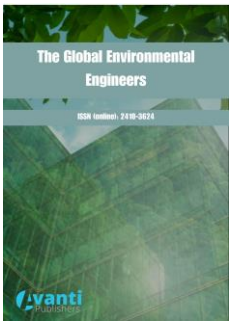
Published by Avanti Publishers

The Global Environmental Engineers

ISSN (online): 2410-3624



Charged Viruses as Programmable Charge Carriers for Sustainable Batteries and Supercapacitors: A Perspective

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ARTICLE INFO

Article Type: Perspective Article

Academic Editor: Cheng Lin

Keywords:
Supercapacitors
Synthetic biology
Sustainable batteries
Virus-templated materials
Bio-inspired energy storage

Timeline:
Received: January 23, 2026
Accepted: February 27, 2026
Published: March 19, 2026

Citation: Weng G-M. Charged viruses as programmable charge carriers for sustainable batteries and supercapacitors: A perspective. Glob Environ Eng. 2026; 13(1): 1-8.

DOI: https://doi.org/10.15377/2410-3624.2026.13.1

ABSTRACT

As the demand for sustainable energy storage increases, alternative concepts beyond conventional inorganic charge carriers are being explored. This Perspective proposes a conceptual framework in which genetically programmable viruses function as mobile charge carriers in batteries and supercapacitors. Unlike previous virus-templated electrode studies, the present work introduces the new concept of viruses operating within the electrolyte as tunable nanoscale charge transporters. The potential advantages, including charge programmability, biodegradability, and compatibility with circular material design, are discussed alongside key technical challenges such as mobility limitations, mass transport constraints, stability, and engineering feasibility. Environmental implications, including lifecycle considerations and biosafety aspects, are also analyzed. This work aims to outline a forward-looking research direction at the interface of synthetic biology and electrochemical energy storage.

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1. Introduction

The international community is intensifying its efforts to address climate change and environmental deterioration, leading to an unprecedented urgency for sustainable energy solutions [1-5]. Renewable energy technologies are essential for greener future; however, a significant challenge still remains: the necessity for eco-friendly and high-performance energy storage systems [6-12]. Conventional lithium-ion batteries, despite their widespread application, rely on finite mineral resources, involve energy-intensive manufacturing processes, and pose significant recycling challenges, which raises questions about their sustainability and environmental impact [13-18]. Therefore, it is crucial to explore alternative solutions that can promote a circular economy and reduce ecological damage (Fig. **1**). This article is presented as a Perspective that outlines a conceptual research direction rather than an experimentally validated system. The key novelty lies in proposing viruses as mobile charge carriers within the electrolyte, which differs fundamentally from previous virus-templated electrode materials. Previous studies have extensively explored viruses as templates for electrode materials [19-21]. In contrast, the present Perspective proposes a fundamentally different role, where viruses themselves function as mobile charge carriers rather than structural scaffolds.

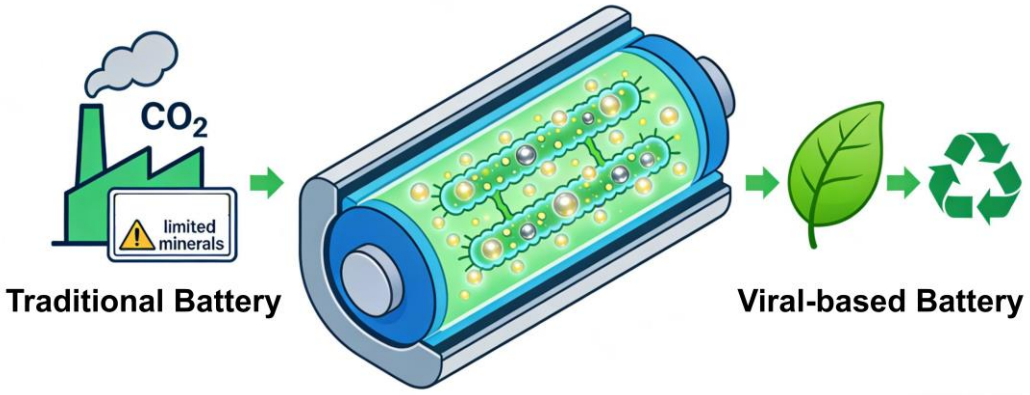

Figure 1: Conceptual contrast between traditional and viral-based battery systems.

