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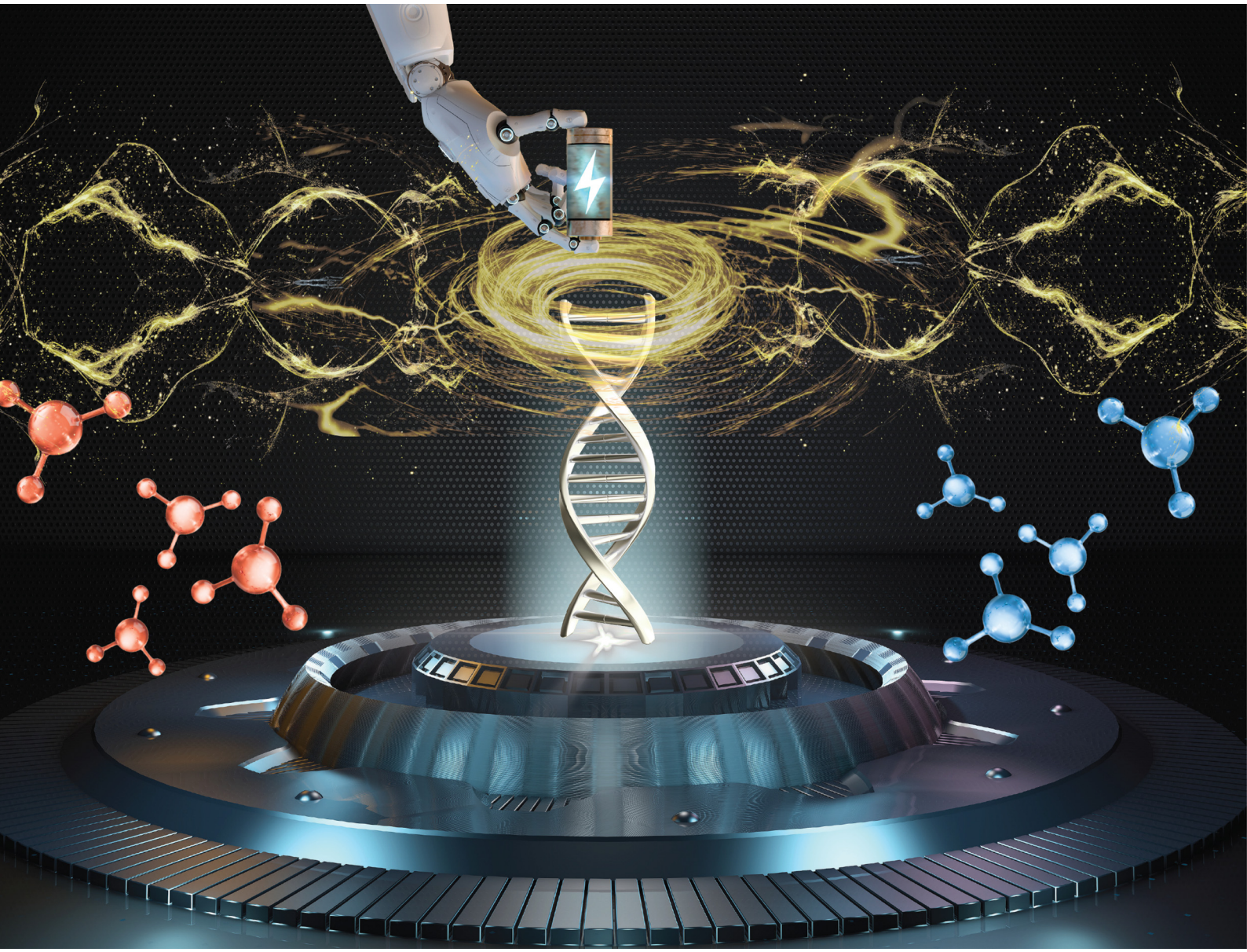

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MINIREVIEW

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DNA-based hydrogels: a promising material for future energy storage applications

Samanth Kokkiligadda,*[a] Surya Kiran Ampasala[a] and Soong Ho Um *[abcd]

DNA hydrogels have emerged as promising natural biomaterials for next-generation energy storage systems, offering a unique combination of biocompatibility, programmability, tunability, and self-assembly capabilities. Traditionally developed using synthetic DNA strands or DNA origami, efforts are turning toward naturally derived genomic DNA, such as that obtained from salmon sperm, chicken blood, and other biowaste sources, offering a more sustainable and cost-effective route. These hydrogels possess inherent sequence diversity and tunable network structures, making them ideal candidates for enhancing ionic conductivity, mechanical stability, and electrochemical performance in devices like batteries and supercapacitors. This review explores the foundational principles, synthesis strategies, and recent advancements in using DNA hydrogels as components in batteries, supercapacitors, and fuel cells. Compared to traditional materials, DNA hydrogels provide sustainable advantages such as biodegradability, mechanical flexibility, and designable structures that respond to environmental stimuli. While challenges like limited conductivity, stability, and scaling issues remain, ongoing research is addressing these through chemical modifications, hybrid composites, and integration with nanomaterials. Looking ahead, the development of smart, multifunctional DNA hydrogels holds significant potential to transform energy storage technologies and contribute to global sustainability goals. This review highlights key opportunities and calls for interdisciplinary efforts to fully realize the capabilities of DNA hydrogels in future energy systems.

