JETIR.ORG ISSN: 2349-5162 | ESTD Year : 2014 | Monthly Issue
JOURNAL OF EMERGING TECHNOLOGIES AND INNOVATIVE RESEARCH (JETIR)
An International Scholarly Open Access, Peer-reviewed, Refereed Journal

# NANOCOMPOSITE ELECTRODES: POWERING THE FUTURE OF SUPERCAPACITORS

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***ABSTRACT*:**
With the rising demand for effective and sustainable energy storage systems, supercapacitors have emerged as promising candidates due to their high power density, rapid charge-discharge capability, and long cycle life. However, their relatively low energy density compared to batteries limits their broader application. Recent advancements in nanocomposite electrode materials have shown great potential in overcoming this limitation, offering a strategic pathway to enhance the electrochemical performance of supercapacitors. Nanocomposites, composed of at least two distinct phases, typically a conductive matrix and a functional nanostructured material, exhibit synergistic properties that are unattainable by individual components alone. These materials combine the high surface area, conductivity, and mechanical stability necessary for efficient charge storage and transport. Carbon-based nanostructures (e.g., graphene, carbon nanotubes), metal oxides, conducting polymers, and transition metal dichalcogenides are among the most explored constituents in nanocomposite electrodes. Their hybridization leads to improved capacitance, energy density, and stability under varying operational conditions. Furthermore, advances in fabrication techniques, such as hydrothermal synthesis, sol-gel methods, and electrochemical deposition, have enabled the precise tuning of nanostructures and interfaces, further optimizing performance. This paper reviews recent developments in nanocomposite electrode materials for supercapacitors, highlighting the design principles, material combinations, and mechanisms behind their enhanced functionality. As research progresses, nanocomposite electrodes are poised to play a pivotal role in the next generation of high-performance, scalable, and environmentally friendly energy storage devices, potentially bridging the gap between conventional capacitors and batteries.

***Index Terms*: Batteries, Capacitors, Supercapacitors, Power density, Nanocomposites, Nanostructures.**

## 1. INTRODUCTION:

The growing global emphasis on clean energy and efficient power management has intensified research into advanced energy storage technologies. Among these, supercapacitors (also known as electrochemical capacitors or ultracapacitors) have emerged as key contenders due to their high power density, exceptional charge–discharge rates, and superior cycle life compared to conventional batteries [1]. Supercapacitors are especially valuable in applications that require rapid energy bursts, such as regenerative braking in electric vehicles, backup power systems, and portable electronics [2]. However, despite their excellent power characteristics, supercapacitors are fundamentally limited by low energy density, which restricts their ability to compete with batteries in high-energy applications [3].

To overcome this limitation, significant research efforts have been devoted to the development of high-performance electrode materials, as these play a pivotal role in determining the electrochemical characteristics of supercapacitors. Traditional carbon-based materials (such as activated carbon, carbon nanotubes, and graphene) offer large surface areas and high electrical conductivity, supporting the formation of an electric double layer at the electrode–electrolyte interface, which is the basis of electric double-layer capacitors (EDLCs) [4]. However, the energy density of EDLCs is typically limited to around 5–10 Wh/kg [5].

On the other hand, pseudocapacitive materials—including transition metal oxides (e.g., $MnO_2$, NiO, $Co_3O_4$) and conducting polymers (e.g., polyaniline, polypyrrole)—store charge through fast and reversible redox reactions, providing much higher specific capacitance and energy density [6]. Yet these materials often suffer from low conductivity, poor mechanical stability, and structural degradation over long-term cycling [7].

To address these trade-offs, the focus has shifted toward the design of nanocomposite electrodes, which strategically combine EDLC and pseudocapacitive materials to harness their complementary properties. These nanocomposites can be engineered to provide enhanced ion transport, improved electronic conductivity, and better structural integrity under repeated cycling conditions [8]. For instance, graphene-based composites with $MnO_2$ or polyaniline have demonstrated significant improvements in both specific capacitance and energy density, while retaining high cycling stability [9, 10].