Explore the domain of bio-inspired energy storage, a cutting-edge intersection of biology and technology that seeks to redefine established concepts [22-26]. While direct experimental validation of charged viruses as charge carriers in energy storage systems remains unreported, emerging interdisciplinary research suggests that biological nanostructures, such as viruses with engineered surface charges, could revolutionize charge transport mechanisms in batteries and supercapacitors [13, 27]. While early concepts of bio-batteries emerged ten years ago, recent progress in synthetic biology, such as CRISPR-Cas9 genome editing [28-30], cell-free biosynthesis [31-33], and machine learning-based material design [34-38], could further advance the development of bio-batteries, particularly in creating a novel type of fully biological battery that utilizes viral charge carriers.

This hypothesis is rooted in viral templating techniques, structural advantages of viral architectures, and analogous charge dynamics observed in other biological systems (e.g., DNA) [39]. While viruses are typically regarded as harmful agents, they exhibit distinctive characteristics that render them surprisingly suitable for this application. Their genetic programmability facilitates the precise alteration of surface charges and structural attributes, and their natural prevalence and biodegradability present a significant advantage over the resource limitations and toxicity linked to traditional battery materials. By harnessing these unique structures [40], we can create transformative electrochemical devices or systems, including next-generation “bio-batteries” [19-21, 41], that not only deliver exceptional performance but also promote sustainability. Fig. (**2**) depicts a concept of an electrochemical system employing charged viruses as charge carriers. These subfigures exemplify scenarios with a single type of charged virus, e.g., either negatively (left-hand side) or positively charged (right-hand side), while future iterations of such systems may ultimately incorporate both negatively and positively charged viruses as charge carriers. Red dashed lines depict the migration of a charged viral species during charging, while blue dashed lines illustrate its movement during discharging. Here, electrode materials can be viral-based, common

(e.g., carbon or metal), or a hybrid of both. When viral-based electrodes are integrated, the system exemplifies a next-generation bio-battery, merging biological programmability with electrochemical functionality. Interestingly, a recent investigation by Cotton and Phan has revealed a significant evolution in the charge of the SARS-CoV-2 spike protein [42]. The study indicated that the charge of the spike protein has notably changed from -8.3 in the original Lineage A and B viruses to -1.26 in the majority of current Omicron variants. Align with a previous report [43], this discovery emphasizes the capacity of viruses to adjust their charge characteristics in response to environmental factors, suggesting the potential for viruses to function as programmable charge carriers.