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1. Introduction

Hydrogels consist of 3D polymer chain networks capable of retaining significant amounts of water within their structure. Thanks to their cross-linked frameworks formed through either covalent or noncovalent interactions, these materials sustain gel-like (solid) consistency even when containing over 90% water. This internal hydration, along with their structural integrity and distinctive unique properties such as excellent flexibility, robust viscoelastic behavior, and rubber-like elasticity, makes hydrogels ideal for various applications.

In the face of growing global energy demands and the transition toward sustainable energy sources, efficient energy storage technologies have become essential to modern infrastructure.[1] These systems are crucial for everything from small handheld devices to big ones like electric cars and power grids.[2] They help balance energy supply and demand, keep the power grid stable and make it easier to use renewable energy sources like wind and solar, which don't always produce power consistently.[3] Traditional storage options such as lithium-ion batteries,[4] redox flow systems,[5] fuel cells,[6] and supercapacitors[7] have seen substantial improvements in recent years, playing a key role in advancing clean energy solutions. However, these systems still face several challenges, including limited capacity, safety concerns, environmental impact, and the need for sustainable and multifunctional materials. To address these limitations, hydrogels have recently gained attention as potential components in energy storage devices, particularly as electrolytes, separators, or electrode binders.[8–10] However, conventional hydrogels often lack the ease of scalable synthesis, ion conductivity, mechanical strength, and functional tunability required for high-performance energy storage. Recently, to enhance these properties, researchers have explored the integration of functional biomolecules into hydrogel networks among which DNA stands out as a uniquely versatile material.

Three-dimensional networks of cross-linked polymers called hydrogels may absorb and hold large amounts of water while preserving their structural integrity. These materials are especially appealing for electrochemical applications due to their

[a] *Laboratory of Advanced Bioinspired Materials and Electrochemistry, School of Chemical Engineering, Sungkyunkwan University, Suwon-si, Gyeonggi-do 16419, South Korea. E-mail: samanth213@skku.edu, sh.um@skku.edu*
[b] *SKKU Advanced Institute of Nanotechnology (SAINT), Sungkyunkwan University, Suwon-si, Gyeonggi-do 16419, South Korea*
[c] *Biomedical Institute for Convergence at SKKU (BICS), Sungkyunkwan University, Suwon-si, Gyeonggi-do 16419, South Korea*
[d] *Institute of Quantum Biophysics (IQB), Sungkyunkwan University, Suwon-si, Gyeonggi-do 16419, South Korea*

unique blend of solid-like mechanical properties and liquid-like transport characteristics.[11,12] The crosslinking structure and polymer content of hydrogels directly influence their fundamental characteristics, including ionic conductivity, mechanical flexibility, and chemical tunability.

Hydrogels combine the mechanical stability of solid-state systems with the ionic conductivity of liquid electrolytes to play a number of vital functions in energy storage systems, including electrolyte, separator, and electrode binders. Hydrogel electrolytes are very useful for flexible and wearable energy devices because they allow for quick ion transport without allowing electrode-to-electrode contact. Ionic conductivities surpassing 20 mS cm^{-1}, along with exceptional mechanical flexibility and long-term cycle stability, have been proven by recent developments in biopolymer-based hydrogel electrolytes. Hydrogels, which are water-rich, porous structure, promotes effective ion transport, and their mechanically adjustable characteristics allow for incorporation into deformable device topologies.[13,14]

Over the past decade, DNA-based hydrogels have attracted significant interest due to the distinctive properties offered by nucleic acids. Since the early days of molecular self-assembly research, DNA (deoxyribonucleic acid) has been recognised as a promising material for building nanoscale structures, due to its predictable and programmable base pairing interactions following Watson–Crick principles.[15,16] While DNA nanotechnology allows for the design of intricate and well-defined nanostructures, extending this precision to bulk-scale DNA hydrogels remains a challenge.[17,18] This is primarily due to the relatively short persistence length of double-stranded DNA and the tendency for design errors to accumulate at larger scales, resulting in more random network architectures.[19,20] Certain DNA molecules undergo structural changes when triggered by stimuli like pH, temperature, or target molecules.[18,21] Incorporating these into hydrogels enables dynamic, responsive behavior.[22–24] Nevertheless, at the nanoscale the fundamental components of DNA-based hydrogels can be designed and controlled using the same principles as DNA nanotechnology, offering a versatile set of building blocks for hydrogel development.[25–27]

