environmental integrity.

Leakage has historically posed a significant challenge for copper–zinc (Cu–Zn) batteries, primarily due to the aqueous nature of the electrolyte used in these systems. Over time, the electrolyte can degrade the battery casing, resulting in leaks that not only compromise the battery's performance but can also lead to corrosion in connected devices. This issue has been a notable drawback, especially in applications where reliability is critical.

To address this problem, modern designs have focused on reinforcing the battery casing and optimizing the electrolyte composition to enhance corrosion resistance. Innovations such as the introduction of gel electrolytes in newer pouch cell designs have further mitigated the risk of leakage, providing a safer and more robust alternative.[105] These gel electrolytes reduce fluidity, thereby decreasing the likelihood of leaks while maintaining good ionic conductivity.

Copper–zinc (Cu–Zn) also sensitive to temperature extremes, which significantly impacts their overall performance. This sensitivity to temperature variations can restrict their practical applications, especially in environments where conditions fluctuate widely. At low temperatures, the electrochemical reactions within the Cu–Zn battery slow down considerably. This deceleration reduces the battery's efficiency and capacity, limiting its ability to deliver adequate power. Users may experience diminished performance, with noticeable drops in voltage and capacity, which can hinder the battery's reliability in cold environments. For instance, during winter months or in high-altitude applications, the lower temperatures can severely compromise the operational efficiency of these batteries, making them less viable for certain uses. Conversely, high temperatures pose a different set of challenges. Elevated temperatures accelerate the degradation of the electrolyte, leading to an increase in self-discharge rates.[106] This degradation not only shortens the lifespan of the battery but can also result in a loss of efficiency. At extreme heat, the materials within the battery may undergo stress, potentially causing structural failures and reducing overall reliability. This thermal sensitivity can limit the use of Cu–Zn batteries in applications that require sustained performance in hot climates or industrial settings where temperatures can rise.

Despite these advancements, Cu–Zn systems remain more susceptible to performance degradation under temperature stress compared to more robust battery chemistries, such as lithium-ion or solid-state batteries. These alternatives often feature better thermal stability and a broader operational temperature range, making them more suitable for demanding applications.

Copper–zinc (Cu–Zn) batteries have traditionally been produced in smaller sizes, catering primarily to educational purposes and low-power applications. Their early forms, such as the Daniell cell, were often large and bulky, making them impractical for many modern uses. However, advancements in technology of battery have led to the development of the more compact designs, including pouch cells, which offer improved form factors while maintaining the fundamental electrochemical properties of Cu–Zn systems. Pouch cells represent a significant innovation in the design of copper–zinc batteries, providing a lightweight and flexible alternative to traditional cylindrical or rectangular battery formats.[107] These modern pouch cells have demonstrated potential for scalability, with some achieving ampere-hour capacities suitable for specific applications. Their compact size and ease of integration make them appealing for use in various low-power devices and educational demonstrations.

Despite these advancements, copper–zinc batteries still face challenges in competing with more widely adopted battery technologies, such as alkaline or lithium-ion batteries. Standardized sizes and form factors of these established batteries allow for seamless integration into consumer electronics, from smartphones to laptops, which limits the market penetration of Cu–Zn batteries. Moreover, the relatively lower energy density and capacity of copper–zinc batteries compared to their lithium-ion counterparts further constrain their adoption in mainstream applications where performance is critical.

Copper–zinc (Cu–Zn) batteries, while historically significant and chemically simple, are not well-suited to the demands of modern energy storage needs. Their relatively low voltage and limited capacity, combined with a short shelf life and susceptibility to leakage and temperature sensitivity, place them at a distinct disadvantage compared to more advanced battery technologies such as lithium-ion, alkaline, or even nickel–metal hydride batteries. These limitations hinder their performance in applications requiring higher energy density and reliability, making them less appealing for mainstream use in consumer electronics and high-energy devices. Despite these challenges, copper–zinc batteries do offer certain advantages that warrant attention, particularly concerning environmental impact and recyclability. This aspect is particularly significant in today's environmentally conscious society, where the search for sustainable energy storage solutions is becoming increasingly important. The ability to recycle copper and zinc further enhances the sustainability of these batteries, as these processes are well-established and economically viable.

