ISSN: 2692-5397
Modern Concepts in Material Science
DOI: 10.33552/MCMS.2025.07.000668
Iris Publishers

Mini Review

Nanostructured Supercapacitors for Healthcare Devices: Advances and Perspectives

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Received Date: October 09, 2025

Published Date: October 16, 2025

Abstract

The rapid advancement of the Internet of Things (IoT) in healthcare has created a growing demand for efficient, miniaturized, and sustainable energy storage solutions. Supercapacitors, particularly those based on nanostructured self-assembled films of graphene oxide and metal oxides, have emerged as promising candidates due to their high-power density, rapid charge/discharge capabilities, and long cycle life. These characteristics make them ideal for powering wearable and implantable health monitoring devices, ensuring continuous and reliable operation. This review explores the potential of nanostructured supercapacitors as energy storage units in IoT-enabled medical applications, emphasizing recent advancements in material science, fabrication techniques, and integration strategies. The discussion also highlights challenges and future perspectives in optimizing the electrochemical performance and biocompatibility of these devices, paving the way for the next generation of smart and self-powered healthcare technologies.

Keywords: Supercapacitors; Nanostructured Films; Internet of Things (IoT); Healthcare Devices

Introduction

The growing demand for portable and wearable electronic devices has driven the development of more efficient and sustainable energy solutions [1]. In the healthcare field, the Internet of Things (I oT) has played a fundamental role in advancing monitoring systems, enabling real-time collection, transmission, and analysis of biomedical data [1]. Devices such as wearable sensors for heart rate, glucose, and muscle activity monitoring, as well as implantable devices like pacemakers and neurostimulators, require reliable and long-lasting energy sources [1]. Although conventional batteries are widely used to power these devices, they have significant limitations, such as prolonged recharge time, degradation over charge and discharge cycles, and environmental impact due to improper disposal. In this context, supercapacitors emerge as a promising alternative due to their high power density, rapid recharge capability, and long lifespan [1-4]. Specifically, supercapacitors based on nanostructured films composed of graphene oxide (GO) and metal oxides have demonstrated excellent performance in improving the efficiency and stability of these devices [2-4]. This mini-review explores the potential use of self-assembled nanostructured films as electrocapacitive layers in the development of supercapacitors for IoT-based healthcare devices. It covers the fundamental principles of supercapacitors, their advantages over conventional batteries, and perspectives on integrating this technology into self-sustaining biomedical devices.

Principles and Advantages of Supercapacitors

Supercapacitors are energy storage devices that operate based on the electrostatic accumulation of charges at the electrode-electrolyte interface or through surface redox reactions. Unlike conventional batteries, which store energy through chemical reactions within the electrode volume, supercapacitors rely on electrostatic capacitance (electric double-layer capacitors) or pseudocapacitance (redox-active materials) to provide long cycle life and fast charging [1-4]. In particular, the key advantages of supercapacitors for medical IoT applications can include:

- High power density: Enables fast recharging and instant energy release, which is crucial for devices requiring immediate response.
- Long lifespan: Supercapacitors can endure millions of charge and discharge cycles without significant degradation, ensuring greater durability in biomedical applications.
- Low toxicity: Advanced materials, such as graphene-based and metal oxide films, enable the development of safer and biocompatible devices.
- Flexibility and miniaturization: Supercapacitors can be manufactured in flexible and ultrathin formats, allowing integration into wearable and implantable devices.
- Sustainability: The use of recyclable materials and eco-friendly manufacturing processes minimizes environmental impact.

Using Nanostructured Films in Supercapacitors

Nanostructured films possess nanoscale architectures, where the materials forming the electrodes are extremely small, significantly increasing the surface area available for energy storage [4]. This increased surface area fosters synergistic interactions among the film compounds, resulting in distinct advantages and playing a pivotal role in the development of advanced electrode materials for supercapacitors, particularly in enhancing performance and electrochemical properties [4]. For instance, the combination of nanomaterials structured through techniques such as Layer-by-Layer (LbL) and Langmuir-Blodgett (LB) allows for the fabrication of highly organized and efficient electrodes for supercapacitors [4,5]. These techniques enable precise control over the thickness and composition of the films, which is advantageous for optimization of electrochemical properties essential for biomedical applications [4-12].