Moreover, nanocomposites enable synergistic effects at the interface of different materials, leading to better electron/ion transfer kinetics and higher electrochemical utilization of active materials [11]. Additionally, the development of novel materials such as M-Xenes, metal–organic frameworks (MOFs), and layered double hydroxides (LDHs) has further diversified the design space for nanocomposite electrodes [12, 13].

Advanced synthesis techniques—such as hydrothermal methods, sol-gel processes, electrochemical deposition, and template-assisted assembly—have made it possible to tailor the morphology, porosity, and interface chemistry of these composites at the nanoscale, thereby optimizing their electrochemical performance [14].

In summary, the development of nanocomposite electrodes represents a transformative strategy for next-generation supercapacitors. By bridging the gap between high-energy and high-power devices, these materials pave the way for scalable, sustainable, and high-performance energy storage systems that can meet the rising demands of modern technologies.

## 2. KNOW THE SUPERCAPACITORS:

In an era marked by rapid technological advancement and an increasing dependence on renewable energy, the demand for efficient and reliable energy storage systems has never been higher. While traditional batteries dominate the market for portable power, they often fall short in terms of charging speed, power density, and cycle life. Supercapacitors—also known as ultracapacitors, have emerged as a promising alternative due to their unique ability to bridge the gap between conventional capacitors and batteries.

Supercapacitors are electrochemical energy storage devices that store energy either through electrostatic charge accumulation (electric double-layer capacitors, or EDLCs) or through fast surface redox reactions (pseudocapacitors) [1]. They are characterized by their high power density, rapid charge/discharge capability, and exceptional cycle life, often exceeding one million cycles, making them ideal for applications in electric vehicles (EVs), consumer electronics, renewable energy grids, and backup power systems [2].

However, the widespread adoption of supercapacitors is still limited by their relatively low energy density compared to batteries. This limitation has driven extensive research into electrode materials, which play a critical role in determining the energy storage capacity and overall performance of supercapacitors. In this context, nanocomposite electrodes, engineered by combining multiple materials at the Nanoscale- have shown tremendous potential in overcoming these barriers. By leveraging the high surface area, improved electrical conductivity, and synergistic properties of nanomaterials, these electrodes offer a path toward high-performance, scalable, and sustainable supercapacitor technologies [8].

The global transition toward electrification and renewable energy integration has intensified the need for energy storage systems that are both efficient and sustainable. Traditional electrochemical batteries, particularly lithium-ion batteries (LIBs), have played a dominant role due to their high energy density and reliable operation. However, their performance is constrained by slow charge, discharge kinetics, limited cycle life, thermal instability, and safety concerns under extreme operating conditions [15]. In this context, supercapacitors, also known as electrochemical capacitors or ultracapacitors, have emerged as a complementary energy storage solution due to their unique advantages.

As the energy storage landscape continues to evolve, nanocomposite electrodes present a promising pathway to bridge the performance gap between batteries and conventional supercapacitors. This article explores the science and technology behind nanocomposite electrode materials, their role in advancing supercapacitor performance, fabrication methods, recent innovations, and the challenges ahead in scaling them for commercial energy systems. This article delves into the role of nanocomposite electrodes in shaping the future of supercapacitors, exploring their material science, fabrication techniques, performance advantages, and the challenges that lie ahead.

## 3. LIMITATIONS OF TRADITIONAL ELECTRODE MATERIALS:

Electrode materials play a critical role in the performance, stability, and overall efficiency of energy storage and conversion systems, particularly in batteries, supercapacitors, and fuel cells. Traditional electrode materials, such as graphite in lithium-ion batteries and activated carbon in supercapacitors, have been widely used due to their availability, cost-effectiveness, and relatively good electrochemical performance [16, 1]. However, as the demand for high-capacity, high-power, and longer-lasting energy storage devices increases, several limitations associated with these conventional materials have become evident.

