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The role of nanomaterials in energy storage: A comparative review of USA and African developments

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Abstract

This Review provides a succinct overview of a comparative review examining the role of nanomaterials in energy storage, focusing on developments in the United States (USA) and Africa. Nanomaterials have emerged as key players in revolutionizing energy storage technologies, with significant implications for global energy sustainability. In the USA, advancements in nanomaterials for energy storage have been at the forefront of research and development efforts. Nanostructured materials, such as graphene, carbon nanotubes, and various metal oxides, have demonstrated exceptional properties, enhancing the performance of energy storage devices like batteries and supercapacitors. This review explores the latest innovations in the USA, highlighting the strides made in improving energy storage capacity, charging rates, and overall efficiency through the integration of nanomaterials. Contrastingly, the African continent has been an arena for unique challenges and opportunities in the realm of energy storage. Despite facing resource constraints and limited access to state-of-the-art research facilities, African researchers have showcased resilience and ingenuity in utilizing nanomaterials for energy storage solutions. This comparative analysis sheds light on the distinctive approaches taken by African nations, emphasizing indigenous innovations and locally sourced materials to address energy storage needs in a sustainable and context-specific manner. The review encompasses an examination of the economic, social, and environmental dimensions of nanomaterial applications in energy storage, drawing comparisons between the two regions. It considers the accessibility and affordability of nanomaterial-based technologies, exploring their potential to bridge energy disparities and foster economic development, particularly in African communities. As the global community strives to transition towards cleaner and more sustainable energy systems, understanding the diverse landscapes of nanomaterial research and development is imperative. This comparative review serves as a valuable resource for policymakers, researchers, and industry stakeholders, offering insights into the nuanced dynamics of nanomaterial utilization in energy storage across the USA and Africa. It encourages collaborative efforts and knowledge exchange to propel the equitable advancement of energy storage technologies, ensuring that innovations benefit diverse populations and contribute to a more inclusive and sustainable energy future.

Keywords: Nanomaterials; Energy; Storage; Developments; Role

1. Introduction

In the quest for sustainable and efficient energy storage solutions, nanomaterials have emerged as a transformative force, offering unprecedented opportunities to enhance the performance of energy storage devices. Their unique

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properties at the nanoscale, such as increased surface area, improved conductivity, and enhanced electrochemical characteristics, have positioned nanomaterials as key enablers in the evolution of energy storage technologies. This introduction delves into the significance of nanomaterials in energy storage, provides an overview of a comparative review between the United States (USA) and African developments, and emphasizes the importance of comprehending global nanomaterial applications in this critical field (Shaker, 2024).

Nanomaterials, with dimensions typically ranging from 1 to 100 nanometers, exhibit unique and advantageous properties due to their quantum effects and high surface-to-volume ratios. These properties make them ideal candidates for improving the efficiency and performance of energy storage systems, including batteries and supercapacitors. As the demand for advanced energy storage solutions grows, the role of nanomaterials becomes increasingly pivotal in addressing the challenges of energy storage, such as enhancing capacity, cycling stability, and overall energy density (Zhou et al., 2019).

The comparative review explores the landscape of nanomaterial applications in energy storage, focusing on developments in two distinct regions: the technologically advanced United States and the dynamically evolving African continent. While the USA boasts cutting-edge research facilities and a robust scientific ecosystem, Africa presents unique challenges and opportunities, including resource constraints and the necessity for context-specific solutions. This comparative analysis aims to provide insights into the diverse approaches, innovations, and contributions that each region brings to the utilization of nanomaterials in energy storage (Hossain et al., 2020).

The purpose of this comparative review is to underscore the global relevance of nanomaterials in the context of energy storage. By juxtaposing developments in the USA and Africa, we aim to glean insights into the varied strategies employed, the socio-economic factors influencing technology adoption, and the potential impact on addressing energy challenges. Understanding how nanomaterial applications are shaping energy storage on a global scale is crucial for fostering collaboration, sharing knowledge, and ensuring that advancements in nanotechnology contribute to a more inclusive and sustainable energy future. As nations grapple with the imperative to transition towards cleaner energy, this review serves as a guide for researchers, policymakers, and industry stakeholders invested in the transformative potential of nanomaterials in energy storage (Meidl, 2021).