Moreover, the low cost and ease of manufacturing copper–zinc batteries make them suitable for specific applications, especially in educational settings and low-power devices. They serve as valuable tools for teaching fundamental electrochemical principles, allowing students and enthusiasts to engage with basic concepts of battery chemistry without the risks associated with more complex and hazardous materials. The simplicity of their design facilitates hands-on learning experiences, making them an excellent choice for laboratories and educational programs focused on science, technology, engineering, and mathematics (STEM).

Although copper-zinc batteries are unlikely to gain widespread use in high-energy or consumer applications, they continue to serve a vital role in niche areas. Their applications in backup power systems, energy storage for renewable sources, or even as portable power supplies for low-energy devices illustrate their practicality in specific contexts. Furthermore, ongoing research in materials science may pave the way for improvements in the performance and efficiency of copper–zinc batteries. Innovations aimed at enhancing their energy density, lifespan, and temperature resilience could potentially expand their applicability in energy storage systems. Despite their limitations, copper–zinc batteries remain a modest yet significant part of the battery landscape. They exemplify a simpler, environmentally friendly approach to energy storage that resonates with the growing emphasis on sustainability. While they may not compete directly with cutting-edge technologies, their unique characteristics position them as a complementary option in the broader spectrum of battery solutions.

3. Comparative analysis

Primary batteries exhibit distinct performance characteristics under varying operating conditions, which are crucial for determining their suitability for specific applications. Discharge performance across load conditions highlights significant variations: alkaline batteries maintain stable voltage under low-to-medium loads but experience a rapid voltage drop under high-load conditions, reducing their effective capacity by up to 40%.[108] In contrast, zinc–carbon batteries are optimized for low-load devices, such as clocks and remote controls, but their voltage declines quickly under high-drain conditions, utilizing less than 60% of their capacity. Lithium primary batteries outperform others with minimal voltage sag, even under high-drain conditions, making them suitable for demanding applications like medical devices and cameras. Temperature sensitivity also plays a pivotal role in battery efficiency and durability. Alkaline batteries retain 80–90% of their capacity at temperatures as low as -20 °C but may leak or degrade above 54 °C. Zinc–carbon batteries suffer up to 50% capacity loss in sub-zero temperatures, while lithium primary batteries exhibit superior performance, retaining over 95% of their capacity across a wide temperature range (-40 °C to 60 °C).[109] Silver oxide batteries perform well at low temperatures but degrade thermally above 45 °C. Self-discharge and shelf-life comparisons further differentiate these batteries. Alkaline batteries exhibit a low self-discharge rate of 2–3% per year, ensuring a shelf life of 5–10 years. Zinc–carbon batteries self-discharge at a higher rate of 7–10% annually, resulting in a shorter shelf life of 2–3 years. Lithium primary batteries excel with an exceptionally low self-discharge rate of less than 1% per year, enabling a functional life exceeding 10 years.[110] Energy density is another critical parameter, with lithium batteries leading at 300 W h kg^{-1}, compared to 150–200 W h kg^{-1} for alkaline batteries and 50–70 W h kg^{-1} for zinc–carbon batteries. Zinc–air batteries, while having a moderate energy density (100–200 W h kg^{-1}), leverage atmospheric oxygen for lightweight designs ideal for compact devices such as hearing aids. From a recycling and environmental impact perspective, modern processes recover 80–90% of zinc and manganese from alkaline batteries, while

Table 1 Comparative table summarizing key characteristics of various primary batteries