One of the primary drawbacks of traditional electrode materials is their limited specific capacity or energy density. For example, graphite anodes, while stable, offer a theoretical capacity of only 372 mAh/g, which restricts the overall energy storage potential of lithium-ion batteries [17]. Additionally, many conventional materials suffer from poor rate capability and slow ion diffusion kinetics, which can significantly affect performance at high charge/discharge rates [18]. Structural degradation over repeated cycles is another major issue, as volume expansion and contraction during charge-discharge cycles can lead to material pulverization and capacity fading [19].

Furthermore, some traditional materials require high-temperature processing or use environmentally harmful chemicals during synthesis, which raises sustainability and safety concerns. Their limited electrochemical window, low conductivity, and poor compatibility with next-generation electrolytes also hinder their application in emerging battery chemistries, such as sodium-ion or solid-state batteries [20].

These limitations have spurred extensive research into alternative materials, including nanostructured compounds, transition metal oxides, conductive polymers, and hybrid composites, which offer enhanced capacity, rate performance, and structural stability. Understanding the shortages of traditional materials is essential to guide the development of next-generation electrodes accomplished of convention the evolving demands of modern energy storage technologies.

## 4. ENTER NANOCOMPOSITES: A GAME CHANGER

As the limitations of traditional electrode materials become increasingly apparent, ranging from low energy densities to poor structural stability, research has turned toward innovative alternatives capable of delivering superior electrochemical performance. Among these, nanocomposites have emerged as a transformative class of materials, offering unique synergies by combining multiple constituents at the nanoscale. These materials, which integrate nanostructured active phases with conductive matrices or structural supports, have shown remarkable promise in overcoming the intrinsic deficiencies of conventional electrodes [21, 22].

Nanocomposites leverage the high surface area, enhanced electrical conductivity, and tunable interfaces of their nanoscale components to significantly improve capacity, rate capability, and cycling stability. For instance, combining transition metal oxides with carbon-based materials such as graphene or carbon nanotubes can enhance charge transport pathways while buffering volume changes during cycling [23]. Moreover, the interfacial interactions within nanocomposites can facilitate faster ion diffusion and reduce the formation of inactive phases, ultimately boosting both performance and lifespan [24].

Beyond electrochemical advantages, nanocomposites offer flexibility in design, allowing for the customization of composition, morphology, and architecture to target specific applications, be it in lithium-ion batteries, supercapacitors, sodium-ion systems, or hybrid energy storage technologies. Their versatility positions them as a critical enabler in the development of next-generation energy storage devices, where demands for higher power, safety, and sustainability are rapidly accelerating.

Thus, the integration of nanocomposites into electrode design marks a paradigm shift, not only improving existing technologies but also unlocking new possibilities in energy conversion and storage systems.

## 5. BENEFITS OF NANOCOMPOSITE ELECTRODES IN SUPERCAPACITORS:

Supercapacitors have garnered significant attention in recent years due to their high power density, long cycle life, and rapid charge–discharge capabilities. However, conventional electrode materials such as activated carbon, though widely used, often suffer from limited energy density and relatively low capacitance due to their purely electrostatic charge storage mechanism [1]. In response, nanocomposite electrodes have emerged as a transformative solution, offering a unique combination of electrochemical and mechanical advantages that significantly enhance the overall performance of supercapacitors.

One of the primary benefits of nanocomposite electrodes is their synergistic effect, which arises from the combination of different functional materials, typically a pseudocapacitive metal oxide or conducting polymer with a conductive carbon-based matrix [2]. This hybrid approach enables the integration of electric double-layer capacitance (EDLC) and faradaic (pseudocapacitive) processes, resulting in higher specific capacitance and improved energy density without sacrificing power performance [23].

