Review Article

Derleme Makalesi

UMÜFED Uluslararası Batı Karadeniz Mühendislik ve Fen Bilimleri Dergisi, 6(2): 53-79, 2024

UMUFED International Journal of Western Black Sea Engineering and Science

e-ISSN: 2687-2927

THE ROLE OF CARBON IN LEAD-ACID BATTERIES: APPLICATIONS, CHALLENGES, AND FUTURE OPPORTUNITIES

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ABSTRACT

The incorporation of various forms of elemental carbon into lead-acid batteries has the potential to significantly enhance battery performance. Carbon materials are commonly used as additives to the negative active material, particularly to improve cycle life and charge acceptance under high-rate partial state-of-charge (HRPSoC) conditions, which are prevalent in hybrid and electric vehicles. Carbon nanostructures and composite materials may also offer similar benefits. However, the impact of carbon on the positive active material is generally more limited compared to its influence on the negative side. Additionally, carbon can serve as a mesh current collector for both negative and positive plates. This advanced technology boosts energy storage efficiency by increasing the battery's specific energy and optimizing active mass utilization. Such batteries, featuring a more robust active mass structure, promise extended cycle life. Recently, another important application of carbon in secondary batteries is its use in supercapacitor electrodes, which can either replace the negative plate or be connected in parallel with the lead plate. These innovative approaches enhance overall battery efficiency by improving specific power and HRPSoC performance. Furthermore, integrating carbon-based technologies into the production of lead-acid batteries can significantly enhance their performance, giving them a competitive advantage over other battery systems. These

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Atıf (Citation): Arslan, S., Yalçın, Z.G., Dağ, M., Akın, M.B., "The Role of Carbon in Lead-Acid Batteries: Applications, Challenges, and Future Opportunities", UMÜFED Uluslararası Batı Karadeniz Mühendislik ve Fen Bilimleri Dergisi, 6(2): 53-79, 2024.

Geliş (Received): 23/09/2024

Kabul (Accepted): 30/12/2024

Yayın (Published): 31/12/2024

advancements also hold substantial potential for delivering more environmentally friendly and cost-effective energy storage solutions.

Keywords: Lead-acid batteries, Carbon, High-rate partial state of charge, HRPSoC, Cycle life.

KURŞUN-ASİT PiLLERDE KARBONUN ROLÜ: UYGULAMALAR, ZORLUKLAR VE GELECEK FIRSATLAR

ÖZET

Kurşun-asit pillere çeşitli biçimlerdeki elementel karbonun eklenmesi, pil performansını önemli ölçüde artırma potansiyeline sahiptir. Karbon malzemeler, özellikle çevrim ömrünü ve yüksek oranlı kısmi şarj durumu (HRPSoC) koşullarında şarj kabulünü iyileştirmek amacıyla negatif aktif malzemeye katkı maddesi olarak yaygın bir şekilde kullanılır. Bu koşullar, hibrit ve elektrikli araçlarda yaygındır. Karbon nanoyapılar ve kompozit malzemeler de benzer faydalar sağlayabilir. Ancak, karbonun pozitif aktif malzeme üzerindeki etkisi, negatif tarafa göre genellikle daha sınırlıdır. Buna ek olarak, karbon, hem negatif hem de pozitif plakalar için bir ağ akım toplayıcısı olarak işlev görebilir. Bu ileri teknoloji, pilin özgül enerjisini artırarak ve aktif kütle kullanımını optimize ederek enerji depolama verimliliğini artırır. Bu tür piller, daha dayanıklı bir aktif kütle yapısına sahip olup, uzatılmış bir çevrim ömrü vaat eder. Son dönemde, karbonun ikincil pillerdeki bir diğer önemli uygulaması, süperkapasitör elektrotlarında kullanılmasıdır. Bu elektrotlar, negatif plakayı değiştirebilir veya kurşun plakayla paralel bağlanabilir. Bu yenilikçi yaklaşımlar, özgül gücü ve HRPSoC performansını iyileştirerek pilin genel verimliliğini artırır. Ayrıca, kurşun-asit pillerin üretimine karbon bazlı teknolojilerin entegre edilmesi, performanslarını önemli ölçüde artırarak diğer pil sistemlerine göre rekabetçi bir avantaj sağlar. Bu gelişmeler, daha çevre dostu ve maliyet açısından etkili enerji depolama çözümleri sunma potansiyeline de sahiptir.