Battery type	Chemistry	Voltage (V)	Capacity (mA h)	Shelf life	Environmental impact	Temperature sensitivity
Alkaline	Zinc (anode), manganese dioxide (cathode)	1.5	700–3000	5–10 years	Relatively low impact, recyclable	Performs well in a wide temperature range (−20 °C to 54 °C)
Zinc–carbon	Zinc (anode), manganese dioxide (cathode), carbon (rod)	1.5	400–1500	2–3 years	Moderate, non-toxic materials	Sensitive to cold, reduced performance in low temperatures
Lithium (primary)	Lithium (anode), manganese dioxide (cathode)	3.0	1200–3000	10+ years	Higher impact due to lithium, less recyclable	Performs well in extreme temperatures (−40 °C to 60 °C)
Silver oxide	Zinc (anode), silver oxide (cathode)	1.55	50–200	3–5 years	High impact due to silver content, but recyclable	Good performance at low temperatures, sensitive to heat
Zinc–air	Zinc (anode), oxygen (cathode)	1.4	300–620	1–2 years	Low impact, relies on air oxygen	Poor in cold, performs best in mild environments
Mercury	Zinc (anode), HgO (cathode)	1.35	50–100	5–10 years	High environmental toxicity, banned in many regions	Performs well in a wide range of temperatures
Copper–zinc (Daniell Cell)	Zinc (anode), copper (cathode)	1.1	Low (100–200)	1–2 years	Low impact, recyclable	Sensitive to both heat and cold

lithium primary batteries achieve a recovery rate of around 60–70%, highlighting room for improvement.[111] Advances in reducing toxic materials, such as eliminating mercury and cadmium, have decreased hazardous waste by up to 95% compared to legacy batteries (Table 1).

4. Enhancing battery sustainability through recycling technologies and policies

The environmental impact of primary batteries is a significant concern, particularly at the end-of-life stage, where improper disposal leads to hazardous waste and resource depletion. To mitigate these impacts, it is essential to improve recycling technologies and policies, as well as battery designs that facilitate recycling.

Advancements in battery design have focused on enhancing recyclability by using more sustainable materials and simplifying the disassembly process. For instance, primary batteries that incorporate less toxic and more abundant materials, such as magnesium or aluminum, offer greater potential for recycling compared to traditional lithium-based batteries. Furthermore, modular battery designs have been introduced, allowing for easier disassembly and material separation, thus improving the efficiency of recycling processes. By focusing on designs that consider recyclability from the outset, manufacturers can significantly reduce the environmental footprint of primary batteries.

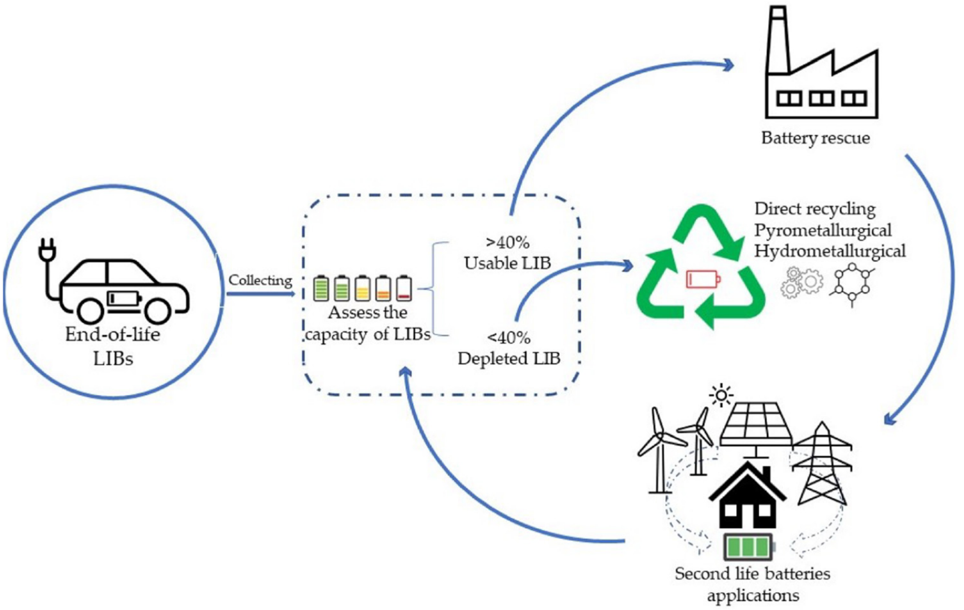

Fig. 18 Flowchart illustrating the recyclability of primary batteries, highlighting key steps such as collection, disassembly, material separation, and recovery processes, along with innovations in sustainable materials and recycling technologies from ref. 112 copyright © 2022 by the authors. Licensee MDPI, Basel, Switzerland.