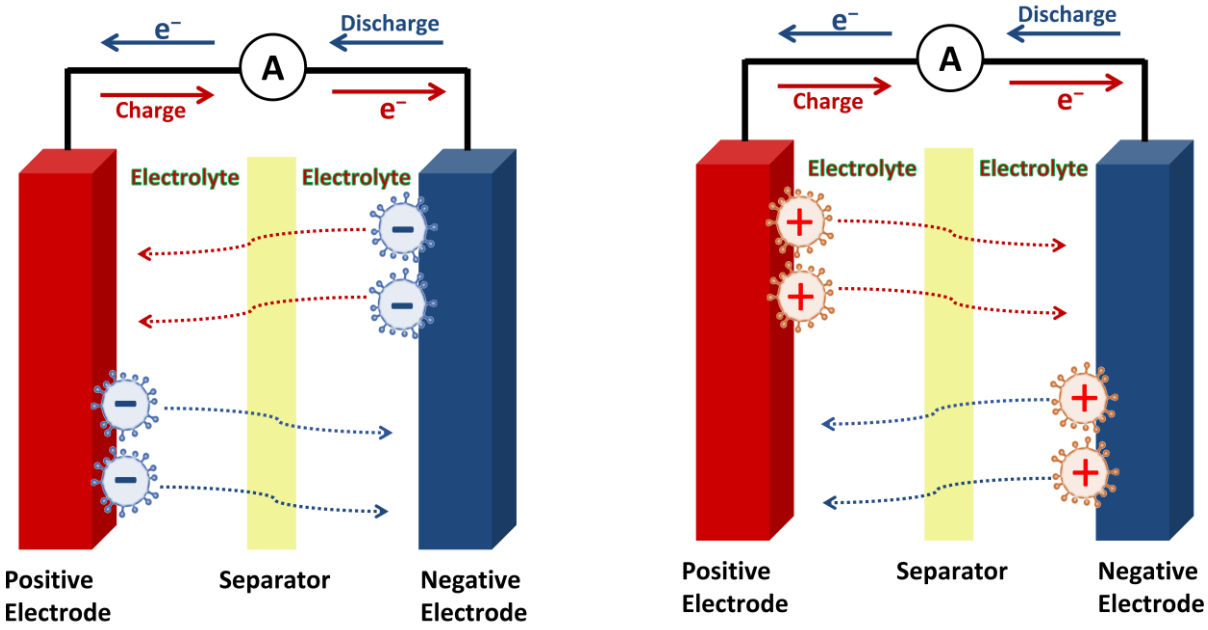

Figure 2: Conceptual illustration (hypothetical) of electrochemical systems where charged viruses function as mobile charge carriers within the electrolyte. The schematic indicates possible locations of viruses (electrolyte phase and electrode interfaces). This figure represents a proposed concept rather than an experimentally demonstrated system.

While the concept of viral-based bio-batteries, especially those that utilize viral charge carriers, remains largely unexamined, this new evidence of the inherent charge tunability of viruses presents unprecedented opportunities for their use in energy storage systems. This advancement challenges the perception that the idea of viral-based bio-batteries is obsolete and lays a strong groundwork for further investigation into this innovative research area. It is also noted that the proposed charged viruses, serving as charge carriers, are envisioned for both batteries and supercapacitors, with potential working mechanisms to diversify as research advances (e.g., novel energy conversion/storage pathways yet to be uncovered), which is why performance metrics remain undetermined. The core function of charged viruses in the proposed system is as mobile charge carriers, with their mechanism of action rooted in fundamental electrochemical principles, adapted to their biological nature. Specifically, in battery-like configurations, they migrate between electrodes under an electric field, driven by electrostatic attraction to oppositely charged surfaces, and balance redox reactions at electrode interfaces, akin to ion shuttling in conventional batteries (e.g., Li^+ in Li-ion battery systems). In supercapacitor-like systems, they accumulate at electrode surfaces to form electrical double layers (EDLs), contributing to capacitance through charge separation at the interface, similar to ions in supercapacitors. Beyond practicality, such exploration holds value in its prospectivity. It may yield not only next-generation biobatteries but also unique insights into bioelectrochemistry.

2. The Viral Advantage: Programmability and Precision

Viruses could be an unexpected yet promising option for bio-engineered charge carriers. Their attractiveness stems from their natural nanoscale structure and the accuracy with which they can be genetically modified. This genetic flexibility enables scientists to create viruses with customized surface charge densities, facilitating enhanced ion adsorption and electron transfer rates in energy storage systems like batteries or supercapacitors.

Viruses possess the remarkable ability to self-assemble into highly organized structures, a characteristic that may resolve inefficiencies associated with traditional electrodes. In the context of lithium-ion batteries, for instance, the uneven distribution of ions during the charging and discharging processes can result in dendrite formation and a subsequent loss of capacity [13]. This structural feature or ability could theoretically eliminate the ion transport bottlenecks caused by disordered material accumulation in conventional batteries. For instance, its nanoscale ordered structure could guide charged species to migrate uniformly along predetermined paths, fundamentally leading to improved mass transport. The precise design of surface charges could enhance compatibility with the electrolyte interface, reducing the accumulation of inactive materials and significantly decreasing capacity fade. This intersection of bioengineering and electrochemistry is providing innovative solutions to overcome the intrinsic defects of traditional batteries.

Importantly, viruses are biodegradable [44] and can be produced on a large scale in a sustainable manner through bacterial fermentation [45], a method that requires minimal energy and generates no toxic byproducts. This is in stark contrast to the extraction of cobalt, lithium, and rare-earth metals, which contributes to environmental degradation and geopolitical conflicts. By utilizing viruses as renewable "bio-factories", the energy storage industry could diminish its dependence on environmentally harmful supply chains.

3. Sustainability and Circular Design

The incorporation of viruses into energy storage systems is consistent with the tenets of a circular economy, which emphasizes the design of materials for reuse, regeneration, and safe biodegradation. In contrast to synthetic polymers and heavy metals that can remain in ecosystems for centuries, components derived from viruses could be engineered to decompose into benign organic substances once a device reaches the end of its useful life. This "cradle-to-cradle" methodology would address the escalating issue of electronic waste, e.g., 62 million metric tonnes in 2022 [46], much of which leaches harmful substances into soil and water sources. From a lifecycle perspective, viral materials produced via fermentation may significantly reduce energy consumption and mining-related emissions compared to metal-based systems, although quantitative LCA remains a subject for future work. Biosafety considerations, including the use of non-replicating or non-infectious viral particles and controlled degradation pathways, will also be critical for environmental risk management and regulatory approval.