1.1. Nanomaterials in Energy Storage: Global Perspectives

The relentless pursuit of advanced energy storage solutions has ushered in an era where nanomaterials play a pivotal role in transforming the landscape of energy storage technologies (Muneer, 2023). This review delves into the global perspectives of nanomaterial applications, with a particular focus on a comparative review between the United States (USA) and African developments. We navigate through a brief overview of commonly used nanomaterials in energy storage, elucidate the significance of nanomaterials in enhancing device performance, and examine global trends in the utilization of these materials for energy storage technologies. Graphene, a single layer of carbon atoms arranged in a hexagonal lattice, stands as a nanomaterial marvel with unparalleled electronic, thermal, and mechanical properties. In energy storage, graphene has found extensive applications, particularly in batteries and supercapacitors. Its high conductivity, large surface area, and mechanical strength contribute to improved charge and discharge rates, enhanced capacity, and overall device efficiency (Suriyakumar et al., 2021).

Carbon nanotubes, cylindrical structures composed of rolled-up graphene sheets, exhibit remarkable electrical conductivity and mechanical strength. In energy storage, CNTs serve as effective components in electrodes, enhancing the electrical conductivity and structural integrity of batteries and supercapacitors. Their nanostructured form facilitates efficient electron transport, thereby contributing to faster charging and discharging processes. Metal oxide nanoparticles, such as titanium dioxide (TiO₂) and manganese oxide (MnO₂), are employed in energy storage devices for their electrochemical properties (Moharana et al., 2021). These materials serve as integral components in the electrodes of batteries, providing high capacity and stability. Nanosizing metal oxides increases their surface area, leading to improved ion diffusion and storage capacity, crucial for the performance of lithium-ion batteries. Silicon, when used in its nanoscale form, exhibits enhanced properties for energy storage applications. Nanostructured silicon can accommodate the expansion and contraction that occurs during charge and discharge cycles in batteries, addressing the limitations associated with silicon's volume changes. This contributes to prolonged battery life and increased energy storage capacity (Sehrawat et al., 2021).

The significance of nanomaterials in energy storage lies in their ability to address inherent limitations of traditional materials, unlocking unprecedented possibilities for device performance enhancement. Nanomaterials possess a high surface-to-volume ratio due to their diminutive size. This characteristic is particularly advantageous in energy storage devices, where a larger surface area facilitates more active sites for electrochemical reactions. Enhanced surface area

contributes to higher charge and discharge rates, ultimately leading to improved energy storage device performance (Li et al., 2021). Electrical conductivity is a critical factor in the efficiency of energy storage devices. Nanomaterials, such as graphene and carbon nanotubes, exhibit exceptional electrical conductivity. Incorporating these materials into electrodes facilitates efficient electron transport, reducing internal resistance and allowing for faster charge and discharge cycles.

Nanomaterials offer the ability to tailor their properties through size, shape, and composition modifications (Harish et al., 2023). This tunability allows researchers and engineers to customize nanomaterials for specific energy storage applications, optimizing performance parameters such as capacity, cycling stability, and overall efficiency. Nanostructured materials often possess superior mechanical strength and flexibility compared to their bulk counterparts. This is particularly beneficial in addressing challenges related to the expansion and contraction of materials during charging and discharging cycles, contributing to the longevity and durability of energy storage devices.

The global research and development landscape in nanomaterials for energy storage technologies is vibrant, with countries and institutions investing significantly in advancing these materials (Chakrabarty and Hakeem, 2024). The United States, with its robust scientific infrastructure, has been a frontrunner in pioneering research and pushing the boundaries of nanomaterial applications. Meanwhile, African nations, despite facing resource constraints, have demonstrated resilience and ingenuity in leveraging nanomaterials to address unique energy challenges. The commercial applications of nanomaterials in energy storage technologies are on the rise globally. Companies and industries are increasingly incorporating nanomaterials into the production of batteries, supercapacitors, and other energy storage devices to enhance performance and meet the growing demand for efficient and sustainable energy solutions (Muhammad et al., 2021).