Compared to conventional hydrophilic polymer hydrogels, DNA-based hydrogels offer several distinct advantages, primarily due to the unique properties of DNA itself.[28,29] The unique molecular framework of DNA can be finely tuned and designed at the nanoscale, allowing for the development of structures specifically optimized for energy storage applications.[30,31] Its inherent ability of electrical conductivity is a key factor in achieving effective energy transfer and retention. Numerous DNA-based hydrogel networks rely on weak noncovalent connections, including hydrogen bonding between base pairs, electrostatic forces, and π–π stacking.[32–34] Unlike covalent bonds, these reversible interactions can dynamically break and reform, giving rise to unique mechanical properties such as shear-thinning, shape-memory, and self-healing capabilities. In addition, DNA's natural biocompatibility and biodegradability make it an eco-friendly material choice, aligning well with the growing demand for sustainable and green energy storage technologies.[35]

In this review, we aim to explore recent advancements in the growing potential of DNA hydrogels in different fields of energy storage. We provide a comprehensive overview of their design principles, physicochemical properties, and recent developments in their application to various energy storage devices. Furthermore, we discuss current challenges and offer insights into future research directions to advance the integration of DNA hydrogels in sustainable energy technologies.

2. DNA hydrogels in energy storage

The rapid growth of global energy demand, driven by digitalization, electrification of transportation, and renewable energy integration, underscores an urgent need for advanced, sustainable energy storage technologies. Addressing this challenge is essential for advancing several key United Nations Sustainable Development Goals (SDGs), particularly SDG 7 (Affordable and Clean Energy)[36] SDG 9 (Industry, Innovation, and Infrastructure),[37,38] and SDG 12 (Responsible Consumption and Production).[39] In this context, there is growing interest in replacing traditional synthetic or traditional materials with bio-derived, environmentally friendly alternatives that minimize ecological impact.

Among the broad array of natural materials being explored such as other biomolecules like amino acids,[40–42] peptides,[43,44] polysaccharides,[45,46] and proteins[47,48] have gained significant attention as sustainable alternatives in efficient hydrogels in various areas of application, as well as in energy storage. In comparison, DNA emerges as a uniquely versatile material due to its well-defined molecular architecture comprising a phosphate backbone, four nucleobases (A, T, G, C), and sugar residues, all of which provide rich chemical functionality.[49–51] The abundance of phosphorus, nitrogen, and oxygen groups facilitates strong interactions with metal ions, enhancing ion transport, conductivity, and charge transfer essential for efficient energy storage. Furthermore, the sugar–phosphate backbone with densely anionic phosphate groups and nucleobase pairing governs hybridization, local charge distribution, and sequence-dependent mechanics, enabling precise molecular programming. These intrinsic properties allow DNA hydrogels to be engineered with tuneable mesh size, crosslink lifetimes, and cation coordination, making them a promising as structural templates and electrolyte matrices.[52–54] Along with biodegradability and well-established manufacturing processes, these materials also deliver flexibility, large surface areas, and improved stability, making them attractive for next-generation batteries, fuel cells, and supercapacitors.

DNA hydrogels, which are formed by crosslinking DNA strands into a three-dimensional porous framework, exhibit favorable properties such as high ionic conductivity, mechanical flexibility, and tuneable chemistry. For example, bio-species-derived genomic DNA hydrogels have demonstrated

ionic conductivities up to 73.27 mS cm^{-1} surpassing values typical for synthetic hydrogels and supporting rapid ion transport in energy storage applications.[55] These hydrogels show exceptional mechanical stretchability and strength, making them resilient under repeated deformation, as required for flexible supercapacitors and wearable devices.[56] The chemistry of DNA hydrogels is highly programmable: through deliberate sequence design and dynamic crosslinking strategies. Additionally, DNA hydrogels can be engineered to incorporate conductive nanomaterials such as carbon nanotubes and polyaniline, as well as electroactive species,[55] thereby expanding their role to multifunctional electrode platforms and hybrid electrolyte systems. One of the standout features of DNA hydrogels is their capacity for programmable molecular recognition, enabling the development of adaptive and intelligent materials that respond to diverse environmental stimuli. The improved charge accumulation observed in DNA hydrogel-based electrolytes arises from their anionic phosphate backbone, which attracts and stabilizes cations at the hydrogel-electrode interface. This facilitates efficient ion transport and enhances double-layer formation, thereby improving device capacitance and stability. However, this effect is ionic in nature and does not imply that DNA hydrogels themselves act as electronic charge-storage electrodes. Pure DNA hydrogels remain electrically insulating, and their direct role is therefore limited to electrolytes, binders, and separators, while DNA-polymer, DNA-carbon hybrids, and DNA-hybrid nanomaterials may extend their application toward electrode design and conductive networks, which are further discussed in the review.