Additionally, viral charge carriers could facilitate the development of entirely new device architectures. For instance, flexible and lightweight bio-batteries utilizing viral electrolytes could transform wearable electronics and medical implants, where biocompatibility is crucial. Researchers have already made strides in creating edible batteries from melanin sourced from cuttlefish ink, demonstrating the potential of biologically derived materials to innovate energy storage solutions [47]. The compatibility of viruses with living systems could further advance this field.

4. Challenges and Considerations

Viral-based energy storage systems, while promising, encounter several significant challenges. Firstly, the issue of scalability is paramount; although the production of engineered viruses at the laboratory level is achievable, transitioning to industrial-scale manufacturing necessitates the development of advanced bioreactor systems and standardized protocols to maintain consistency. Secondly, the stability of viral structures under operational conditions, such as exposure to high voltage, extreme temperatures, or extended cycling, requires thorough testing. Viruses are naturally adapted to biological environments rather than electrochemical cells, and their protein-based structures may be susceptible to degradation under stress.

In addition, ethical and regulatory challenges must be addressed. The public's perception of viruses, even those that are non-infectious, may lead to resistance due to their associations with disease. Therefore, clear communication regarding safety measures, such as the use of non-pathogenic strains and the implementation of fail-safe mechanisms, will be essential for fostering societal acceptance. Concurrently, regulatory frameworks need to adapt to accommodate these innovative biohybrid devices, ensuring a balance between fostering innovation and conducting comprehensive risk assessments.

Furthermore, as a nascent concept, direct performance metrics (e.g., energy/power densities) for electrochemical systems using charged viruses as charge carriers remain undetermined, as few such established systems yet exist. Compared to conventional ionic charge carriers (e.g., Li^+, Cl^-) which are atomic or molecular-scale with minimal mass, viruses are larger nanoscale particles with greater mass. Specifically, bare ions (e.g., Li^+, ~0.6 nm, ~6.94 Da) [13] are far smaller and lighter than viruses (e.g., the SARS-CoV-2 spike protein, ~65–125 nm and ~141–200 kDa in general) [48, 49], presenting inherent challenges for both gravimetric and volumetric performance metrics (e.g., fewer charge carriers per unit mass and volume), unless viral surface charge density is engineered to be exceptionally high. From a transport perspective, the electrophoretic mobility of nanoscale viral particles is expected to be several orders of magnitude lower than that of small ions, which may limit power performance. Their large hydrodynamic size may also increase electrolyte viscosity and introduce risks of pore blockage in dense electrode structures. Therefore, future systems would likely require low-viscosity media and hierarchical porous electrodes to ensure effective mass transport. Additionally, unlike common ions, viruses could offer precise engineering of surface charge (density/distribution) and shape, enabling selective transport, enhanced interface interactions, and adaptive responses to environmental cues. These features may enable niche applications (e.g., biocompatible devices) where conventional systems struggle due to the limitation of intrinsic properties of fixed ion. However, the unique nature of nanoscale charged viruses as charge carriers creates distinct needs for battery components compared to Li-ion batteries (smaller ions). Li-ion battery electrodes use dense structures for ion intercalation. Viral systems may need 3D porous architectures (maximizing surface interaction without trapping viruses) and tunable surface chemistry (enhancing charge transfer without irreversible adsorption). These tailored material needs highlight a key direction for future development.

In parallel, the concept of using charged viruses as charge carriers differs fundamentally from established bioelectrochemical systems. Microbial fuel cells rely on metabolic electron generation, enzymatic biobatteries on catalytic redox reactions, and DNA-based systems on structural or redox-active properties, none of these position biological entities as mobile charge carriers. To provide clearer context, it is worth noting that some systems overlap: for instance, DNA-based biobatteries, as highlighted in literature [50], often integrate with enzymatic cascades where DNA acts as a scaffold to accommodate high densities of catalysts (including enzymes), while enzyme cascades enhance energy densities. Charged viruses, by contrast, are envisioned as engineerable, mobile charge transporters. Their tunability (via genetic modification of surface charge, distribution, and shape) exceeds that of microorganisms (metabolically constrained), enzymes (catalytically focused), or DNA (structurally limited). Conceptually, viral production may offer cost advantages over nutrient-dependent microbes or labile enzymes, though this requires validation. Future research will clarify their complementarity to existing technologies. However, direct performance, stability, or cost comparisons remain premature, as experimental data for viral-based systems are lacking. Instead, Table **1** provides a conceptual overview, contrasting core biological or chemical entities, charge carrier types, tunability, and key traits across these systems.