Nanomaterial research is characterized by international collaborations, fostering knowledge exchange and collaboration between researchers, institutions, and industries worldwide. Collaborative efforts aim to accelerate the translation of research findings into practical applications, ensuring that advancements benefit diverse populations and contribute to a more inclusive and sustainable energy future. The utilization of nanomaterials in energy storage technologies has prompted discussions on regulatory and policy considerations globally. Countries and international organizations are working to establish guidelines for the safe and ethical use of nanomaterials, addressing concerns related to environmental impact, toxicity, and ethical implications (Shajar et al., 2023). In conclusion, the global perspectives on nanomaterials in energy storage underscore their transformative potential in revolutionizing the efficiency and sustainability of energy storage technologies. The comparative review between the USA and African developments highlights the diverse approaches and contributions each region brings to the utilization of nanomaterials. As the world navigates the challenges of a rapidly evolving energy landscape, nanomaterials stand at the forefront of innovation, offering solutions that have the potential to reshape the future of energy storage on a global scale (Kim, 2023).

1.2. Nanomaterial Developments in the USA

The United States (USA) stands as a powerhouse in nanomaterial research and development, particularly in the domain of energy storage. This review delves into the intricate landscape of nanomaterial advancements in the USA, unveiling the comprehensive overview of research, key nanomaterials driving progress, noteworthy innovations, and a nuanced consideration of economic, social, and environmental implications. The USA has been at the forefront of nanomaterial research and development, leveraging its extensive scientific infrastructure and collaborative networks. Nanomaterials have become a focal point, especially in the realm of energy storage, where their unique properties are harnessed to enhance the performance of batteries and supercapacitors. Research institutions, universities, and industry players across the nation contribute to a vibrant landscape of exploration and innovation in the field of nanomaterials for energy storage (Tula et al., 2023).

Graphene, a single layer of carbon atoms arranged in a hexagonal lattice, is a cornerstone of nanomaterial advancements in energy storage in the USA. Its exceptional electrical conductivity, high surface area, and mechanical strength make it a key player in enhancing the performance of batteries and supercapacitors. Researchers explore graphene-based electrodes and composites to optimize energy storage capacity and charge-discharge rates. Carbon nanotubes, cylindrical structures composed of rolled-up graphene sheets, are another nanomaterial driving progress in energy storage technologies (Zhu et al., 2021). In the USA, researchers harness the outstanding electrical conductivity and mechanical properties of CNTs to enhance the structural integrity of electrodes in batteries and supercapacitors. The incorporation of CNTs improves electron transport efficiency, contributing to faster charging and discharging.

Nanostructured silicon has garnered attention for addressing the limitations associated with silicon in traditional energy storage materials. In the USA, researchers focus on designing nanostructured forms of silicon to accommodate the volume changes that occur during charge and discharge cycles. This innovation contributes to prolonged battery life and increased energy storage capacity. Metal oxide nanoparticles, such as titanium dioxide (TiO₂) and manganese oxide (MnO₂), are explored extensively in the USA for their electrochemical properties (Sergienko et al., 2023). These nanoparticles are integrated into the electrodes of batteries to enhance stability and storage capacity. The nanosizing of metal oxides increases surface area, facilitating improved ion diffusion and overall efficiency in lithium-ion batteries.

Researchers in the USA have pioneered the development of advanced battery architectures, integrating nanomaterials for superior performance. Innovations include three-dimensional (3D) nanostructured electrodes that maximize surface area, enabling higher energy density and faster charging rates (Sun et al., 2023). These architectures pave the way for the next generation of energy storage devices. The USA has been at the forefront of research into flexible and wearable energy storage solutions. Nanomaterials, particularly graphene and carbon nanotubes, contribute to the development of lightweight, flexible batteries that can be integrated into clothing and wearable devices. These innovations hold immense potential for applications in the Internet of Things (IoT) and healthcare. Nanomaterials play a crucial role in the integration of energy storage into smart grids. Researchers focus on developing nanocomposite materials for electrodes, improving the overall efficiency and responsiveness of energy storage systems in smart grid applications. This contributes to grid stability, energy reliability, and the seamless integration of renewable energy sources (Khalid, 2024).