3. Role in batteries

3.1. Battery fundamentals

Batteries are electrochemical devices that use reversible redox processes at two electrodes, a cathode (positive electrode) and an anode (negative electrode), separated by an electrolyte to transform chemical energy into electrical energy. Because of their high energy density, extended cycle life, and efficiency, rechargeable batteries, especially lithium-ion batteries, or LIBs, are the most widely used energy storage technology. They are extensively utilised in grid-level applications, electric cars, and portable electronics. However, LIBs have drawbacks such as dependence on non-renewable resources, dendritic development, electrolyte instability, and safety hazards. To enhance performance and make next-generation battery chemistries possible, there is a rising interest in flexible, safe, and sustainable electrolytes and binders.[57,58] DNA hydrogels provide a number of strategies to overcome the main drawbacks of traditional lithium-ion battery systems, building on the battery principles previously mentioned. Their special blend of programmable chemistry, mechanical flexibility, and ionic conductivity allows them to serve as multifunctional binders, protective interfacial layers, and solid polymer electrolytes that can all improve sustainability, performance, and safety at the same time. The intrinsic limitations of existing battery systems, including those on temperature sensitivity, interfacial resistance, and electrolyte safety, have spurred extensive research into alternative materials and device architectures. One of the innovative technologies that offers unique advantages in addressing these problems and creating eco-friendly production methods is bio-derived materials.

3.2. Solid polymer electrolyte

The properties of the electrolyte heavily influence the performance of lithium-ion batteries (LIBs). Recent research has demonstrated that incorporating DNA into polyvinylidene fluoride (PVDF) matrices can modulate the crystallinity of the polymer, thereby enhancing ionic conductivity. Specifically, the negatively charged phosphate groups in DNA interact with the PVDF chains, disrupting their crystalline structure and creating more amorphous regions that facilitate lithium-ion transport (Fig. 1a). An optimal DNA concentration was found to reduce crystallinity effectively, leading to improved battery performance. In contrast, excessive DNA content could increase crystallinity and hinder ion transport. Batteries utilizing PVDF with 1% DNA exhibited a high capacity of 120 mAh g^{-1} at 0.5C and maintained approximately 71% of their capacity after 500 cycles.[59]

Interestingly, DNA can also act as a protective barrier on the electrode surface, helping to minimize unwanted side reactions and reduce the risk of dendrite growth. This not only improves the overall safety of the battery but also extends its lifespan (Fig. 1b). One notable example involves the development of a composite structure SiMPs@GO coated with single-stranded DNA for lithium-ion batteries.[60] The battery demonstrated a high capacity of 808 mAh g^{-1} even after 450 charge–discharge cycles.[61]

Anode-free batteries are a promising technology for the future of advanced energy storage. Still, one major drawback

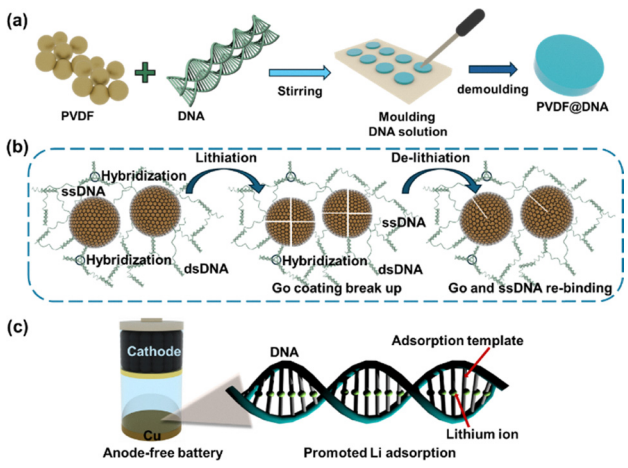

Fig. 1 (a) Schematic illustration of the preparation of PVDF@DNA solid electrolytes. (b) The design of SiMPs@GO/ssDNA and the evolution during the charge/discharge process.[60] (c) Schematic illustration of an anode-free Li metal battery using a DNA-modified Cu current collector.

of anode-free batteries is their poor cycling stability and limited lithium plating/stripping efficiency, which hinders their practical application (Fig. 1c).[62]