Table 1: Conceptual comparison of key electrochemical systems, highlighting core entities, charge carriers, and distinctive traits.

System Type	Core Biological or Chemical Entity	Charge Carrier Type	Tunability	Conceptual Advantages	Current Limitations
Viral-based system	Charged viruses	Nanoscale viral particles	High (genetic engineering of charge density, shape)	Tailored charge transport Adaptive design	A proposed concept Components not yet optimized
Li-ion battery	Inorganic compounds (e.g., $LiCoO_2$, graphite)	Li^+ ions	Low (fixed ion properties)	Mature high energy density	Limited by rare materials Safety concerns
Microbial fuel cell	Living microorganisms (e.g., bacteria)	Ions (e.g., H^+)	Low (metabolic pathways hard to reengineer)	Renewable (uses organic waste)	Slow kinetics Nutrient dependence
Enzymatic biobattery	Enzymes	Ions (e.g., K^+)	Moderate (limited protein engineering)	High reaction specificity	Enzyme degradation Low stability
DNA-based system	DNA strands	Ions (e.g., H^+)	Moderate (sequence-based structural tuning)	Scaffold for high catalyst density	Poor mobility as charge carriers Limited charge transport

5. Future Directions and Implications

To transform the concept of viral energy storage into a tangible reality, it is crucial to foster interdisciplinary collaboration. Innovations in synthetic biology may improve the efficacy of viral charge carriers; for example, CRISPR-based modifications could allow viruses to "self-repair" minor structural impairments during their operation [28]. Additionally, machine learning could expedite the design process for viral proteins that possess optimal electrochemical properties. The investigation of charged viruses as charge carriers extends beyond energy storage; it signifies a transformative shift towards bio-inspired innovation. By drawing insights from nature's extensive evolutionary history, scientists can create technologies that are not only efficient but also fundamentally compatible with ecological systems.

Furthermore, technologies based on viruses have the potential to democratize energy storage access. In contrast to lithium, which is predominantly found in a limited number of countries, viruses can be cultivated in various locations with basic biotechnological resources, thereby enabling developing regions to engage in the transition to green energy. Notably, viruses offer unique tunability compared to inorganic ions, i.e., their surface charge density, shape, and surface chemistry could be modified to optimize mobility, reduce aggregation, or enhance electrode interactions, probably enabling tailored transport efficiency. While this perspective focuses on their role as charge carriers, future research could uncover novel charge storage mechanisms (e.g., virus-mediated intercalation, capsid redox activity) as the field matures.

6. Conclusion

The idea of utilizing charged viruses as charge carriers for electrochemical systems is innovative, probably lead to a revolutionary breakthrough. In other words, the concept of using charged viruses as charge carriers represents an exploratory research direction rather than a near-term technological solution. Despite the numerous challenges as mentioned above, the intersection of biotechnology, materials science, and sustainability research presents a promising avenue for rethinking energy storage solutions. By harnessing the programmability, renewability, and biodegradability of viruses, we may move closer to a future where technology not only mitigates environmental damage but also contributes to the regeneration of our planet.

Conflict of Interest

The author has no competing interests to declare.

Funding

This work received no external funding.