Moreover, nanocomposite electrodes often exhibit enhanced ion and electron transport due to the increased interfacial contact and reduced diffusion distances provided by their nanoscale architecture. For instance, incorporating metal oxides such as $MnO_2$ or $NiCo_2O_4$ into carbon nanotubes or graphene matrices can provide faster charge transport pathways, reduce internal resistance, and improve cycling stability [4]. The carbonaceous components act as buffers that mitigate volume expansion and maintain structural integrity during repeated charge–discharge cycles, thereby extending device lifespan [25].

Another notable benefit is the tailorability of nanocomposite electrodes. Researchers can fine-tune material morphology, pore structure, and composition to optimize ion accessibility, surface area, and conductivity. This level of control enables the design of electrodes with specific performance targets, such as high-rate capability for fast-charging applications or high energy density for grid storage systems [26].

In summary, nanocomposite electrodes offer a pathway to overcoming the inherent limitations of traditional materials in supercapacitors by delivering superior capacitance, energy density, rate performance, and mechanical stability. These multifaceted benefits make them ideal candidates for next-generation energy storage systems.

## 6. FABRICATION TECHNIQUES NANOCOMPOSITE ELECTRODES:

The performance of nanocomposite electrodes in supercapacitors is heavily influenced by the fabrication techniques used during their synthesis. These techniques not only determine the physical and chemical characteristics of the nanocomposite, such as particle size, morphology, porosity, and surface area, but also directly affect ion/electron transport, structural stability, and electrochemical behavior. A variety of fabrication methods have been developed to engineer nanocomposites with optimal properties, often by integrating pseudocapacitive and conductive materials at the nanoscale.

### 6.1. Hydrothermal and Solvothermal Methods

Hydrothermal synthesis is widely used for fabricating metal oxide–carbon nanocomposites due to its simplicity, scalability, and ability to produce highly crystalline nanostructures with controlled morphology. In this method, precursors are reacted in a sealed autoclave under elevated temperature and pressure, facilitating the formation of uniform nanostructures such as nanorods, nanosheets, or nanospheres [27]. This technique is especially useful for incorporating materials like $MnO_2$, $NiCo_2O_4$, or $Fe_3O_4$ into conductive carbon substrates.

### 6.2. Chemical Vapor Deposition (CVD)

CVD is a gas-phase technique commonly employed for growing thin films or coatings of carbon nanomaterials such as carbon nanotubes (CNTs) or graphene on substrates. In supercapacitor applications, CVD is used to deposit carbon layers onto metal oxides or other active materials to enhance electrical conductivity and surface area [28]. The advantage of CVD lies in the precise control of layer thickness and uniformity, which is critical for achieving high-performance electrodes.

### 6.3. Electrochemical Deposition

Electrochemical deposition is a facile and controllable technique used to deposit active materials onto conductive substrates through the application of an electric current. It allows for uniform coating of pseudocapacitive materials like conducting polymers or transition metal oxides onto carbon backbones, enabling strong adhesion and improved charge transfer [29]. The deposition parameters can be tuned to control the thickness, morphology, and porosity of the electrode layer.

### 6.4. Sol-Gel Process

The sol-gel method is another popular technique for fabricating oxide-based nanocomposites. It involves the transition of a solution (sol) into a solid gel phase, followed by drying and calcination. This process is known for producing homogeneous and fine nanostructures at relatively low temperatures. It is particularly suited for synthesizing nanocomposites with high surface area and uniform dispersion of active materials [30].

### 6.5. Mechanical Mixing and Ball Milling

Mechanical methods like ball milling and ultrasonication are commonly used for preparing nanocomposites by physically mixing different components, such as carbon materials and metal oxides. While these techniques are less precise in controlling morphology, they offer advantages in terms of simplicity, scalability, and cost-effectiveness, making them suitable for industrial-scale fabrication [31].

## 7. CHALLENGES AND FUTURE DIRECTIONS:

Despite the considerable promise of nanocomposite electrodes in advancing supercapacitor technologies, several critical challenges remain that hinder their widespread commercialization and long-term performance. These limitations span across materials design, fabrication scalability, cost-efficiency, and long-term operational stability, prompting ongoing research and innovation in the field.