Anahtar kelimeler: Kurşun-asit piller, Karbon, Yüksek oranlı kısmi şarj durumu, HRPSoC, Çevrim ömrü.

1. INTRODUCTION

Various forms of carbon have found extensive applications in different electrochemical power sources. The unique properties and diverse allotropes of carbon play a crucial role in enhancing multiple aspects of lead-acid batteries. In recent years, the use of carbon-based materials in battery technologies has significantly increased. Research indicates that incorporating activated carbon into the negative plates of lead-acid batteries can significantly extend their lifespan [1]. Additionally, carbon materials offer alternative solutions to enhance the performance of energy storage systems. The use of carbon rod collectors in recycling zinc-carbon batteries, particularly in creating sustainable cathodes for rechargeable zinc-ion batteries, further emphasizes the critical importance of carbon in battery technology [2]. Furthermore, the recovery of spent lead paste through environmentally friendly leaching processes using oxalate solutions provides an effective method for sustainably reclaiming lead, a crucial component in lead-acid battery production [3,4]. These advancements highlight the growing significance of carbon in energy storage systems.

Lead-Acid Batteries

A lead-acid battery is a secondary cell where metallic lead at the negative electrode and lead (IV) oxide at the positive electrode are transformed into lead (II) sulfate during the discharge process. Both reactions take place in the presence of sulfuric acid (H_2SO_4) as the electrolyte [5]. The discharge reaction is represented by Equation (1) [6].

$$Pb + PbO_2 + 2H_2SO_4 \rightleftarrows 2PbSO_4 + 2H_2O \quad (1)$$

The advantage of lead-acid batteries lies in their ability to operate for extended periods under variable charging conditions and their low self-discharge rate. However, their drawbacks include high weight due to low specific energy and a limited number of charge/discharge cycles [7]. In 1860, Planté developed a secondary cell with high power and capacity, using a design similar to that used by Offershaus and Hare for voltaic cells. In this design, two long and wide lead plates were rolled together, separated by a thick cloth, and immersed in a glass jar filled with water acidified with one-tenth sulfuric acid. The initial performance of a nine-cell secondary battery with a total surface area of ten square meters was presented at the March 26, 1860, meeting of the Academy of Sciences. The work Recherches sur l'Électricité includes hand-drawn illustrations of various electrical devices as some of the earliest battery designs [8].

Each illustration depicts a different electrical cell or battery design, reflecting early explorations of electrical energy storage and transmission. Figure 1a shows a secondary cell, referred to as Couple secondaire à lames de plomb en spirale, featuring spiral-wound lead plates used for electrochemical energy storage. Figure 1b illustrates a secondary battery with a large surface area, labeled Batterie secondaire de grande surface. Figures 1c and Figure 1d depict a secondary cell with parallel lead plates, labeled Secondary cell with parallel lead plates, where letters a, b, c, and a', b', c' represent the parallel lead plates. Figure 1e presents a design with lead plates separated by rubber strips, intended to insulate the lead plates from each other [9].

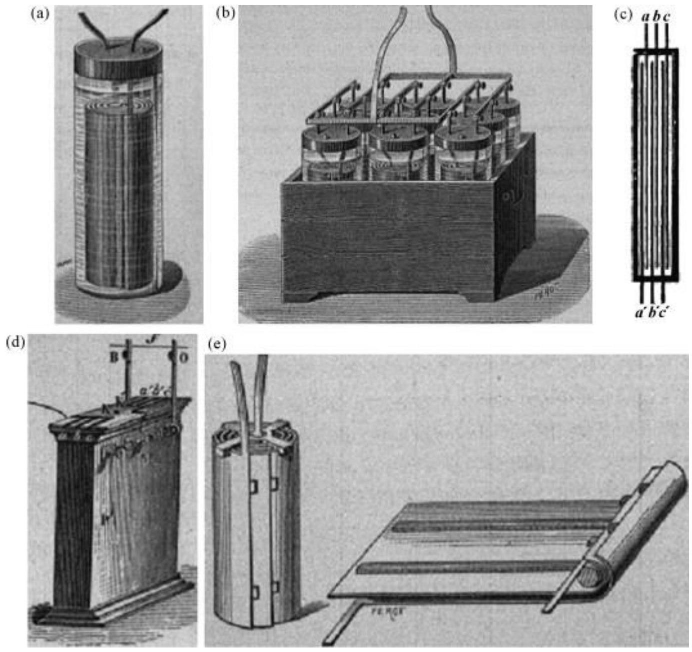

Figure 1. Illustrations from *Recherches sur l'Électricité*. (a) A secondary cell with spiral-wound lead plates. (b) A secondary battery with a large surface area. (c and d) A secondary cell with parallel lead plates (a, b, c, a′, b′, c′). (e) Lead plates separated by rubber strips [9].