A recent approach to address this issue was to develop an anode-free battery incorporating a DNA-based interfacial layer. The nitrogen-containing groups in DNA form temporary bonds with lithium ions, helping to guide their distribution and promote uniform nucleation and deposition. This also improves ionic conductivity, reduces dendrite growth, and enhances cycling stability. As a result, the battery delivered over 400 stable cycles showing a 186% performance boost compared to a bare copper foil.[62] This work underscores the promise of DNA as a tunable and eco-friendly interfacial material for future anode-free battery technologies.[61]

3.3. Binder

Researchers explored the use of a novel binder combining renatured DNA and alginate to enhance the performance of silicon-based anodes. This binder draws inspiration from mucin, a naturally occurring amphiphilic macromolecule known for its lubricating properties. By mimicking mucin's structure, the DNA–alginate binder exhibits amphiphilic characteristics, facilitating a homogeneous distribution of electrode components and improving adhesion to the current collector. These attributes contribute to enhanced cyclability and structural integrity of both silicon and silicon-graphite blended electrodes. In this study, researchers designed an amphiphilic binder system for silicon anodes comprising thermally renatured DNA (reDNA) and alginate (ALG) (Fig. 2a). The reDNA component provides hydrophobicity through its heterocyclic aromatic groups, enabling strong interactions with hydrophobic carbon conductive agents and graphite in blended electrodes. Conversely, ALG preferentially adheres to hydrophilic silicon particles.[37] Structurally, reDNA directs the formation of a three-dimensional interconnected network by leveraging partial rehybridization during the renaturation process. In both silicon and silicon-graphite blended electrodes, the DNA–alginate binder improves cyclability by promoting the uniform distribution of electrode components inside the electrode and their increased adherence onto a current collector.[63]

A series of ferrocene-based pyrrolidines were synthesized *via* [3+2] dipolar cycloaddition with yields up to 86% seen in Fig. 2b. Electrochemical analysis, performed using cyclic and differential pulse voltammetry, revealed a quasi-reversible one-electron oxidation attributed to the ferrocene unit. Upon addition of calf thymus DNA, a notable decrease in anodic peak current and a ~50 mV negative shift in oxidation potential were observed, confirming electrostatic interaction between the ferrocenium ion and the DNA phosphate backbone. Binding constants ranged from 7.4×10^3 to 4.1×10^4 M^{-1}, and the binding site size was consistently 0.5 base pairs, indicating non-covalent ionic binding. Molecular docking supported these findings, showing major groove binding dominated by electrostatic forces. These results suggest the compounds' potential as

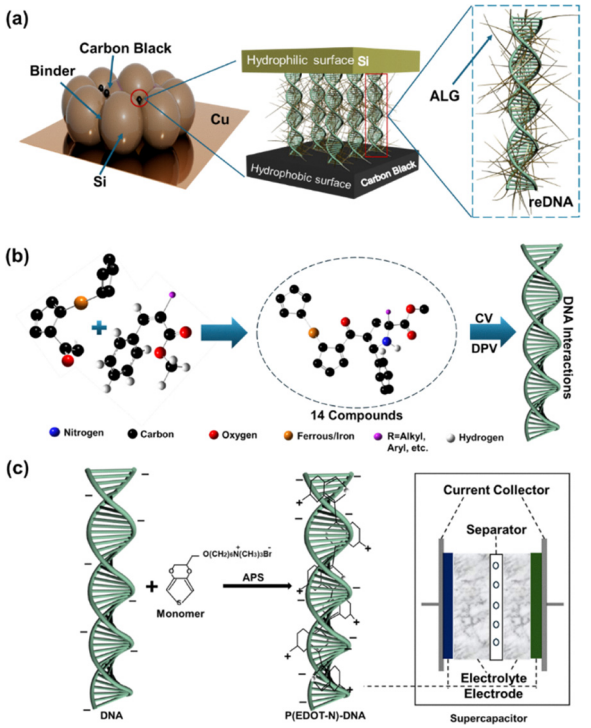

Fig. 2 (a) Schematic illustration of the reDNA/ALG hybrid binder at Si/C interface in the electrode. (b) Synthesis scheme of methyl 2-alkyl-5-aryl-4-ferrocenoylpyrrolidine-2-carboxylates. (c) Schematic representation of the synthesis process of cationic P(EDOT-N) and preparation of the P(EDOT-N)_DNA composite by oxidative polymerization for supercapacitor electrodes.