Fig. 18 shows, the flowchart illustrates the recyclability of primary batteries, emphasizing key stages such as collection, disassembly, material separation, and recovery processes, along with innovations aimed at improving sustainability in battery recycling Additionally, innovative techniques, such as the use of biodegradable binders and conductive polymers, are being explored to enhance the recovery of valuable metals like zinc and manganese. Recycling technologies for primary batteries have also seen significant improvements. Currently, several processes, such as mechanical separation, pyrometallurgical, and hydrometallurgical methods, are used to recover valuable metals from spent batteries. However, these methods often require significant energy input and may still leave behind harmful residues. Recent advancements in selective dissolution techniques and biotechnological methods aim to reduce energy consumption and environmental impact. For example, bioremediation processes using bacteria and fungi to recover metals like cobalt, nickel, and lithium are being explored, offering a more sustainable approach to recycling. Additionally, the development of closed-loop recycling systems, where battery materials are continuously reused without degradation of quality, presents an exciting future for improving the sustainability of primary batteries.

The effectiveness of battery recycling is not only dependent on technological advancements but also on the policies that govern recycling practices. Different countries and regions have implemented varying policies, which significantly influence the efficiency of recycling systems and the overall sustainability of battery usage. In the European Union, for example, the Battery Directive and the Waste Electrical and Electronic Equipment (WEEE) Directive set high standards for the collection, recycling, and disposal of batteries. These policies mandate that a substantial portion of batteries be recycled and that manufacturers design products with end-of-life recycling in mind. Conversely, in many developing regions, the lack of effective regulations and infrastructure for battery recycling means that many batteries are improperly disposed of, leading to environmental contamination. In countries like the United States, recycling efforts for primary batteries remain fragmented, with no federal mandate on battery recycling. This inconsistency across borders highlights the need for global cooperation in establishing standardized recycling policies and practices that ensure the sustainable management of primary batteries.

To improve the recyclability of primary batteries, it is crucial to address both design and policy challenges. Future developments should focus on the integration of more sustainable materials that are easier to recycle and on the development of smarter, more efficient recycling technologies. Additionally, harmonizing battery recycling regulations worldwide and promoting international cooperation could significantly improve recycling rates and reduce environmental impacts. By aligning technological advancements with robust policies, it is possible to move toward a more sustainable future for primary batteries, minimizing their ecological footprint while maximizing the recovery of valuable resources.

5. Challenges and limitations

Regardless of their extensive use and numerous advantages, primary batteries face several challenges and limitations that restrict their application and raise concerns about their sustainability and environmental impact. As single-use, non-rechargeable batteries, primary batteries are designed for convenience and low-cost solutions, but these features also bring significant drawbacks. Addressing these issues is essential for the future of battery technology, particularly in an era increasingly focused on sustainability and efficient energy storage.

One of the most pressing challenges of primary batteries is their environmental impact. Since primary batteries are single-use devices, they must be discarded once their energy is depleted. This creates a substantial amount of waste, contributing to the growing e-waste problem. Millions of primary batteries are thrown away each year, often ending up in landfills where they can leach toxic chemicals into the environment. Many primary batteries contain very harmful substances like mercury, cadmium, and they can lead, which can also contaminate soil and water, posing serious risks to ecosystems and health of a human. While there has been progress in reducing or minimising the use of toxic materials—such as the removal of mercury from most consumer alkaline batteries—the problem of e-waste remains significant. While primary batteries continue to contribute significantly to e-waste, emerging battery design innovations can play a vital role in mitigating their environmental impact. The shift towards biodegradable materials, such as bio-derived binders and cellulose-based separators, presents a promising solution. These materials break down naturally, reducing waste accumulation in landfills. Additionally, zinc-based primary batteries, such as zinc–air batteries, hold substantial promise due to the high recyclability of zinc, which could potentially reduce the demand for virgin materials.

Innovative changes in battery chemistries are also showing significant potential for reducing toxicity and improving recyclability. Non-toxic, water-based electrolytes and modular designs that allow for easy disassembly can drastically simplify the recycling process, making it more economically viable and efficient. However, these solutions are still in early stages of development, and scalability and economic feasibility remain major challenges. Further research in these areas will be critical to ensuring the environmental sustainability of primary batteries.