Today, batteries are made from polypropylene or polyethylene plastics. The plates consist of a lead alloy grid with an active mass (positive or negative) applied to it. It is well known that during battery operation, electrochemical reactions occur, involving the oxidation of lead in the paste. Figure 2 provides a representative image of modern batteries [10].

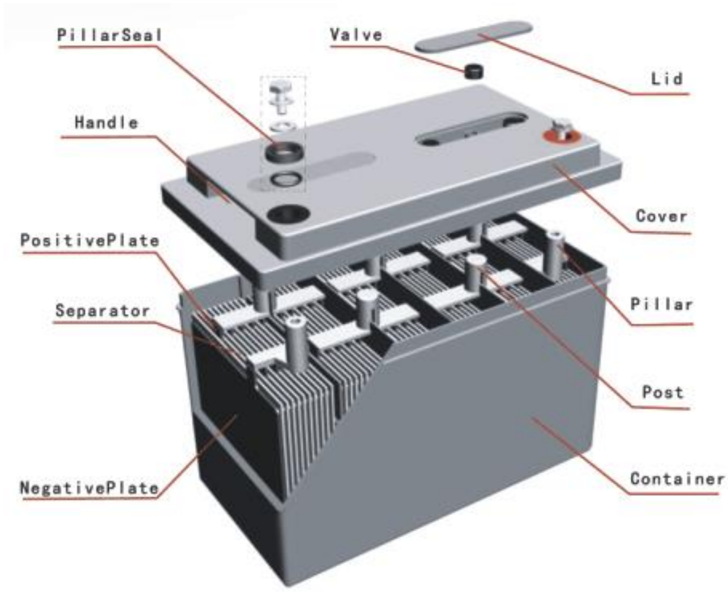

Figure 2. Representative image of a modern battery [10].

2. IMPACT OF CARBON ON LEAD-ACID BATTERIES

The performance of lead-acid batteries is directly dependent on the properties of the negative and positive active materials, as well as the current collector. These active materials are the sites where electrochemical reactions occur, determining the mechanisms of energy storage and release in the battery. The current collector, typically made of lead or lead alloys, serves as a conductive framework that facilitates the flow of electrons between the active materials and the external circuit, ensuring efficient energy transfer. During charging, the negative active material (NAM) is reduced to lead (Pb), and during discharging, it is converted into lead sulfate ($PbSO_4$). This transformation forms the basis of the battery's energy storage and release processes. The positive active material (PAM) is typically found in the form of lead dioxide (PbO_2). This material plays a critical role in the oxidation reactions involved in the battery's energy storage and release. Table 1 provides a comparative overview of the roles, materials, and functions of the current collector, PAM, and NAM in lead-acid batteries. It highlights the distinct contributions of each component to the battery's overall functionality, including their specific roles in energy storage, material composition, and involvement in electrochemical reactions. To enhance the performance of lead-acid batteries and overcome their limitations, carbon additives targeting both negative and positive active materials, as well as current collectors, have become a major focus of research and development efforts. Carbon materials offer an innovative solution to extend the cycle life of batteries while improving energy storage efficiency.

Table 1. Comparison of Roles and Properties of Current Collector, PAM, and NAM in Lead-Acid Batteries

Aspect	Current Collector	PAM	NAM
Function	Conducts electrons to/from active materials	Stores/releases energy via oxidation	Stores/releases energy via reduction
Material	Lead grid or lead alloy	Lead dioxide (PbO_2)	Sponge lead (Pb)
Role in Reaction	Passive conductor	Active participant in redox reactions	Active participant in redox reactions

2.1. The Role of Carbon Materials in Optimizing NAM

Lead-acid batteries are among the most widely used rechargeable energy storage systems, where the NAM primarily consists of sponge Pb. This material plays a critical role in electrochemical reactions, enabling energy storage and release [7]. The porous structure of NAM provides a distinct advantage by facilitating the diffusion and distribution of sulfuric acid electrolyte, increasing the active surface area available for redox reactions [11]. The efficiency of charge and discharge processes is directly influenced by the surface area and porosity of the negative electrode [12]. However, over time, the porous lead structure tends to degrade, resulting in reduced cycle life and diminished capacity [13].