DNA-interactive electroactive agents for bioelectrochemical applications.[64]

A novel cationic poly(3,4-ethylenedioxythiophene) DNA composite (P(EDOT-N)–DNA) was synthesized *via in situ* oxidative polymerization of an EDOT-N monomer using salmon sperm DNA as the template as shown in Fig. 2c. The resulting material formed a porous micro structured network with high surface area, as confirmed by scanning electron microscopy and fluorescence imaging, which is favorable for efficient ion diffusion and charge storage. The composite exhibited a broad UV-vis absorption between 300 and 700 nm (EDOT-N)–DNA composite demonstrated excellent electrochemical properties when tested as a supercapacitor electrode in 1 M $LiPF_6$ electrolyte (EC/DMC/DEC 1 : 1 : 1), with a maximum specific capacitance of 32 F g^{-1} at 1 mV s^{-1}. Even at a high scan rate of 100 mV s^{-1}, the material retained 62% of its maximum capacitance, showing strong rate capability. Galvanostatic charge–discharge tests under a current density of 800 mA g^{-1} within a voltage window of 0–2.7 V revealed a stable triangular profile, indicating reasonable charge–discharge reversibility. Furthermore, the P(EDOT-N)–DNA composite displayed low cytotoxicity at concentrations up to 300 mg L^{-1}, highlighting its potential as a biocompatible, environmentally friendly electrode material for next-generation energy storage devices, particularly in biological or green-electronic environments.[65]

4. Applications for supercapacitors

4.1. Fundamentals of supercapacitors

Supercapacitors, also known as electrochemical capacitors, store energy through electrostatic charge accumulation rather than chemical reactions, enabling rapid charge/discharge cycles and exceptional power density. In contrast to batteries, the electrical double layer (EDL) that forms at the electrode–electrolyte interface, where ions build up on electrode surfaces without passing through electron transfer reactions, is where supercapacitors store energy. Supercapacitors are also referred to as electrical double-layer capacitors (EDLCs).[66,67] Supercapacitors require electrodes with high surface area and efficient charge transport pathways. Traditional supercapacitor systems often rely on synthetic polymeric electrolytes or binders, but limitations in ionic conductivity, mechanical flexibility, and sustainability restrict their broader deployment. DNA hydrogels, with their porous architecture and programmable chemistry, offer a novel route to address these challenges.[68]

4.2. DNA hydrogels as templates for conductive networks

The templating capabilities of DNA hydrogels demonstrated above represent only one pathway for enhancing supercapacitor performance. While structural templating enables high surface area and controlled porosity, the intrinsic electrochemical properties of DNA networks offer additional opportunities for charge storage enhancement. The phosphate-rich backbone and programmable architecture of DNA hydrogels can directly participate in charge storage mechanisms, extending beyond their role as passive structural supports.

A couple of researchers fabricated DNA hydrogels by enzymatic crosslinking of X-shaped DNA monomers, resulting in a hierarchical pore structure with macropores (>1 μm) and mesopores (~ 10 nm). These hydrogels were coated with polyelectrolyte multilayers of poly(3,4-ethylenedioxythiophene): poly(styrene sulfonate) PEDOT:PSS and poly diallyl dimethylammonium chloride (PDADMAC) using a layer-by-layer deposition process. The resulting polyelectrolyte multilayer-coated DNA hydrogels exhibited low sheet resistance (as low as 66 $\pm$ 6 Ohm sq^{-1} with five bilayers) and maintained structural integrity, demonstrating their potential as electrode materials in supercapacitors, as shown in Fig. 3.[69] DNA hydrogels were constructed and analyzed, some of which had embedded percolating networks and used DNA-wrapped CNTs and DNA-attached AuNPs as crosslinkers. This approach began at the molecular level with the design of DNA sequences and advanced toward the formation of macroscale hydrogels through bottom-up fabrication. We used the crosslinker plus spacer design, in which oligonucleotides were designed to form molecular networks *via* sequence-directed hybridization with sticky ends on crosslinker units and coupling components to construct 3D networks as shown in Fig. 3.[70]

A hybrid nanowire was created by electrostatically adsorbing gold nanoparticles (AuNPs) and polyaniline onto DNA. Their findings indicate that the ultranarrow hybrid nanowire, measuring less than 3 nm in width and height, is conductive and