### 7.1. Complex and Costly Synthesis Processes:

One of the primary challenges lies in the complexity and cost of fabrication techniques. Many high-performance nanocomposites require multistep processes such as hydrothermal synthesis, chemical vapor deposition (CVD), or sol-gel techniques, which may involve expensive precursors, long processing times, and high energy inputs [23]. These constraints present a barrier to scaling up production for industrial applications, especially when cost-effectiveness and simplicity are essential.

### 7.2. Poor Long-Term Stability:

While nanocomposites often demonstrate excellent initial performance, long-term electrochemical stability can be problematic. Repeated charge–discharge cycles can lead to structural degradation, active material detachment, or electrolyte decomposition, especially when using transition metal oxides or conducting polymers that undergo significant volume changes during cycling [32]. This results in capacity fading, reducing the device's operational lifespan.

### 7.3. Interface Compatibility and Contact Resistance:

Achieving strong interfacial interactions between different components within the nanocomposite is essential for optimal electron and ion transport. However, poor interface compatibility and high contact resistance are common issues, particularly when combining dissimilar materials (e.g., metal oxides and carbon matrices). These issues can limit the synergistic effects expected from hybrid structures [2].

### 7.4. Environmental and Safety Concerns:

The use of toxic solvents, heavy metals, or non-renewable raw materials in some nanocomposite formulations raises environmental and health concerns. Furthermore, the chemical stability and flammability of certain materials under extreme conditions (high voltage, temperature) must be addressed to ensure safety in real-world applications [33].

### Future Directions:

To address the challenges outlined above, future research in nanocomposite electrode development is expected to follow several key directions:

Green and Scalable Synthesis Methods: Developing eco-friendly, low-cost, and scalable fabrication techniques—such as aqueous-phase synthesis, microwave-assisted methods, or bio-inspired processes—will be critical for transitioning from lab-scale to commercial production [34].
Advanced Structural Engineering: The design of hierarchical and 3D architectures can enhance electron pathways, improve mechanical integrity, and increase accessible surface area. 3D printing and templating methods are being explored for this purpose [35].
Multifunctional and Smart Materials: The integration of self-healing, thermally stable, or sensor-integrated nanocomposites may open up new applications in wearable electronics, smart grids, and hybrid energy systems.
Machine Learning and AI for Materials Discovery: The use of artificial intelligence (AI) and machine learning to predict optimal material combinations and performance metrics is gaining momentum and could accelerate innovation in this field [36].

## 8. CONCLUSION:

Nanocomposite electrodes represent a significant advancement in the field of energy storage, offering superior electrochemical performance, enhanced conductivity, and improved stability compared to traditional materials. Their unique structure and tunable properties make them ideal for addressing the increasing demands of modern energy systems.

As we look toward the future, nanocomposite electrodes are poised to play a critical role in shaping next-generation energy storage technologies. From enabling faster charging and longer-lasting batteries to supporting higher energy densities, these materials are key to unlocking more efficient and sustainable energy solutions.

The outlook is promising, with their potential to power green technologies, support the growth of smart devices, and accelerate the adoption of electric vehicles, nanocomposite electrodes stand at the forefront of the transition to a cleaner, smarter, and more energy-resilient world.

## 9. REFERENCES:

[1] Conway, B. E. **(2013)**. Electrochemical supercapacitors: scientific fundamentals and technological applications. Springer Science & Business Media.

[2] Simon, P., & Gogotsi, Y. **(2008**). Materials for electrochemical capacitors. Nature Materials, 7(11), 845-854.

[3] Miller, J. R., & Simon, P. **(2008)**. Electrochemical capacitors for energy management. Science, 321(5889), 651-652.