The inclusion of carbon materials in the negative electrodes of lead-acid batteries has been extensively studied as a means of addressing these limitations. Research demonstrates that carbon additives significantly enhance the performance, cycle life, and efficiency of lead-acid and lead-carbon batteries [14-16]. This improvement is primarily attributed to the unique properties of carbon, such as its high electrical conductivity and chemical stability.

Carbon materials, including multi-walled carbon nanotubes (MWCNT), have been shown to improve the conductivity of the negative electrode, thereby enhancing discharge performance [17]. Additionally, carbon helps slow the growth of $PbSO_4$ crystals, mitigating the issue of sulfation—a common cause of reduced battery efficiency. For example, the integration of lead nanoparticles into nanoporous carbon regulates the formation of $PbSO_4$ crystals, improving electrical conductivity, enhancing battery performance, and suppressing hydrogen gas evolution during operation [16]. Similarly, lead oxide coated with N-doped graphene oxide composites effectively reduces $PbSO_4$ crystal aggregation, accelerates redox processes, and stabilizes the electrode structure over extended use, thus prolonging the battery's cycle life [18, 19].

Various types of carbon materials, including graphite, carbon black, carbon nanotubes (CNTs), and activated carbon, have been utilized in lead-acid batteries to optimize the properties of NAM [20-23]. Each of these materials offers specific benefits:

The positive impact of carbon additives on lead-acid battery performance extends beyond laboratory studies to commercial applications. These additives enhance the rheological and electrical properties of electrodes, underscoring their importance in optimizing battery functionality. Additionally, the versatility of carbon materials has been explored in other battery technologies, such as zinc slurry air-flow batteries, highlighting their potential for diverse energy storage systems [24].

Incorporating carbon materials into batteries also aligns with global sustainability goals. Biomass-derived carbon materials, such as biochar, have shown promising properties for battery electrode applications, offering high specific capacity, excellent cycling performance, and high initial discharge efficiency [25-27]. These materials contribute to environmental sustainability by utilizing renewable resources and reducing the environmental footprint of energy storage systems [25,27].

Life cycle assessments (LCAs) further demonstrate the environmental advantages of carbon additives, providing insights into their impact on greenhouse gas emissions and energy consumption when compared to traditional battery technologies like lithium-ion and lead-acid batteries [28,29]. However, the performance of carbon materials depends on factors such as the type of carbon used, its quantity, and its interaction with NAM. Therefore, optimizing the type and amount of carbon for specific applications is critical for maximizing the benefits of these materials in lead-acid batteries.

2.2. The Role of Carbon Materials in Optimizing PAM

In lead-acid batteries, the PAM, typically PbO_2, plays a pivotal role in determining the battery's overall performance and longevity [7]. Its efficiency directly impacts the energy storage and power delivery capabilities of the battery. Maintaining high charge efficiency is crucial to prevent deposit formation on the electrodes and reduce Pb^{2+} concentration in the electrolyte, both of which limit the cycle life of the battery [30,31]. Phosphate ions have been shown to reversibly adsorb onto PbO_2 during charging, altering the crystal growth of PbO_2 on the lead grid and making it more resistant to reduction into lead sulfate [32]. This resistance minimizes chemical degradation and passivation, which are common issues in PAM, highlighting the potential of further material innovations to address these challenges.

Carbon materials are emerging as critical enhancers of PAM performance due to their high conductivity, lightweight nature, and chemical stability. Incorporating carbon increases the electrical conductivity of PAM, accelerating electron transfer and optimizing the efficiency of charge and discharge cycles. For example, activated carbon derived from coconut shells has been shown to significantly enhance the electrical conductivity of PAM, speeding up charge transfer processes [33]. Moreover, carbon improves the mechanical durability of the PbO_2 structure, preventing cracking and shedding of active material, which are key factors in extending battery lifespan during long-term use [20].

Another critical benefit of carbon is its ability to slow the corrosion process in PAM. This reduction in corrosion helps maintain the structural integrity of the electrode, minimizing internal resistance and capacity loss, especially in batteries with long cycle lives [34]. Carbon materials also enhance thermal management in lead-acid batteries. By dissipating heat more efficiently, carbon prevents overheating of PAM under high-temperature conditions, improving thermal stability and ensuring safer battery operation. Research has demonstrated that carbon materials improve heat distribution and prevent the overheating of active materials, thereby supporting safe and efficient battery use under extreme conditions [35-37].