Recycling primary batteries is another major challenge. Unlike secondary (rechargeable) batteries, which can be reused multiple times, primary batteries are typically disposed of after a single use. This makes recycling programs for primary batteries less economically viable, as the materials extracted from them are often not valuable enough to justify the costs of collection and processing. The infrastructure for recycling primary batteries is also limited, particularly in comparison to the more established recycling systems for secondary batteries. As a result, only a small percentage of primary batteries are recycled, with the majority ending up in landfills. This creates a gap in sustainable waste management, highlighting the need for more efficient recycling processes or the development of more environmentally friendly primary battery technologies. One promising approach involves the use of zinc–air batteries, which leverage zinc as a highly recyclable material. Advances in electrode designs aim to simplify the disassembly process, making it easier to recover zinc and other components efficiently. Similarly, the adoption of non-toxic and water-based electrolytes offers a sustainable alternative to traditional alkaline or lithium-based chemistries, significantly reducing environmental hazards and simplifying recycling workflows. Emerging biodegradable materials, such as cellulose-based separators, bio-derived binders, and biodegradable polymers, are gaining attention for their ability to break down naturally, minimizing waste and facilitating eco-friendly disposal. Recyclable electrode materials, such as manganese dioxide, further enhance the viability of recycling by enabling the recovery and reuse of high-purity materials. Additionally, modular battery designs that allow for the easy separation of components during recycling streamline the material recovery process, offering a sustainable pathway for primary battery technologies.

Recycling primary batteries, particularly in regions with underdeveloped infrastructure, remains a significant challenge. While current methods, such as mechanical separation, pyrometallurgical, and hydrometallurgical processes, are effective to some extent, they are often energy-intensive and leave behind hazardous by-products. As a result, there has been significant interest in novel recycling methods, such as bioremediation techniques, which utilize bacteria and fungi to recover metals like zinc, nickel, and lithium in an environmentally friendly manner. These technologies not only reduce the environmental impact but also have the potential to lower energy consumption in the recycling process. Another promising approach is the use of closed-loop recycling systems that allow for the continuous reuse of materials without degrading their quality. However, these systems face significant economic barriers, such as the high initial investment in infrastructure and technology. Additionally, the development of modular battery designs that facilitate the easy separation of components during recycling can significantly reduce processing time and costs. Yet, challenges related to scalability and widespread implementation remain.

Policy also plays a crucial role in improving recycling efforts. While European Union regulations, such as the Battery Directive, mandate high recycling rates, there is a marked disparity in policies across different regions. In many developing countries, lack of legislation and recycling infrastructure significantly hamper battery recycling efforts. Countries like the United States lack a federal mandate for recycling primary batteries, which results in fragmented and less effective recycling systems. To address these discrepancies, future research should focus on harmonizing global recycling policies and developing international standards for recycling processes. This would enable a more efficient and sustainable global approach to primary battery recycling.

Another key limitation of primary batteries is their inflexibility in terms of reuse and recharging. Once a primary battery is depleted and ruined, it cannot be recharged, requiring replacement. This makes them less convenient and more costly in the long run or longer time of use compared to rechargeable batteries, especially in applications where devices are used frequently or for extended periods. The need for frequent replacements also contributes to the environmental waste problem, as users must continually purchase and discard new batteries. For many modern consumers, the inconvenience of constantly replacing batteries makes primary batteries less attractive compared to rechargeable alternatives that can be used for months or even years before needing replacement.

In addition to environmental and performance challenges, safety issues can also arise with primary batteries, particularly under certain extreme conditions. While primary batteries are generally safe for most consumer applications, they can pose risks if improperly handled or subjected to harsh environments. For instance, some primary batteries, particularly lithium-based ones, can leak or even explode if exposed to excessive heat, physical damage, or improper disposal. This presents a potential safety hazard, particularly in sensitive applications such as medical devices or military operations. Improving the safety of primary batteries, especially under extreme conditions, remains a challenge for manufacturers.

Moreover, the lack of innovation in primary battery technology has become a concern. In recent years, much of the research and development area in field of battery technology has focused on secondary (rechargeable) batteries, driven by the rapid growth of industries like consumer electronics, eVs, and renewable energy storage. As a result, primary batteries have seen fewer advances in terms of energy efficiency, environmental sustainability, and performance optimization. While secondary batteries have benefited from breakthroughs in materials science and battery chemistry, such as the development of lithium-ion and solid-state batteries, primary batteries have largely remained the same in terms of their core technology. This stagnation in innovation limits their ability to meet the evolving demands of modern technology and consumer expectations.