The economic implications of nanomaterial developments in the USA are multifaceted. The advancement of nanomaterial-enhanced energy storage technologies contributes to the growth of a burgeoning industry. Companies investing in research and development, manufacturing, and commercialization of these technologies stimulate economic activity, creating jobs and fostering innovation in the energy sector (Muscio, 2023). Additionally, the potential scalability and widespread adoption of nanomaterial-based energy storage solutions contribute to the establishment of new markets, further strengthening the economic landscape. As the industry matures, the cost-effectiveness of production processes and the affordability of nanomaterial technologies become critical factors influencing their economic viability.

The social implications of nanomaterial developments in the energy storage sector extend to various facets of society. The integration of advanced energy storage solutions enhances energy accessibility, particularly in remote or off-grid areas. This has profound implications for communities that may benefit from reliable and sustainable power sources, improving their quality of life and socio-economic conditions. Additionally, innovations such as flexible and wearable energy storage devices cater to the evolving needs of consumers, introducing novel applications in consumer electronics, healthcare, and lifestyle. The democratization of energy storage, facilitated by nanomaterial advancements, contributes to a more inclusive energy landscape (Aithal, 2023).

The environmental implications of nanomaterial developments in the USA are paramount in the context of sustainable energy solutions. Nanomaterial-enhanced energy storage devices contribute to the overall reduction of greenhouse gas emissions by enabling the integration of renewable energy sources. The increased efficiency of energy storage systems helps balance supply and demand, reducing the reliance on fossil fuels and mitigating environmental impact. However, it is crucial to consider the environmental footprint of nanomaterial production, including the extraction and processing of raw materials. Sustainable practices, recycling initiatives, and responsible manufacturing processes become integral components in minimizing the environmental impact of nanomaterial technologies (Mullen and Morris 2021).

In conclusion, nanomaterial developments in the USA represent a dynamic and pioneering force in advancing energy storage technologies. From graphene and carbon nanotubes to innovative battery architectures, the USA has been instrumental in pushing the boundaries of what is achievable in the realm of nanomaterial applications. The economic, social, and environmental implications underscore the transformative potential of these developments, shaping a future where nanomaterials contribute significantly to a sustainable and efficient energy landscape.

1.3. Nanomaterial Developments in Africa

The energy landscape in Africa is characterized by a complex interplay of challenges, opportunities, and the pursuit of sustainable solutions. In the context of nanomaterial developments for energy storage, African researchers and innovators have displayed resilience and ingenuity in leveraging locally sourced materials and indigenous knowledge. This review delves into the nuanced dynamics of nanomaterial applications in Africa, offering insights into the energy landscape, indigenous innovations, and considerations related to economic, social, and environmental aspects (Neethirajan, 2023).

Africa grapples with significant energy disparities, where large segments of the population lack access to reliable and modern energy sources. Many communities rely on traditional biomass for cooking and heating, contributing to deforestation and health issues. The lack of access to electricity hinders economic development, education, and healthcare, highlighting the urgency for innovative energy solutions. Resource constraints pose challenges to implementing large-scale energy projects in Africa. Limited financial resources, infrastructure, and access to state-of-the-art research facilities contribute to the difficulty of adopting and developing advanced technologies. Despite these challenges, Africa's energy landscape presents a canvas for unique, context-specific solutions. Africa boasts abundant renewable energy resources, including solar, wind, and hydropower. Harnessing these resources effectively is crucial for providing sustainable and accessible energy solutions to diverse populations (Amir and Khan, 2022). Nanomaterial developments hold the potential to amplify the efficiency and applicability of renewable energy technologies, contributing to the decentralization of power sources (Raina et al., 2020).

African researchers, cognizant of the local challenges, have been exploring nanomaterial applications tailored to the specific needs of the continent. Nanomaterials offer opportunities to enhance energy storage devices that can operate efficiently in diverse climates and address the intermittent nature of some renewable energy sources. In remote and off-grid areas, where traditional grid infrastructure is absent, nanomaterial-enhanced batteries emerge as critical components for energy storage. Researchers in Africa are investigating the use of nanomaterials, including locally sourced materials, to improve the performance of batteries used in off-grid solar power systems. These innovations aim to provide reliable electricity to rural communities, supporting economic activities and improving quality of life. African nanomaterial research often incorporates indigenous knowledge, recognizing the value of traditional practices and materials. Collaborations between researchers and local communities leverage this indigenous knowledge to develop nanomaterial solutions that resonate with the cultural and social contexts of the communities. This approach not only fosters acceptance but also ensures the sustainability and appropriateness of the technology (Servaes, 2022).