Various types of carbon materials, including graphite, carbon black, CNTs, and graphene, have been integrated into PAM, each with distinct advantages [38-44].

Research continues to focus on optimizing carbon additives to enhance the performance, lifespan, and efficiency of lead-acid batteries.

2.3. The Role of Carbon Materials in Optimizing Current Collectors

Recent studies have supported the potential benefits of carbon-based materials in enhancing the performance of lead-acid batteries. For example, Banerjee et al. (2017) demonstrated that incorporating single-walled carbon nanotubes (SWCNT) into battery electrodes significantly improved battery service life and operational efficiency by suppressing sulfation processes [34]. Similarly, Li et al. (2022) reported that integrating nanometer-sized lead sulfate carbon composites into the anode material enhanced cycle life and electrochemical activity, suggesting that carbon materials can also function as effective current collectors [44]. Additionally, other studies have explored the potential of carbon-based materials to maintain structural integrity and efficiency, particularly under harsh operating conditions, highlighting the value of innovative materials in battery technologies [45,46]. These findings underscore the transformative role of carbon materials in optimizing lead-acid battery technology and the need for continued innovation in energy storage solutions.

2.4. Applications of Carbon Materials on Lead-Acid Batteries and Benefits

Carbon materials play a vital role in enhancing the performance of lead-acid batteries due to their excellent electrical conductivity, lightweight structure, high surface area, and chemical stability. Different structural forms of carbon, such as graphite, carbon black, CNTs, and graphene, each bring unique properties that can significantly improve battery efficiency and durability. For example, graphite facilitates efficient electron transport due to its layered structure, while carbon black provides high surface area and conductivity, making it an effective conductive agent [47,48]. CNTs and graphene, with their exceptional mechanical properties and electronic conductivity, are particularly effective in improving electrode performance across various battery types, including lead-acid batteries [49,50]. The integration of these carbon materials enhances electrode conductivity and increases the overall energy density and cycle life of batteries, demonstrating their critical role in advancing energy storage technologies [49,50].

Graphite, with its unique hexagonal layered structure, is instrumental in improving the performance of lead-acid batteries. Its high electrical conductivity facilitates rapid electron transfer during charge and discharge cycles, which is crucial for effective energy storage [51]. Additionally, graphite's chemical stability in both acidic and basic environments makes it suitable for use in lead-acid batteries, preserving its structural integrity and reducing the risk of corrosion and degradation over time [52]. Graphite's abundance and low production cost further enhance its commercial appeal [53]. However, its mechanical durability may not always meet the demands of specific applications, necessitating further research to address its limitations [51,53].

Carbon black is an amorphous form of carbon that is increasingly utilized in energy storage applications due to its high surface area and conductivity. Its high surface area enhances electrochemical reactions within the battery, increasing capacity and improving battery performance [39]. Carbon black's conductivity enables faster charge and discharge cycles and enhances overall energy storage efficiency [20]. Despite its advantages, carbon black faces challenges such as agglomeration, which can disrupt electrode homogeneity, and higher production costs compared to graphite, limiting its widespread adoption [20,53]. Ongoing research aims to address these limitations and maximize the potential of carbon black in lead-acid batteries by optimizing its distribution and reducing costs [44].

CNTs are a significant innovation in energy storage, offering exceptional mechanical durability, high conductivity, and large surface area. Their integration into lead-acid batteries enhances battery performance by improving structural integrity, extending battery lifespan, and increasing the efficiency of charge and discharge cycles [54,55]. CNTs also promote efficient electrochemical reactions by providing a larger active surface area, which increases the overall capacity of the battery [20,49]. However, their widespread adoption is limited by high production costs and the technical challenges of achieving homogeneous distribution within electrode structures [55]. Addressing these issues could unlock the full potential of CNTs for commercial applications [54,55].

Graphene, a two-dimensional material composed of a single layer of carbon atoms, is a transformative material in energy storage due to its exceptional electrical conductivity, lightweight nature, and large surface area. It improves charge and discharge rates by reducing internal resistance and enhancing energy transfer efficiency [56,57]. Graphene also contributes to the portability and energy density of lead-acid batteries, making it particularly advantageous for portable devices and electric vehicles [56,59]. Its durability and chemical stability ensure consistent performance under varying environmental conditions, contributing to the long-term reliability of energy storage systems [56,57]. However, the high production costs and technical challenges of integrating graphene into battery structures limit its large-scale adoption [57-61].