Additionally, cost considerations pose another limitation for primary batteries. While they are generally cheaper upfront than rechargeable batteries, the cumulative cost of replacing primary batteries over time can be significant, especially in high-use applications. For consumers and businesses looking to minimize long-term costs, rechargeable batteries often present a more economical option, as they can be recharged and reused many times before needing replacement. In applications where devices are used frequently, the repeated purchase of primary batteries can become financially burdensome, making them less attractive from a cost-efficiency perspective.

6. Future trends and research directions

The future of primary (non-rechargeable) batteries lies in advancing their performance, sustainability, and application in

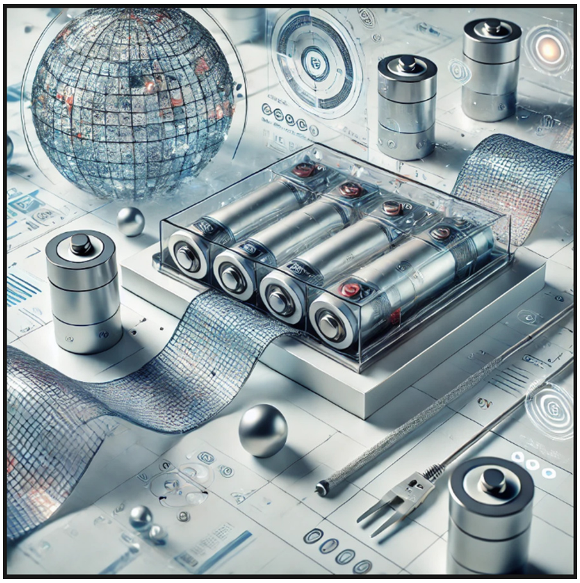

Fig. 19 Futuristic battery technologies: a glimpse into advanced research trends, featuring flexible batteries, solid-state designs, and nanomaterial-based innovations for next-generation energy storage solutions produced from Lexica (AI).

increasingly diverse fields. Although rechargeable batteries receive more attention due to their use in high-drain applications, primary batteries still hold significance for numerous sectors, especially where low-power, long-duration, and reliable energy sources are critical. Future trends in primary battery research will focus on enhancing energy density, improving environmental sustainability, and developing specialized batteries for niche applications. As shown in Fig. 19, futuristic battery technologies, including flexible batteries, solid-state designs, and nanomaterial-based innovations, are paving the way for next-generation energy storage solutions.

6.1. Energy density and performance enhancements

One of the major research directions for primary batteries is improving energy density. Increasing the amount of the energy that can be stored in a small volume is crucial for extending the life of primary batteries in low-drain devices and expanding their potential uses in high-performance applications. For example, lithium-based primary batteries, such as lithium–thionyl chloride ($Li–SOCl_2$) cells, are reknowned for their high energy density and long shelf life, making them prefect for specialized applications like military and aerospace technologies. Future research is likely to focus on optimizing lithium chemistry further, while also exploring new materials for anodes, cathodes, and electrolytes that can offer even higher energy densities without compromising safety or cost. Advances in nanotechnology also present opportunities for enhancing the performance of primary batteries. Nanomaterials such as graphene and carbon nanotubes could be integrated into battery electrodes to increase surface area and improve electron conductivity, resulting in higher energy storage capabilities. Additionally, novel electrolyte formulations could be developed to enhance ionic conductivity and minimize internal resistance, further boosting battery efficiency.