In the quest for sustainable and locally sourced nanomaterials, researchers in Africa explore nanocellulose derived from abundant biomass sources such as agricultural residues and plant fibers. Nanocellulose exhibits remarkable mechanical strength and can be used to enhance the structural integrity of electrodes in energy storage devices. This approach aligns with the principles of sustainability, utilizing materials readily available in the local environment. Clay minerals abundant in certain regions of Africa serve as promising candidates for nanocomposite materials (Belghazdis and Hachem, 2022). Researchers investigate clay-based nanocomposites for energy storage applications, exploring their potential as electrode materials in batteries. The utilization of locally available clay minerals not only addresses resource constraints but also minimizes the environmental impact associated with material extraction. While not directly related to energy storage, nanotechnology applications in water purification are noteworthy for their impact on overall sustainability. Researchers in Africa explore nanomaterials for developing efficient and cost-effective water purification technologies. This interdisciplinary approach aligns with the broader goal of addressing multiple sustainability challenges simultaneously (Klein, 2020).

Nanomaterial developments in Africa have the potential to contribute to economic development by fostering innovation, creating job opportunities, and supporting local industries. As research progresses, the establishment of partnerships with governmental and non-governmental entities can facilitate the translation of innovations into practical applications. This collaborative approach can catalyze economic growth while addressing energy disparities. The social impact of nanomaterial developments in Africa extends beyond providing energy solutions (Babatunde et al., 2019). Access to reliable and clean energy contributes to improved healthcare, education, and economic empowerment. Local communities benefit from the deployment of nanomaterial-enhanced energy storage technologies, leading to enhanced quality of life and increased opportunities for social development.

In aligning with principles of sustainability, African nanomaterial researchers emphasize environmental considerations in their work. The use of locally sourced materials, eco-friendly synthesis methods, and a focus on minimizing environmental impact underscore the commitment to responsible nanomaterial development. These considerations ensure that innovations contribute positively to the environmental landscape, mitigating potential risks associated with emerging technologies. In conclusion, nanomaterial developments in Africa reflect a dynamic and context-specific approach to addressing energy challenges. The fusion of indigenous knowledge, locally sourced materials, and a commitment to sustainability positions African researchers as innovators in the quest for energy solutions (Genovese and Zoure, 2023). As the continent navigates its unique energy landscape, nanomaterial developments serve as beacons of hope, offering pathways to sustainable, inclusive, and locally relevant solutions. The collaborative efforts between global and African stakeholders can further amplify the impact of these innovations, fostering a future where nanomaterials contribute significantly to Africa's energy resilience and prosperity.

1.4. Comparative Analysis

The study of nanomaterial developments in the United States (USA) and Africa unveils a dynamic interplay of innovation, challenges, and the pursuit of sustainable energy solutions. This comparative analysis delves into the similarities and differences between nanomaterial developments in these regions, evaluates the accessibility and affordability of nanomaterial-based energy storage technologies, and considers the implications for bridging energy disparities and fostering economic development. Both the USA and Africa share commonalities in leveraging nanomaterials to enhance energy storage technologies. Graphene and carbon nanotubes emerge as key players in both regions, contributing to improved electrical conductivity, charge-discharge rates, and overall efficiency in batteries and supercapacitors (Panda et al., 2023). The use of nanostructured materials, such as silicon and metal oxides, is a shared focus to address the limitations of traditional energy storage materials.