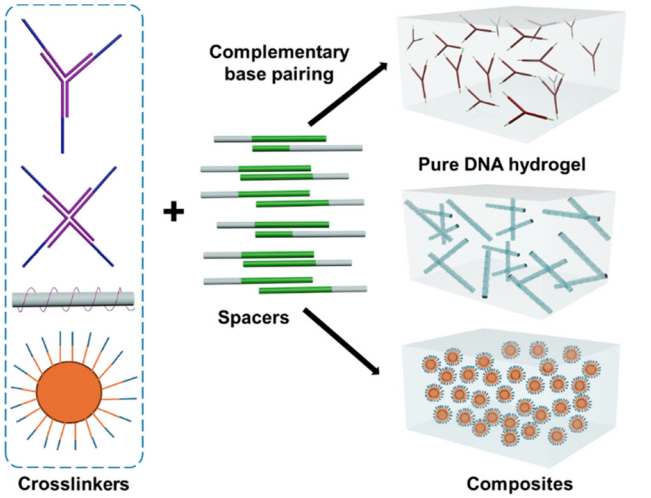

Fig. 3 A schematic representation shows the development of a hydrogel based on DNA. DNA–carbon nanotube (CNT) conjugates, DNA–gold nanoparticle (AuNP) conjugates, and Y-shaped and X-shaped DNA tiles as crosslinkers for hydrogel synthesis.

suitable for use in electronic nanodevices.[56] This flexibility, combined with biocompatibility, supports integration into wearable systems operating in physiological fluids. Recent advances in biopolymer-based hydrogel electrolytes further underscore DNA's role in enhancing charge storage *via* electric double-layer capacitance (EDLC) and pseudo-capacitance mechanisms.

4.3. Enhanced charge storage mechanisms

The enhanced charge storage mechanisms of DNA hydrogels capacity to actively contribute to supercapacitor performance. However, realizing the full potential of these systems requires optimization of the electrolyte properties and ionic transport pathways within the DNA network itself. The high ionic conductivity and biocompatibility of DNA hydrogels position them as promising candidates for replacing conventional liquid electrolytes while maintaining or improving device performance.

Incorporating conductive polymers into DNA hydrogel frameworks not only provides electrical conductivity but also greatly boosts their electrochemical behavior.[71] Polymers like polyaniline (PANI), polypyrrole (PPy), and PEDOT:PSS create interconnected conductive pathways within the hydrogel, supporting efficient electron movement throughout the structure. This turns the hydrogel into both a mechanical support and an electrochemically active material.

Due to their porous and water-rich structure, DNA hydrogels enable fast ion movement and diffusion, which helps lower internal resistance and supports high-rate charging and discharging. The phosphate groups along the DNA backbone naturally attract positively charged ions, improving charge accumulation at the interface with the conductive polymer. As a result, the combination of fast ion transport and enhanced electron conductivity leads to higher capacitance and improved overall energy storage performance.[32]

These hybrid hydrogels work effectively even in biological environments like phosphate-buffered saline (PBS) or simulated body fluids, thanks to their biocompatibility, flexibility, and adjustable chemical properties. They remain stable over multiple charging cycles, making them ideal for use in bio-integrated systems such as wearable and implantable supercapacitors or biosensing devices. In addition, the ability to program DNA sequences offers precise structural control and integration of functional groups or biological recognition sites, paving the way for intelligent, multifunctional energy storage solutions in biomedical fields.[55]

4.3. DNA gel electrolytes

Beyond their roles as templates and charge storage enhancers, DNA hydrogels can function as complete electrolyte systems, replacing conventional liquid electrolytes in supercapacitors while providing additional advantages in safety, flexibility, and biocompatibility. The inherent ionic conductivity of DNA networks, arising from their phosphate-rich backbone and water-rich structure, enables direct application as quasi-solid electrolytes that eliminate the need for separators while maintaining high ionic mobility.

Pure DNA gels exhibit an ionic conductivity of 12.4 mS cm^{-1} at 25 °C, attributed to electrostatic interactions between the phosphate groups in the DNA backbone and surrounding Na^+/K^+ ions. Eliminating separators reduces interfacial resistance, enabling a 98% Coulombic efficiency over 10 000 cycles.[71,72] Researchers investigate how different factors, including the type of electrolyte (symmetrical *vs.* unsymmetrical) and ionic strength, affect the kinetics of DNA release from PVA–DNA cryogel membranes. In general, variations that increase the surfactant's hydrophobicity favour interactions with DNA because they result in a lower critical aggregation concentration. The effect of alkyltrimethyl ammonium-based and bolaamphiphile cationic surfactants on the release kinetics of DNA from PVA–DNA matrices was investigated.[73]

The breakthrough innovation of using DNA hydrogel as electrolytes made it possible for researchers to develop a novel electrolyte composition of PANI/CNTs/PAH/Dgel for supercapacitor was shown in Fig. 4a.[32] This study showcased a specific capacitance of 146.4 F g^{-1}, a power density of 23.3 kW kg^{-1} and an energy density of 13.0 Wh kg^{-1}. Apart from this, DNA hydrogels showed advantageous development in the field of light harvesting physical devices as well as in the development of photonic devices. In this context researchers developed a multilayer structure by mixing PNPs–DNA which displayed an enhanced dielectric constant within low-frequency range.[74]