6.2. Environmental sustainability and recycling

With growing concerns over e-waste and battery disposal, primary batteries contribute significantly to global electronic waste, accounting for approximately 3% of total e-waste. Annually, over 15 billion primary batteries are produced, with many, especially alkaline and zinc–carbon batteries, ending up in landfills where their toxic components, including zinc, manganese, and traces of lead, leach into ecosystems, posing severe risks to human and environmental health. To address this, research focuses on environmentally friendly chemistries, such as biodegradable or recyclable batteries using organic materials like cellulose, lignin, or starch, which minimize reliance on hazardous metals. Enhanced recycling technologies, such as hydrometallurgical and biotechnological methods, are advancing material recovery with reduced energy consumption. However, recycling policies differ globally, with the EU enforcing stringent targets under its Battery Directive, while many developing nations lack formal frameworks. Harmonizing global recycling standards and advancing closed-loop systems, which reuse recovered materials in battery production, are essential for sustainability. Additionally, modular battery designs enabling easier disassembly further reduce e-waste. By combining innovative designs, advanced recycling methods, and policy harmonization, the environmental impact of primary batteries can be significantly mitigated, paving the way for a more sustainable future.

6.3. Specialized applications and miniaturization

The growing demand for primary batteries in specialized fields such as medical devices, aerospace, and the Internet of Things (IoT) is shaping future research directions. Medical implants, sensors, and other tiny devices require compact batteries with high energy density, reliability, and safety. Miniaturization is a key trend in battery design, with researchers focusing on reducing battery size while maintaining performance. Primary batteries are also essential in remote and harsh environments, where recharging is impractical. For example, space exploration and deep-sea missions rely on long-lasting, reliable power sources. Future trends in primary battery research will address the need for robust, high-performance batteries that can withstand extreme temperatures, radiation, and other environmental challenges.

6.4. New chemistries and emerging technologies

Emerging battery technologies are an exciting frontier for primary batteries. Researchers are exploring new chemistries, such as zinc–air and magnesium-based batteries, that promise higher energy densities and lower environmental impact. Zinc–air batteries, in particular, use of the oxygen from the atmosphere as a reactant, potentially offering high energy output in a lightweight design. Magnesium batteries are being researched for their potential to replace lithium in primary batteries, as magnesium is more abundant and safer to handle.

6.5. Integration with IoT devices and innovations for harsh environments

Future trends in primary battery research are increasingly focused on integrating these power sources with IoT devices, which require long-lasting, reliable, and compact batteries for wireless sensors, smart wearables, and other remote applications. The demand for batteries with high energy density and extended operational lifespans is driving innovations in lithium-based chemistries, enabling IoT devices to function for years in sectors like agriculture, healthcare, and environmental monitoring. Additionally, primary batteries designed for harsh environments are becoming critical for aerospace, military, and deep-sea exploration applications. These environments demand batteries that can withstand extreme temperatures, radiation, and pressure while providing consistent power. Magnesium-based primary batteries, for example, offer higher energy density and safety, making them ideal for such specialized applications. As the need for power in challenging conditions and connected devices grows, primary batteries will continue to evolve to meet the performance, durability, and sustainability requirements of these diverse sectors.

The future of primary battery research is focusing on improving energy as well as power density, sustainability, and application versatility. As industries continue to evolve, especially in fields such as medical technology, IoT, and aerospace, the demand for high-performance, environmentally friendly primary batteries will grow. Addressing current challenges and advancing these technologies will ensure that primary batteries continue to play a crucial role in both everyday devices and specialized applications.

7. Conclusion

Primary batteries continue to hold significant importance in a wide range of applications, from household devices to specialized fields such as medical equipment and aerospace. Despite the increasing focus on rechargeable technologies, primary batteries remain irreplaceable in scenarios where long-term reliability, cost-effectiveness, and minimal maintenance are essential. This review has examined the current state of primary battery technology, highlighting both their strengths and limitations. While primary batteries are valued for their simplicity and ease of use, key challenges remain, including environmental sustainability, performance in high-drain applications, and limited recycling options.

Future research efforts are focused on improving energy density, exploring environmentally friendly materials, and enhancing battery designs for specialized uses, such as medical implants and remote sensing devices. Innovations in nanotechnology, materials science, and biodegradable chemistries present exciting possibilities for the evolution of primary batteries. By addressing these challenges, primary batteries can continue to play a critical role in energy storage solutions, contributing to a sustainable and energy-efficient future.

Ethical approval

All the authors have worked in accordance with ethical standard and approved by Netaji Subhas University of Technology.

Data availability

All the data is presented in the manuscript. No supplementary data is needed.

Conflicts of interest

It is declared that this article is original and written by the stated authors. There is no conflict of interest between the authors. No conflicts of interest exist among the authors.

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