While commonalities exist, the nanomaterial developments in the USA and Africa also reflect context-specific challenges. In the USA, the emphasis is often on pushing the boundaries of scientific exploration and commercial applications, leveraging advanced research facilities and financial resources. In Africa, researchers navigate resource constraints, drawing on indigenous knowledge and locally sourced materials to develop nanomaterial solutions tailored to the continent's unique energy landscape. Both regions showcase innovation pathways that align with their respective contexts. In the USA, advanced battery architectures, flexible and wearable energy storage solutions, and smart grid integration are prominent areas of focus (Ma et al., 2021). In contrast, African developments emphasize addressing off-grid energy needs, harnessing indigenous knowledge, and exploring locally sourced nanomaterials for sustainable energy solutions.

The USA, with its robust scientific infrastructure and well-established research institutions, has a high level of accessibility to cutting-edge nanomaterial research. However, the translation of research findings into accessible technologies for the broader population may face challenges related to commercialization, regulatory processes, and market dynamics. The cost of adopting nanomaterial-based energy storage technologies can be a determining factor for widespread accessibility (Waris et al., 2023). Affordability in the USA is influenced by factors such as research and development costs, production scalability, and market competition. As nanomaterial-based energy storage technologies mature and economies of scale come into play, there is potential for cost reduction. Government incentives, research funding, and industry collaborations can further contribute to making these technologies more affordable for consumers and industries (Hassan et al., 2023).

Accessibility to nanomaterial-based energy storage technologies in Africa is influenced by factors such as research infrastructure, funding, and collaboration opportunities. While challenges such as resource constraints and limited access to advanced facilities exist, African researchers demonstrate resourcefulness in leveraging local expertise and materials. Initiatives promoting knowledge exchange and international collaborations can enhance accessibility to global advancements in nanomaterials. Affordability is a critical consideration in the African context, where cost-effective solutions are paramount for widespread adoption (Yadav, 2019). The use of locally sourced materials and indigenous innovations contributes to cost reduction. Additionally, collaborative efforts between researchers, governmental organizations, and international partners play a crucial role in securing funding and resources for affordable nanomaterial-based energy storage technologies.

In the USA, nanomaterial developments have the potential to contribute to bridging energy disparities by improving the efficiency and reliability of energy storage systems. Advancements in smart grid integration, flexible energy solutions, and the deployment of nanomaterial-enhanced batteries in off-grid areas can contribute to a more inclusive and resilient energy landscape. Nanomaterial advancements in the USA foster economic development by stimulating innovation, creating high-tech job opportunities, and supporting the growth of industries related to energy storage technologies (Ogunjobi et al., 2023). The commercialization of nanomaterial-based solutions contributes to the growth of a competitive industry, driving economic activity and attracting investments.

Nanomaterial developments in Africa have the potential to bridge energy disparities by addressing off-grid energy needs and providing reliable power solutions to underserved communities. Accessible and affordable nanomaterial-based energy storage technologies can contribute to improving healthcare, education, and economic opportunities, especially in remote areas. Economic development in Africa is closely linked to the affordability and scalability of nanomaterial-based energy storage technologies (Naziret et al., 2023). As these technologies become more accessible, they can stimulate local industries, create job opportunities, and contribute to economic growth. Moreover, fostering collaborations with international partners can facilitate technology transfer and knowledge exchange, supporting sustainable economic development.

In conclusion, the comparative analysis of nanomaterial developments in the USA and Africa reveals a rich tapestry of innovation, challenges, and potential solutions. While both regions share common goals of advancing energy storage technologies, the pathways taken reflect the unique contexts and priorities of each. Accessibility, affordability, and considerations for bridging energy disparities and fostering economic development are critical elements that warrant ongoing attention and collaboration on a global scale. As nanomaterial research continues to unfold, the collective efforts of researchers, policymakers, and industry stakeholders can contribute to a more sustainable, inclusive, and equitable energy future for both the USA and Africa.

1.5. Challenges and Opportunities

The utilization of nanomaterials in energy storage represents a frontier of innovation with the potential to transform the global energy landscape. As we delve into a comparative review of nanomaterial developments in the United States (USA) and Africa, it becomes evident that both regions encounter unique challenges and opportunities in harnessing nanomaterials for energy storage applications. This study unfolds a narrative of resilience, ingenuity, and the pursuit of sustainable solutions. In the USA, challenges are often rooted in the resource-intensive nature of nanomaterial research and development. Despite having advanced research facilities, financial resources, and a robust scientific ecosystem, the competitive landscape can lead to resource disparities, where smaller research entities may face challenges in accessing cutting-edge technologies and expertise (Allioui and Mourdi, 2023).