Acknowledgments

The author acknowledges the valuable comments from Dr. Rosalba A. Rincón and the anonymous reviewers.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

[1] Laimon M, Yusaf T. Towards energy freedom: exploring sustainable solutions for energy independence and self-sufficiency using integrated renewable energy-driven hydrogen system. Renewable Energy. 2024; 222: 119948. https://doi.org/10.1016/j.renene.2024.119948

[2] Gao Y, Liu S, Chen R, Li Z, Wu X, Ma W, *et al*. Natural hydrogen: a mini-review unveiling its potential as a key to sustainable future for energy. EcoEnergy. 2025; 3(4): e70026. https://doi.org/10.1002/ece2.70026

[3] Zhang Z, Zhang H, Jiang H, Li L. Green ammonia: revolutionizing sustainable energy for a carbon-free future. J Mater Chem A. 2024; 12(48): 33334-61. https://doi.org/10.1039/D4TA07339H

[4] Shah SS, Aziz MA, Al Marzooqi M, Khan AZ, Yamani ZH. Enhanced light-responsive supercapacitor utilizing $BiVO_4$ and date leaves-derived carbon: a leap towards sustainable energy harvesting and storage. J Power Sources. 2024; 602: 234334. https://doi.org/10.1016/j.jpowsour.2024.234334

[5] Sead FF, Jadeja Y, Kumar A, MM R, Kundlas M, Saini S, *et al*. Carbon quantum dots for sustainable energy: enhancing electrocatalytic reactions through structural innovation. Nanoscale Adv. 2025; 7(13): 3961-98. https://doi.org/10.1039/D5NA00205B

[6] Jafarizadeh H, Yamini E, Zolfaghari SM, Esmaeilion F, Assad MEH, Soltani M. Navigating challenges in large-scale renewable energy storage: barriers, solutions, and innovations. Energy Rep. 2024; 12: 2179-92. https://doi.org/10.1016/j.egyr.2024.08.019

[7] Tian J, Wu Z, Weng G-M. Waste resin derived carbon materials for sodium-ion batteries. Green Chem Technol. 2024; 1(1): 10004. https://doi.org/10.70322/gct.2024.10004

[8] Weng G-M. An investigation of $Ag/NaTi_2(PO_4)_3$ seawater battery toward scalable energy storage. Glob Environ Eng. 2024; 11: 54-62. https://doi.org/10.15377/2410-3624.2024.11.4

[9] Bertaglia T, Costa CM, Lanceros-Méndez S, Crespilho FN. Eco-friendly, sustainable, and safe energy storage: a nature-inspired materials paradigm shift. Mater Adv. 2024; 5(19): 7534-47. https://doi.org/10.1039/D4MA00363B

[10] Xu M, Wang X, Wang Z, Zhao P, Dai Y. Preliminary design and performance assessment of compressed supercritical carbon dioxide energy storage system. Appl Therm Eng. 2021; 183: 116153. https://doi.org/10.1016/j.applthermaleng.2020.116153

[11] Phan AL, Le PM, Wang C. Realizing high-energy and long-life Li/SPAN batteries. Joule. 2024; 8(6): 1601-18. https://doi.org/10.1016/j.joule.2024.04.003

[12] Mao M, Luo C, Pollard TP, Hou S, Gao T, Fan X, *et al*. A pyrazine-based polymer for fast-charge batteries. Angew Chem Int Ed. 2019; 58(49): 17820-6. https://doi.org/10.1002/anie.201910916

[13] Deng C, Li X, Chen R, Ye K, Lipton J, Maclean SA, *et al*. Recent advances in rocking chair batteries and beyond. Energy Storage Mater. 2023; 60: 102820. https://doi.org/10.1016/j.ensm.2023.102820

[14] Thompson DL, Hartley JM, Lambert SM, Shiref M, Harper GD, Kendrick E, *et al*. The importance of design in lithium ion battery recycling: a critical review. Green Chem. 2020; 22(22): 7585-603. https://doi.org/10.1039/D0GC02745F

[15] Mao J, Ye C, Zhang S, Xie F, Zeng R, Davey K, *et al*. Toward practical lithium-ion battery recycling: adding value, tackling circularity and recycling-oriented design. Energy Environ Sci. 2022; 15(7): 2732-52. https://doi.org/10.1039/D2EE00162D

[16] Ma X, Meng Z, Bellonia MV, Spangenberger J, Harper G, Gratz E, *et al*. The evolution of lithium-ion battery recycling. Nat Rev Clean Technol. 2025; 1(1): 75-94. https://doi.org/10.1038/s44359-024-00010-4

[17] Huang B, Pan Z, Su X, An L. Recycling of lithium-ion batteries: recent advances and perspectives. J Power Sources. 2018; 399: 274-86. https://doi.org/10.1016/j.jpowsour.2018.07.116

[18] Yang Y, Okonkwo EG, Huang G, Xu S, Sun W, He Y. On the sustainability of lithium ion battery industry: a review and perspective. Energy Storage Mater. 2021; 36: 186-212. https://doi.org/10.1016/j.ensm.2020.12.019