Supercapacitors based on nanostructured films have exhibited outstanding electrochemical performance. The integration of a nanostructured electrocapacite layer with high surface area enhances supercapacitor capacitance and cyclic stability [4-12]. Moreover, nanostructures provide the necessary flexibility and mechanical resilience for applications in flexible supercapacitors without compromising electrical performance. A variety of nanostructured materials, including carbon-based nanostructures, metal oxides, and conductive polymers, can be incorporated into these films to further optimize their properties [4,6-11].

The use of GO and metal oxides hold immense potential for transforming energy storage in IoT-based healthcare devices [1-3]. Their unique properties enable the achievement of the desired performance, including high power density, mechanical flexibility, and biocompatibility. These characteristics establish them as key components in the development of sustainable and autonomous biomedical systems [1-3].

Application of Supercapacitors in Healthcare Devices

Nanostructured materials integrated into supercapacitors can enable the development of miniaturized, flexible, and lightweight energy storage devices, crucial for wearable and implantable medical sensors. These devices require efficient power sources capable of sustaining continuous operation while ensuring biocompatibility and mechanical stability [1,4]. For healthcare monitoring, supercapacitors play a vital role, enabling real-time data collection and transmission without frequent battery replacements. They can be integrated into biosensors for glucose monitoring, electrocardiogram patches for cardiac health assessment, and even neurostimulation devices. Additionally, the ability of supercapacitors to operate under dynamic conditions, such as mechanical deformations in wearable electronics, makes them ideal candidates for next-generation IoT health systems [1,4].

Recent studies have demonstrated the great potential of supercapacitors for applications in healthcare IoT devices for biomedical sensing and implantable devices. The incorporation of biosupercapacitors utilizing bioactive materials could open new possibilities for implantable energy storage systems, ensuring efficient and reliable operation within biological environments [8-11]. An example is an implantable biosupercapacitor that integrates PEDOT with ferritin nanoparticles within carbon nanotube structures, ensuring high conductivity and achieving an impressive capacitance of 32.9 mF cm^{-2} [12]. Another study developed an implantable biosupercapacitor utilizing a glucose oxidase-modified fiber, which demonstrated a high power density of 22.6 mW cm^{-2} [13]. Additionally, researchers proposed an energy storage device capable of harvesting energy from lactate present in human sweat by incorporating carbon nanotubes and electrodeposited polypyrrole, a conducting polymer, with excellent stability and high power output [14]. Another emerging research direction explores how the integration of piezoelectric materials with supercapacitors could enable self-powered medical devices, harnessing biomechanical movements as a sustainable energy source [15,16].

Conclusions and Future Perspectives

The advancement of nanotechnology has played a crucial role in the evolution of supercapacitors as a promising alternative to conventional batteries in IoT medical devices. The use of nanostructured films enables the fabrication of supercapacitors with enhanced properties, which make them ideal for wearable and implantable devices. Future research directions should focus on optimizing material compositions and fabrication techniques to further enhance the performance of these supercapacitors. Despite the considerable advantages of nanomaterial-based supercapacitors for IoT healthcare applications, several challenges still must be addressed. Nevertheless, future advancements in materials engineering and nanotechnology are expected to drive innovative strategies to enhance the efficiency and integration of supercapacitors in biomedical devices.

Acknowledgement

The authors thank the Brazilian funding agencies FAPEMIG (Grants APQ-00495-24, BPD-00880-22 and RED-00045-23). We also thank the National Institute of Organic Electronics (INEO) Network (Brazil).

Conflict of Interest

The authors declare that there is no conflict of interest.