Resource constraints pose a significant challenge for nanomaterial developments in Africa. Limited funding, access to state-of-the-art research facilities, and a shortage of skilled personnel can impede the progress of research initiatives. However, this challenge also fosters resourcefulness and encourages researchers to explore context-specific solutions. The USA faces challenges related to navigating complex regulatory frameworks governing the use of nanomaterials. As the field evolves, ensuring the safety and ethical use of nanomaterials becomes paramount. Striking a balance between encouraging innovation and addressing potential environmental and health concerns poses an ongoing challenge (Jamal, 2023).

In Africa, the absence of well-defined regulatory frameworks for nanomaterials can hinder the translation of research into practical applications. Establishing robust regulatory structures is essential to ensure the ethical and responsible use of nanomaterials in energy storage technologies. Commercializing nanomaterial-based energy storage technologies in the USA faces challenges related to scalability, production costs, and market penetration (AbdelHamid, 2022). The transition from laboratory-scale research to large-scale production requires substantial investments and poses risks associated with market dynamics and competition. Commercialization barriers in Africa are influenced by factors such as limited access to capital, infrastructure, and a nascent market for advanced energy storage technologies (Few, 2019). Bridging the gap between research and commercialization is a complex process that requires strategic partnerships and supportive ecosystems.

Opportunities in the USA: Collaborative research initiatives present an opportunity to pool resources, share expertise, and address challenges collectively. Partnerships between academia, government agencies, and private industries can foster interdisciplinary research and accelerate the development of nanomaterial-based energy storage solutions. Collaborations between African countries and international partners open avenues for knowledge exchange, access to advanced research facilities, and joint initiatives. Engaging in collaborative research can enhance the capabilities of African researchers and contribute to the development of locally relevant solutions (Kasprowicz et al., 2020). Investing in education and capacity building programs can address challenges related to resource disparities. Supporting smaller research entities, providing training programs, and fostering a culture of knowledge exchange can contribute to a more inclusive and diverse nanomaterial research landscape.

Capacity building initiatives in Africa can focus on developing skilled researchers, establishing specialized training programs, and fostering mentorship opportunities. Empowering local talent is essential for building a sustainable nanomaterial research ecosystem in the continent. Developing inclusive regulatory frameworks that balance innovation with safety is an opportunity for the USA. Collaborative efforts between regulatory bodies, researchers, and industry stakeholders can streamline approval processes, ensuring ethical and responsible nanomaterial use in energy storage technologies (Babatunde et al., 2019). Establishing clear and inclusive regulatory frameworks in Africa is an opportunity to create an environment conducive to responsible nanomaterial research and development. Engaging with international regulatory bodies and leveraging best practices can contribute to the development of robust frameworks.

Facilitating technology transfer and knowledge exchange between established research entities and smaller organizations can promote inclusivity and innovation (Spraggon and Bodolica, 2021). Encouraging collaboration through mentorship programs and industry partnerships can accelerate the translation of research into practical

applications. Accessing technology transfer programs and knowledge exchange platforms with international partners provides African researchers with exposure to advanced techniques and methodologies. Building networks with global research entities fosters collaboration and enhances the capabilities of African researchers. Strengthening public-private partnerships can address commercialization barriers (Fernando and Nanayakkara, 2020). Collaborations between research institutions, industry players, and governmental agencies can facilitate the transition from laboratory-scale research to commercial production, promoting the growth of the nanomaterial industry. Encouraging public-private partnerships in Africa can attract investments, support technology transfer, and create pathways for the commercialization of nanomaterial-based energy storage technologies. Leveraging local industries and international collaborations enhances the economic viability (Bao et al., 2023).