[19] Lee YJ, Yi H, Kim WJ, Kang K, Yun DS, Strano MS, *et al*. Fabricating genetically engineered high-power lithium-ion batteries using multiple virus genes. Science. 2009; 324: 1051-5. https://doi.org/10.1126/science.1171541

[20] Oh D, Qi J, Lu YC, Zhang Y, Shao-Horn Y, Belcher AM. Biologically enhanced cathode design for improved capacity and cycle life for lithium-oxygen batteries. Nat Commun. 2013; 4: 2756. https://doi.org/10.1038/ncomms3756

[21] Nam KT, Kim DW, Yoo PJ, Chiang CY, Meethong N, Hammond PT, *et al*. Virus-enabled synthesis and assembly of nanowires for lithium ion battery electrodes. Science. 2006; 312(5775): 885-8. https://doi.org/10.1126/science.1122716

[22] Ren J, Liu Q, Pei Y, Wang Y, Yang S, Lin S, *et al*. Bioinspired energy storage and harvesting devices. Adv Mater Technol. 2021; 6(9): 2001301. https://doi.org/10.1002/admt.202001301

[23] Dodón A, Quintero V, Chen Austin M, Mora D. Bio-inspired electricity storage alternatives to support massive demand-side energy generation: a review of applications at building scale. Biomimetics. 2021; 6(3): 51. https://doi.org/10.3390/biomimetics6030051

[24] Qu L, Gou Q, Deng J, Zheng Y, Li M. A perspective of bioinspired interfaces applied in renewable energy storage and conversion devices. Langmuir. 2024; 40(13): 6601-11. https://doi.org/10.1021/acs.langmuir.3c03679

[25] Liang H, Ni J, Li L. Bio-inspired engineering of Bi_2S_3-PPy yolk-shell composite for highly durable lithium and sodium storage. Nano Energy. 2017; 33: 213-20. https://doi.org/10.1016/j.nanoen.2017.01.033

[26] Wang H, Yang Y, Guo L. Nature-inspired electrochemical energy-storage materials and devices. Adv Energy Mater. 2017; 7(5): 1601709. https://doi.org/10.1002/aenm.201601709

[27] Patil BP, Jagtap RM, Pardeshi SK. Electrochemical performance enhancement of lanthanum nickelate by Sr doping for supercapacitor application. Discov Electrochem. 2025; 2(1): 19. https://doi.org/10.1007/s44373-025-00033-x

[28] Borca MV, Berggren KA, Ramirez-Medina E, Vuono EA, Gladue DP. CRISPR/Cas gene editing of a large DNA virus: African swine fever virus. Bio Protoc. 2018; 8: 2978. https://doi.org/10.21769/BioProtoc.2978

[29] Sokra I, Somaly S, Lika R, Marady V. CRISPR-Cas9 genome editing in microorganisms: principles, tools, and applications. J Agric Technol. 2026; 2(1): 118-28.

[30] Mocchetti A, De Rouck S, Naessens S, Dermauw W, Van Leeuwen T. SYNCAS-based CRISPR-Cas9 gene editing in predatory mites, whiteflies and stinkbugs. Insect Biochem Mol Biol. 2025; 177: 104232. https://doi.org/10.1016/j.ibmb.2024.104232

[31] Liu WQ, Ji X, Ba F, Zhang Y, Xu H, Huang S, *et al*. Cell-free biosynthesis and engineering of ribosomally synthesized lanthipeptides. Nat Commun. 2024; 12: 4336. https://doi.org/10.1038/s41467-024-48726-y

[32] Xu X, Wen Q, Wang C, Yang M, Zhang W, Xing J. Engineering a 4-vinylguaiacol oxygenase for cofactor-free, cell-free vanillin biosynthesis. ACS Sustain Chem Eng. 2025; 13(50): 21544-55. https://doi.org/10.1021/acssuschemeng.5c08487

[33] Rasor BJ, Erb TJ. Cell-free systems to mimic and expand metabolism. ACS Synth Biol. 2025; 14(2): 316-22. https://doi.org/10.1021/acssynbio.4c00729

[34] Wu C, Wan B, Entezari A, Fang J, Xu Y, Li Q. Machine learning-based design for additive manufacturing in biomedical engineering. Int J Mech Sci. 2024; 266: 108828. https://doi.org/10.1016/j.ijmecsci.2023.108828