References

1. Meimei Yu, Yuanyou Peng, Xiangya Wang, Fen Ran (2023) Emerging Design Strategies Toward Developing Next-Generation Implantable Batteries and Supercapacitors. Advaced Functional Materials 33(37): 2301877.
2. Xin Li, Bingqing Wei (2013) Supercapacitors based on nanostructured carbon. Nano Energy 2(2): 159-173.
3. Mingjia Zhi, Chengcheng Xiang, Jiangtian Li, Ming Li, Nianqiang Wu (2013) Nanostructured carbon–metal oxide composite electrodes for supercapacitors: a review. Nanoscale 5(1): 72.
4. Danilo A Oliveira, Gabriel B de Carvalho, Paulo V Morais, Luciano Caseli, José R Siqueira Jr, (2025) in Supercapacitors Fundamentals, Advances and Future Applications, Royal Society of Chemistry, 2025 3(12): 399-423.
5. Osvaldo N Oliveira Jr, Rodrigo M Iost, José R Siqueira Jr, Frank N Crespilho, Luciano Caseli (2014) Nanomaterials for Diagnosis: Challenges and Applications in Smart Devices Based on Molecular Recognition. ACS Applied Materials & Interfaces 6(17): 14745-14766.
6. Danilo A Oliveira, Jodie L Lutkenhaus, José R Siqueira Jr (2021) Building up nanostructured layer-by-layer films combining reduced graphene oxide-manganese dioxide nanocomposite in supercapacitor electrodes. Thin Solid Films 718: 138483.
7. Danilo A Oliveira, Ranilson A da Silva, Marcelo O Orlandi, José R Siqueira Jr (2022) Exploring ZnO nanostructures with reduced graphene oxide in layer-by-layer films as supercapacitor electrodes for energy storage. Journal of Materials Science 57(2): 7023.
8. Danilo A Oliveira, José R Siqueira Jr (2025) Layer-by-Layer Films of Graphene Oxide–MnO2–NbO2 for Nanostructured Energy Storage Applications. ACS Applied Nano Materials 8: 19202-192114.
9. Felipe M Marinho, Rebeca R Rodrigues, Kevin F dos Santos, Laura O Peres, Danilo A Oliveira, José R Siqueria Jr, Luciano Caseli (2025) Immobilization of Laccase and Graphene Oxide in Langmuir–Blodgett Films as a Dual-Function Platform for Biosensors and Biosupercapacitors. ACS Omega 10: 46554-46568.
10. Gabriel Nerath, Danilo A Oliveira, José R Siqueira Jr, Luciano Caseli (2025) Using Carbon Nanotubes to Improve Enzyme Activity and Electroactivity of Fatty Acid Langmuir–Blodgett Film-Incorporated Galactose Oxidase for Sensing and Energy Storage Applications. ACS Applied Materials & Interfaces 17(9): 13018-13028.
11. Fábio A Scholl, Danilo A Oliveira, José R Siqueira Jr, Luciano Caseli (2023) Exploring Langmuir-Blodgett films with phospholipid-graphene oxide/MnO2 as a hybrid nanostructured interface for supercapacitor applications. Colloids and Surfaces A: Physicochemical and Engineering Aspects 664: 131128.
12. Hyeon J Sim, Changsoon Choi, Dong Y Lee, Hyunsoon Kim, Ji-Hyun Yun, et al. (2018) Biomolecule based fiber supercapacitor for implantable device. Nano Energy 47: 385-392.
13. Zheyan Qian, Yiqing Yang, Liyuan Wang, Jiajia Wang, Yue Guo, et al. (2023) An Implantable Fiber Biosupercapacitor with High Power Density by Multi-Strand Twisting Functionalized Fibers. Angewandte Chemie International Edition 62(28): e202303268.
14. Jian Lv, Lu Yin, Xiaohong Chen, Itthipon Jeerapan, Cristian A Silva, et al. (2021) Wearable Biosupercapacitor: Harvesting and Storing Energy from Sweat. Advanced Functional Materials 31: 2102915.
15. Balwan Singh, Bhavya Padha, Sonali Verma, Soumitra Satapathi, Vinay Gupta, et al. (2022) Recent advances, challenges, and prospects of piezoelectric materials for self-charging supercapacitor. Journal of Energy Storage 47: 103547.
16. Ananthakumar Ramadoss, Balasubramaniam Saravanakumar, Seung W Lee, Young-Soo Kim, Sang J Kim, et al. (2015) Piezoelectric-Driven Self-Charging Supercapacitor Power Cell. ACS Nano 9(4): 4337-4345.