Carbon materials are increasingly used in lead-acid batteries due to their remarkable properties, offering significant advantages in improving battery performance. Among these properties, high electrical conductivity is a primary benefit, enabling faster charge and discharge cycles. This is especially critical for applications requiring rapid energy delivery, as it reduces internal resistance and enhances the battery's overall efficiency [62]. For instance, the integration of CNTs into battery structures creates a conductive network that improves charge transfer, thereby boosting electrochemical performance [63]. Similarly, graphene's exceptional conductivity facilitates efficient electron transport, further optimizing battery performance [62].

Beyond conductivity, the lightweight nature of carbon materials provides another advantage, particularly in reducing the total weight of lead-acid batteries. This characteristic is especially beneficial for portable applications where energy density is a key requirement [62,64]. Materials such as graphene and CNTs, with their large surface area, enable more efficient electrochemical reactions, potentially increasing the battery's capacity and overall performance [62,65].

In addition to the advancements brought by carbon materials such as graphite, carbon black, carbon nanotubes, and graphene in lead-acid batteries, RVC has emerged as a next-generation material with significant potential to optimize battery performance. Its high surface area and porous structure make it an attractive candidate for enhancing energy storage systems.

RVC is a lightweight, porous material that is increasingly used as a current collector in lead-acid batteries. Its unique open-cell foam structure provides a large surface area, enabling better contact with the electrolyte and enhancing charge transfer and electrochemical reaction rates [66]. This large surface area, combined with RVC's high porosity, facilitates effective penetration of the electrolyte, which optimizes battery performance and increases energy storage capacity [66].

Additionally, RVC exhibits excellent electrical conductivity, which accelerates charge and discharge cycles, thereby improving the overall efficiency of batteries. Its ability to reduce internal resistance makes RVC particularly beneficial for applications requiring rapid energy delivery [66]. Furthermore, RVC's mechanical durability helps maintain the structural integrity of batteries over extended cycles, contributing to improved lifespan and reliability. Its chemical stability offers resistance to corrosion and degradation, further extending battery life and enhancing the robustness of energy storage systems [66].

Despite its many advantages, the adoption of RVC faces challenges. The high production costs and integration difficulties with existing battery designs remain significant barriers to its widespread commercial use [64, 66]. These challenges emphasize the importance of ongoing research aimed at optimizing production processes, reducing costs, and improving integration methods [65].

Efforts to address these limitations focus on developing scalable manufacturing techniques and exploring innovative applications of RVC in energy storage systems. By overcoming these barriers, RVC could become a transformative material in lead-acid battery technology, providing enhanced performance and longevity for various applications.

2.5. The Role of RVC in Lead-Acid Batteries

Traditionally, lead and its alloys have been used as current collectors in lead-acid batteries. While effective, these materials exhibit significant drawbacks, such as high weight, susceptibility to corrosion, and limited cycle life. Corrosion of the current collectors during charge and discharge cycles can result in capacity loss and reduced battery lifespan [67]. This degradation is further exacerbated by local cell reactions at the interface between the active material and the current collector, weakening structural integrity and electrode adhesion [52].

Recent advancements in materials science have driven the exploration of alternative current collector materials to address these limitations. Copper foam substrates, for instance, have been investigated for their potential to improve battery performance by providing a more stable interface and reducing battery weight. Lead-foam grids created through electrodeposition on such substrates have shown promise in enhancing electrochemical performance [68]. Additionally, advanced materials like graphene and CNTs, known for their lightweight properties, high conductivity, and corrosion resistance, have opened new avenues for current collector design. While primarily studied in lithium-ion batteries, these materials hold potential for future research in lead-acid batteries, offering the possibility of higher energy densities and extended cycle lives [37,62].

Reticulated Vitreous Carbon (RVC) is emerging as a transformative material for current collectors in lead-acid batteries. It offers several key advantages that can significantly enhance battery performance. RVC’s low density reduces the overall weight of the batteries, making it particularly advantageous for portable applications such as automotive batteries and electronic devices, where lighter weight translates to improved efficiency and usability [69].

One of RVC’s standout features is its high electrical conductivity, which facilitates efficient electron flow between electrodes. This capability accelerates charge and discharge cycles, improving the operational efficiency of batteries—a critical feature for applications demanding rapid energy delivery and recovery [70]. Moreover, RVC’s mechanical durability ensures structural integrity under harsh environmental conditions, extending battery lifespan and reliability [64].