[4] Zhai, Y., Dou, Y., Zhao, D., Fulvio, P. F., Mayes, R. T., & Dai, S. **(2011)**. Carbon materials for chemical capacitive energy storage. Advanced materials, 23(42), 4828-4850.

[5] Frackowiak, E., & Beguin, F. **(2001)**. Carbon materials for the electrochemical storage of energy in capacitors. Carbon, 39(6), 937-950.

[6] Wang, H., Casalongue, H. S., Liang, Y., & Dai, H. **(2010)**. Ni (OH) 2 nanoplates grown on graphene as advanced electrochemical pseudocapacitor materials. Journal of the American Chemical Society, 132(21), 7472-7477.

[7] Dubal, D. P., Ayyad, O., Ruiz, V., & Gomez-Romero, P. **(2015)**. Hybrid energy storage: the merging of battery and supercapacitor chemistries. Chemical Society Reviews, 44(7), 1777-1790.

[8] Zhang, L. L., & Zhao, X. S. **(2009).** Carbon-based materials as supercapacitor electrodes. Chemical society reviews, 38(9), 2520-2531.

[9] Yu, G., Xie, X., Pan, L., Bao, Z., & Cui, Y. **(2013)**. Hybrid nanostructured materials for high-performance electrochemical capacitors. Nano Energy, 2(2), 213-234.

[10] Liu, C., Yu, Z., Neff, D., Zhamu, A., & Jang, B. Z. **(2010)**. Graphene-based supercapacitor with an ultrahigh energy density. Nano letters, 10(12), 4863-4868.

[11] Wang, Y., Song, Y., & Xia, Y. **(2016)**. Electrochemical capacitors: mechanism, materials, systems, characterization and applications. Chemical Society Reviews, 45(21), 5925-5950.

[12] Lukatskaya, M. R., Mashtalir, O., Ren, C. E., Dall'Agnese, Y., Rozier, P., Taberna, P. L., ... & Gogotsi, Y. **(2013)**. Cation intercalation and high volumetric capacitance of two-dimensional titanium carbide. Science, 341(6153), 1502-1505.

[13] Salunkhe, R. R., Kaneti, Y. V., & Yamauchi, Y. **(2017)**. Metal–organic framework-derived nanoporous metal oxides toward supercapacitor applications: progress and prospects. ACS nano, 11(6), 5293-5308.

[14] Kötz, R., & Carlen, M. J. E. A. **(2000)**. Principles and applications of electrochemical capacitors. Electrochimica acta, 45(15-16), 2483-2498.

[15] Tarascon, J. M., & Armand, M. **(2001)**. Issues and challenges facing rechargeable lithium batteries. nature, 414(6861), 359-367.

[16] Goodenough, J. B., & Kim, Y. **(2010)**. Challenges for rechargeable Li batteries. Chemistry of materials, 22(3), 587-603.

[17] Tarascon, J. M., & Armand, M. **(2001)**. Issues and challenges facing rechargeable lithium batteries. nature, 414(6861), 359-367.

[18] Arico, A. S., Bruce, P., Scrosati, B., Tarascon, J. M., & Van Schalkwijk, W. **(2005)**. Nanostructured materials for advanced energy conversion and storage devices. Nature Materials, 4(5), 366-377.

[19] Zhang, W. J. **(2011)**. A review of the electrochemical performance of alloy anodes for lithium-ion batteries. Journal of Power Sources, 196(1), 13-24.

[20] Pan, H., Hu, Y. S., & Chen, L. **(2013)**. Room-temperature stationary sodium-ion batteries for large-scale electric energy storage. Energy & Environmental Science, 6(8), 2338-2360.

[21] Simon, P., & Gogotsi, Y. **(2008)**. Materials for electrochemical capacitors. Nature Materials, 7(11), 845-854.

[22] Lu, X., Yin, Y., Zhang, L., Xi, L., Oswald, S., Deng, J., & Schmidt, O. G. **(2016)**. Hierarchically porous Pd/NiO Nano membranes as cathode catalysts in Li-O2 batteries. Nano Energy, 30, 69-76.