[35] Lee J, Park D, Lee M, Lee H, Park K, Lee I, *et al*. Machine learning-based inverse design methods considering data characteristics and design space size in materials design and manufacturing: a review. Mater Horiz. 2023;10(12): 5436-56. https://doi.org/10.1039/D3MH00039G

[36] Sheini Dashtgoli D, Taghizadeh S, Macconi L, Concli F. Comparative analysis of machine learning models for predicting the mechanical behavior of bio-based cellular composite sandwich structures. Materials. 2024; 17(14): 3493. https://doi.org/10.3390/ma17143493

[37] Goshisht MK. Machine learning and deep learning in synthetic biology: key architectures, applications, and challenges. ACS Omega. 2024; 9(9): 9921-45. https://doi.org/10.1021/acsomega.3c05913

[38] Notin P, Rollins N, Gal Y, Sander C, Marks D. Machine learning for functional protein design. Nat Biotechnol. 2024; 42(2): 216-28. https://doi.org/10.1038/s41587-024-02127-0

[39] Sontz PA, Muren NB, Barton JK. DNA charge transport for sensing and signaling. Acc Chem Res. 2012; 45(10): 1792-800. https://doi.org/10.1021/ar3001298

[40] Kurta RP, Donatelli JJ, Yoon CH, Berntsen P, Bielecki J, Daurer BJ, *et al*. Correlations in scattered X-ray laser pulses reveal nanoscale structural features of viruses. Phys Rev Lett. 2017; 119(15): 158102. https://doi.org/10.1103/PhysRevLett.119.158102

[41] Moskvitch K. Growing batteries from viruses. New Sci. 2014; 221(2958): 30-1. https://doi.org/10.1016/S0262-4079(14)60429-2

[42] Cotten M, Phan M. Evolution of increased positive charge on the SARS-CoV-2 spike protein may be adaptation to human transmission. iScience. 2023; 26: 106230. https://doi.org/10.1016/j.isci.2023.106230

[43] Duran-Meza AL, Villagrana-Escareo MV, Ruiz-García J, Knobler CM, Gelbart WM. Controlling the surface charge of simple viruses. PLoS One. 2021; 16(9): e0255820. https://doi.org/10.1371/journal.pone.0255820

[44] Tóthová L, Bábíková J, Celec P. Phage survival: the biodegradability of M13 phage display library in vitro. Biotechnol Appl Biochem. 2012; 59(6): 490-4. https://doi.org/10.1002/bab.1050

[45] Warner CM, Barker N, Lee SW, Perkins EJ. M13 bacteriophage production for large-scale applications. Bioprocess Biosyst Eng. 2014; 37: 2067-72. https://doi.org/10.1007/s00449-014-1184-7

[46] Serpe A, Purchase D, Bisschop L, Chatterjee D, De Gioannis G, Garelick H, *et al*. 2002–2022: 20 years of e-waste regulation in the European Union and the worldwide trends in legislation and innovation technologies for a circular economy. RSC Sustain. 2025; 3: 1039-83. https://doi.org/10.1039/D4SU00548A

[47] Kim YJ, Wu W, Chun SE, Whitacre JF, Bettinger CJ. Biologically derived melanin electrodes in aqueous sodium-ion energy storage devices. Proc Natl Acad Sci U S A. 2013; 110(52): 20912-7. https://doi.org/10.1073/pnas.1314345110

[48] Peisahovics F, Rohaim MA, Munir M. Structural topological analysis of spike proteins of SARS-CoV-2 variants of concern highlight distinctive amino acid substitution patterns. Eur J Cell Biol. 2022; 101(4): 151275. https://doi.org/10.1016/j.ejcb.2022.151275

[49] Huang Y, Yang C, Xu X-f, Xu W, Liu S-w. Structural and functional properties of SARS-CoV-2 spike protein: potential antivirus drug development for COVID-19. Acta Pharmacol Sin. 2020; 41(9): 1141-9. https://doi.org/10.1038/s41401-020-0485-4

[50] Chen H, Simoska O, Lim K, Grattieri M, Yuan M, Dong F, *et al*. Fundamentals, applications, and future directions of bioelectrocatalysis. Chem Rev. 2020; 120(23): 12903-93. https://doi.org/10.1021/acs.chemrev.0c00472