The material's chemical stability is another significant advantage. Unlike traditional lead-based collectors that are prone to corrosion, RVC resists degradation, maintaining low internal resistance and minimizing capacity loss over time [67]. This corrosion resistance is crucial for enhancing the long-term stability of lead-acid batteries and improving their performance in various applications [70].

RVC's porous structure further enhances its utility. The increased surface area enables better interaction with the active materials and electrolyte, optimizing electrochemical reactions. This leads to greater charge transfer efficiency, increased energy storage capacity, and improved overall performance of lead-acid batteries [64].

Despite its advantages, the widespread adoption of RVC in lead-acid batteries faces several challenges. The high production costs of RVC and the complexities associated with its integration into existing battery designs limit its commercial viability [64,66]. To overcome these barriers, research is focusing on optimizing production processes, reducing costs, and improving integration methods [65]. Scalable manufacturing techniques and innovative applications are key areas of development to make RVC more accessible for energy storage systems.

Researchers have also explored the use of carbon foam materials, such as carbonized pitch-impregnated polyurethane foam, as current collectors. These materials have demonstrated improved discharge capacity due to their ability to form smaller $PbSO_4$ crystals, which allow more charge cycles. However, lower conductivity and issues like plate shedding have been noted, especially for foam collectors on the positive plate [71-74].

Other studies have investigated advanced materials, such as graphene-aligned graphite foams and composite structures, to enhance current collector performance. While promising in certain aspects, these materials also face challenges related to adhesion, durability, and cost, underscoring the need for further research [76,77].

Similarly, the application of carbon as a capacitor in lead-acid batteries offers an innovative approach to addressing these challenges, providing enhanced energy storage capabilities and improved performance metrics by leveraging the unique properties of carbon materials.

2.6. The Use of Carbon as a Capacitor in Lead-Acid Batteries

Lead-acid batteries have been a reliable and cost-effective solution for energy storage applications for decades. However, limitations in capacity, cycle life, and energy density have prompted researchers to seek innovative improvements. One promising approach is the integration of carbon materials, particularly in the form of supercapacitors, to enhance the performance of lead-acid batteries.

The incorporation of carbon materials, such as single-walled carbon nanotubes (SWCNTs), has demonstrated significant potential in improving the electrochemical properties of lead-acid batteries. Research indicates that doping lead-acid batteries with CNTs can enhance conductivity and increase the active surface area, ultimately improving capacity and extending cycle life [34]. These advancements address the traditional shortcomings of lead-acid batteries, such as their relatively low energy density and limited cycle life, through the use of advanced materials [53]. Furthermore, combining supercapacitors with lead-acid batteries has proven to be an effective strategy for optimizing energy storage systems, particularly in applications requiring rapid charge and discharge cycles [81,82].

Hybridizing lead-acid batteries with supercapacitors offers a synergistic improvement in performance. Increasing the volumetric ratio of supercapacitors in a composite energy storage system allows supercapacitors to handle high power demands, while the lead-acid battery provides energy storage. This approach not only increases energy density but also extends the overall lifespan of the energy storage system [83]. Such synergy is especially advantageous for applications like hybrid electric vehicles, where frequent cycling is required [84].

Another benefit of incorporating carbon materials into lead-acid batteries is their ability to address performance issues under varying temperature conditions. Research has shown that adding carbon-based materials can improve the low-temperature performance of lead-acid batteries, expanding their operational range and reliability across diverse environments [53]. This enhancement is particularly critical for applications such as electric vehicles and renewable energy systems, where temperature fluctuations can significantly impact battery performance.

Carbon materials are critical components in supercapacitors due to their exceptional properties, including high electrical conductivity, large surface area, and chemical stability. Supercapacitors, known for their rapid charge and discharge capabilities, significantly benefit from the integration of carbon materials. For instance, interconnected carbon nanosheets derived from hemp have demonstrated ultra-fast charge storage capabilities, achieving high specific capacitance values under various scan rates and temperatures [85].

Materials such as activated carbon and CNTs also improve capacitance by increasing ion adsorption due to their large surface areas, which can reach up to 3000 m^2/g [86]. Hierarchical porous carbon monoliths, an important feature of high-voltage aqueous supercapacitors, combine large surface areas with structural integrity, enhancing ion accessibility and charge storage efficiency [87, 88]. The chemical stability of carbon materials ensures durability in energy storage processes, making them ideal for long-term solutions [89, 90].