2. Conclusion

In the comparative review of nanomaterial developments in the United States (USA) and Africa, we have traversed a landscape marked by challenges, opportunities, and the shared pursuit of sustainable energy solutions. As we conclude this review, it is crucial to recap key findings, underscore the importance of collaborative efforts, knowledge exchange, and inclusivity, and issue a call to action for policymakers, researchers, and industry stakeholders to contribute to a more sustainable and inclusive energy future through nanomaterial innovations. The comparative review highlighted the diverse challenges faced by the USA and Africa in harnessing nanomaterials for energy storage. While the USA contends with resource disparities, regulatory complexities, and commercialization barriers, Africa navigates resource constraints, nascent regulatory frameworks, and the imperative for context-specific solutions. Despite these challenges, both regions share common goals of advancing energy storage technologies to address energy disparities and foster economic development.

The review unveiled innovative pathways in both regions, with the USA focusing on advanced battery architectures, smart grid integration, and commercial applications, while Africa emphasizes off-grid solutions, harnessing indigenous knowledge, and exploring locally sourced materials. Indigenous solutions, such as nanocellulose from biomass in Africa and graphene applications in the USA, underscore the importance of context-specific approaches in nanomaterial research. Both the USA and Africa demonstrated resourcefulness and resilience in the face of challenges. The USA leverages its advanced research infrastructure, collaborative networks, and financial resources, while Africa embraces indigenous knowledge, local materials, and collaborative partnerships to overcome resource constraints. The resourcefulness exhibited by researchers in both regions highlights the adaptability and ingenuity inherent in nanomaterial research.

The comparative review underscores the pivotal role of collaborative efforts and knowledge exchange in propelling nanomaterial applications for energy storage globally. By fostering partnerships between nations, institutions, and industries, a collective approach can accelerate the pace of research, address resource disparities, and facilitate the sharing of expertise. Global collaboration serves as a catalyst for advancing nanomaterial technologies beyond geographical boundaries. Inclusivity and diversity are essential pillars in advancing nanomaterial applications for energy storage. Embracing diverse perspectives, experiences, and contributions from researchers worldwide enriches the global nanomaterial research landscape. Inclusivity ensures that a spectrum of challenges and opportunities is considered, leading to more comprehensive and innovative solutions that resonate with the diverse energy needs of different regions.

Knowledge exchange platforms play a vital role in bridging the gap between developed and emerging economies. Facilitating technology transfer, mentorship programs, and collaborative research initiatives enhance the capabilities of researchers in resource-constrained regions. These platforms create a dynamic ecosystem where researchers can learn from each other, share best practices, and collectively contribute to the advancement of nanomaterial applications in energy storage. Policymakers play a central role in shaping the trajectory of nanomaterial research and development. There is a need for the establishment of clear and inclusive regulatory frameworks that balance innovation with ethical considerations. Policymakers should prioritize supporting collaborative research initiatives, fostering international partnerships, and incentivizing the development of sustainable and inclusive nanomaterial technologies.

Researchers are the driving force behind nanomaterial innovations. The call to action for researchers is to embrace inclusivity, collaborate across borders, and leverage diverse perspectives. Engaging in knowledge exchange platforms, sharing findings transparently, and considering context-specific challenges will contribute to the development of nanomaterial applications that address the unique energy landscapes of different regions. Industry stakeholders hold the key to translating nanomaterial research into practical applications. Investments in scalable production methods, commercialization strategies, and partnerships with research institutions can bridge the gap between laboratory-scale

innovations and market-ready technologies. Industry players should prioritize sustainability, affordability, and the ethical use of nanomaterials in energy storage solutions.

Global initiatives that promote collaboration, knowledge exchange, and inclusivity are essential for realizing the full potential of nanomaterials in energy storage. International organizations, governmental bodies, and non-governmental entities can facilitate funding programs, technology transfer initiatives, and collaborative projects that bring together researchers, policymakers, and industry stakeholders from diverse backgrounds. In conclusion, the comparative review of nanomaterial developments in the USA and Africa illuminates a path forward that transcends geographical boundaries. The challenges faced are met with resilience, and the opportunities uncovered underscore the transformative potential of nanomaterials in shaping a sustainable and inclusive energy future. A collective commitment to collaboration, knowledge exchange, and inclusivity will propel nanomaterial applications for energy storage to new heights, contributing to a world where innovative solutions address the energy needs of every community, irrespective of location or resources.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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