[23] Wang, G., Zhang, L., & Zhang, J. **(2012)**. A review of electrode materials for electrochemical supercapacitors. Chemical Society Reviews, 41(2), 797-828.

[24] Xia, X., Tu, J., Zhang, Y., Wang, X., Gu, C., & Zhao, X. **(2015)**. A new type of multifunctional electrode materials: Design, preparation, and performance. Advanced Energy Materials, 5(7), 1401803. https://doi.org/10.1002/aenm.201401803

[25] El-Kady, M. F., & Kaner, R. B. **(2013)**. Scalable fabrication of high-power graphene micro-supercapacitors for flexible and on-chip energy storage. Nature communications, 4(1), 1475.

[26] Lu, X., Yin, Y., Zhang, L., Xi, L., Oswald, S., Deng, J., & Schmidt, O. G. **(2016)**. Hierarchically porous Pd/NiO nanomembranes as cathode catalysts in Li-O2 batteries. Nano Energy, 30, 69-76.

[27] Zhao, Y. Q., Fan, L. Z., Zhou, M., Guan, H. T., & Qiao, S. Z. **(2010)**. Hydrothermal synthesis and electrochemical capacitance of $MnO_2$ nanostructures with controlled morphologies. Journal of Materials Chemistry, 20(27), 5546–5553. https://doi.org/10.1039/c0jm00059g

[28] Zhou, Y., Ding, L., Shi, K., Dai, Y. Z., Ai, N., Wang, J., & Pei, J. **(2012)**. A Non-fullerene small molecule as efficient electron acceptor in organic bulk heterojunction solar cells. Advanced Materials, 24(7), 957-961.

[29] Ferrara, G., Damen, L., Arbizzani, C., Inguanta, R., Piazza, S., Sunseri, C., & Mastragostino, M. **(2011)**. SnCo nanowire array as negative electrode for lithium-ion batteries. Journal of Power Sources, 196(3), 1469-1473.

[30] Liu, J., Jiang, J., Cheng, C., Li, H., Zhang, J., Gong, H., & Fan, H. J. **(2011)**. $Co_3O_4$ nanowire@$MnO_2$ ultrathin nanosheet core/shell arrays: A new class of high-performance pseudocapacitive materials. Advanced Materials, 23(18), 2076–2081. https://doi.org/10.1002/adma.201004607

[31] Zhou, G., Wang, D. W., Li, F., & Cheng, H. M. **(2014)**. Carbon-based nanocomposites for electrochemical energy storage. Energy & Environmental Science, 7(2), 505–518. https://doi.org/10.1039/C3EE43024A

[32] Lu, X., Yin, Y., Zhang, L., Xi, L., Oswald, S., Deng, J., & Schmidt, O. G. **(2016)**. Hierarchically porous Pd/NiO nanomembranes as cathode catalysts in Li-O2 batteries. Nano Energy, 30, 69-76.

[33] Zhai, Y., Dou, Y., Zhao, D., Fulvio, P. F., Mayes, R. T., & Dai, S. **(2011)**. Carbon materials for chemical capacitive energy storage. Advanced materials, 23(42), 4828-4850.

[34] Dashliborun, A. M., & Larachi, F. **(2020)**. Tracer dispersion in trickle beds under tilts and roll motions–CFD study and experimental validation. Chemical Engineering Journal, 386, 122845.

[35] Zhao, W., Wang, Z., Zhang, J., Wang, X., Xu, Y., Ding, N., & Peng, Z. **(2021)**. Vat photopolymerization 3D printing of advanced soft sensors and actuators: from architecture to function. Advanced Materials Technologies, 6(8), 2001218.

[36] Butler, K. T., Davies, D. W., Cartwright, H., Isayev, O., & Walsh, A. **(2018)**. Machine learning for molecular and materials science. Nature, 559(7715), 547-555.