The various roles and benefits of carbon materials in lead-acid batteries, spanning NAM, PAM, current collectors, and capacitors, are summarized in Table 2, providing a comparative perspective on their applications and contributions to performance enhancement.

Table 2. Comparison of Carbon Materials' Roles and Benefits in Optimizing Lead-Acid Battery Components

Aspect	Optimizing NAM	Optimizing PAM	Current Collectors	As Capacitors
Role in Battery	Enhances conductivity, reduces $PbSO_4$ crystal growth, improves cycle life and discharge performance	Increases conductivity, prevents active material degradation, slows corrosion, and improves thermal management	Facilitates electron flow, reduces weight, resists corrosion, and improves structural integrity	Improves charge-discharge rates, increases energy density, and extends cycle life
Carbon Materials Used	Graphite, carbon black, CNTs, graphene, activated carbon	Graphite, carbon black, CNTs, graphene, activated carbon	Reticulated Vitreous Carbon (RVC), carbon foam, graphene-aligned graphite foams	CNTs, graphene, activated carbon, hemp-derived carbon nanosheets
Key Benefits	Boosts redox reactions	Enhances electrical and thermal conductivity	Accelerates charge-discharge cycles	Rapid energy delivery
	Stabilizes electrode structure	Prevents cracking and shedding	Optimizes electrolyte interaction	Maintains performance under varying temperatures
	Mitigates sulfation effects	Improves corrosion resistance	Reduces internal resistance	Mitigates sulfation effects
Challenges	Material interaction optimization	Addressing cost and scalability	High production costs	High production costs

	Quantity calibration for specific applications	Integration with existing technologies	Integration with existing designs	Complex integration
Applications	Renewable energy systems, high-power output applications	Energy storage systems requiring durability and efficiency	Automotive batteries, portable devices, renewable energy storage	Hybrid electric vehicles, portable energy solutions, temperature-sensitive applications

Integrating carbon as a capacitor in lead-acid batteries can enhance performance in several key ways. First, carbon increases the charge and discharge rates of the batteries, making them more efficient for high-power applications. This capability is critical for energy-intensive uses, where rapid energy delivery is essential. Second, incorporating carbon capacitors improves the energy density of batteries, enabling the storage of more energy within the same volume, which is an important factor for portable energy storage solutions.

Additionally, the use of carbon capacitors extends the cycle life of lead-acid batteries. Carbon materials enhance the chemical and mechanical stability of the electrodes, maintaining performance over extended use. Moreover, carbon capacitors help mitigate adverse effects such as sulfation in lead-acid batteries, reducing internal resistance and preventing capacity loss, thereby improving the batteries' long-term performance [91].

Despite their numerous advantages, the use of carbon as a capacitor in lead-acid batteries faces challenges. The high production costs of carbon materials and the complexities associated with their integration into existing battery technologies pose significant barriers to widespread adoption. However, ongoing advancements in production methods and material design aim to address these limitations.

The application of carbon as a capacitor represents an innovative approach to enhancing lead-acid battery performance. By improving charge-discharge rates, energy density, cycle life, and overall durability, carbon capacitors offer substantial potential to transform this field. In the future, overcoming the challenges of cost and integration could enable the broader adoption of carbon capacitors, significantly enhancing the efficiency and durability of energy storage solutions.

3. CONCLUSION

The integration of carbon materials into lead-acid batteries has proven to be a transformative approach to overcoming the traditional limitations of these batteries, particularly in enhancing cycle life and charge acceptance. Additives such as carbon black, graphene, and activated carbon play a pivotal role in boosting the overall performance of lead-acid batteries. By increasing conductivity and inhibiting the excessive formation of lead sulfate crystals, these materials address critical performance bottlenecks. These enhancements are particularly vital for applications requiring frequent cycling and high power output, such as renewable energy storage systems and electric vehicles.

Ongoing research and development in optimizing the types and quantities of carbon materials used in lead-acid batteries are driving continuous improvements in efficiency, durability, and reliability. The incorporation of carbon not only extends the operational life of these batteries but also improves their suitability for high-demand applications, bridging the gap between conventional lead-acid batteries and more expensive advanced technologies.

In conclusion, carbon-enhanced lead-acid batteries present a cost-effective and practical energy storage solution, meeting the growing demands for performance and sustainability. Continued advancements in this field are poised to further reinforce the relevance of lead-acid batteries in the global energy landscape, particularly in sectors where cost-efficiency, safety, and reliability are paramount.

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