A recent report has described PEM-Dgel supercapacitors with multilayer polyelectrolytes, optimized for high capacitance and stability in bioenvironments, as shown in Fig. 4b. The electrochemical performance of PEM-Dgel supercapacitors was evaluated by varying the number of polyelectrolyte multilayers (PEM*n*-Dgel, n = 1–5) deposited on the DNA-based gel. Increasing the number of PEMs improved the specific capacitance by forming multiple polyelectrolyte double layers, which reduced electrochemical resistance. The capacitance increased almost

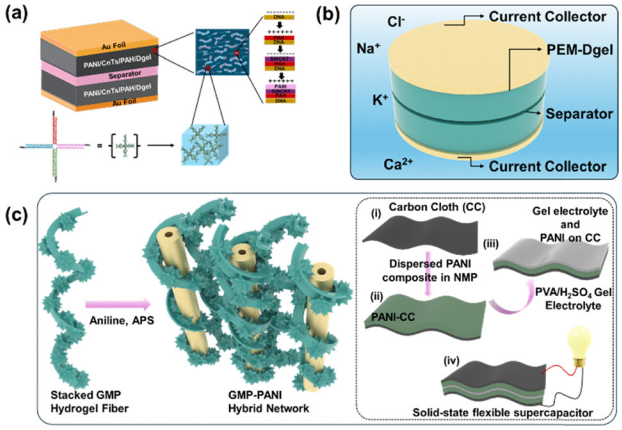

Fig. 4 (a) Schematic illustration of the experimental procedures adopted in this study and assembly of a Dgel-based supercapacitor. (b) Schematic representation of the PEM-Dgel supercapacitor. (c) Schematic representation of GMP-PANI hybrid networks and guanosine 5′-monophosphate and fabrication of a flexible supercapacitor.

linearly up to three layers and reached a saturation value (~57 F g^{-1} at 25 mV s^{-1}) beyond that, as additional layers contributed little net gain due to the increased mass. Coating with pseudocapacitive Mn_3O_4 further enhanced the capacitance to 99.5 F g^{-1} through synergistic redox reactions. The PEM-Dgel devices also showed excellent cycling stability, retaining over 88% of capacitance after 1000 cycles in H_2SO_4, and maintained high performance in various biofluids, including PBS, artificial urine, and cell culture medium. These results demonstrate that DNA-based gels with multilayer polyelectrolytes can deliver high capacitance, long-term stability, and reliable performance in bioenvironments, highlighting their potential for bio-integrated energy storage devices.[69]

The potential of GMP-based gels as solid polymer electrolytes in energy storage devices has been demonstrated in Fig. 4c. A study has highlighted the potential of guanosine monophosphate (GMP)-derived self-assembled gels in forming conductive hybrid networks with polyaniline (PANI). In this system, strong ionic interactions between the phosphate groups of GMP and the aminic/iminic nitrogen atoms of PANI chains give rise to a mechanically robust hybrid gel. Rheological and morphological analyses confirmed the uniform incorporation of polyaniline fibers within the GMP matrix, without macroscopic phase separation, thereby ensuring structural integrity. This hybridization strategy not only enhanced the mechanical strength compared to pristine GMP gels but also imparted exceptional electrochemical properties. The GMP–PANI hybrid demonstrated a high specific capacitance (405 F g^{-1} at 0.5 A g^{-1}) in a three-electrode configuration, as well as excellent cycling stability, retaining ~87% capacitance after 20 000 cycles in a solid-state symmetric supercapacitor. Furthermore, a tandem arrangement of five devices successfully powered multiple LED bulbs of different colors, illustrating the practical viability of this bio-inspired hybrid system. These findings exemplify how DNA-inspired gel electrolytes and their derivatives can be synergistically combined with

conducting polymers to achieve biocompatible, flexible, and high-performance energy storage devices.[75]

The gel electrolyte applications described above highlight DNA hydrogels' versatility across multiple supercapacitor components from electrode templates to active electrolyte matrices. This multifunctional capability extends beyond conventional energy storage to emerging applications where biocompatibility and environmental stability are critical. The programmable nature of DNA sequences and their compatibility with biological systems create unique opportunities for specialized energy storage applications, particularly in bioelectrochemical devices and biofuel cells.

4.4. Role in biofuel cells and bioelectrocatalytic applications

The biocompatible nature of DNA hydrogels opens unique opportunities in bioelectrochemical energy systems, where traditional synthetic materials may interfere with biological processes or cause toxicity concerns. Unlike conventional supercapacitors that rely purely on physical or chemical charge storage, bioelectrocatalytic systems harness the efficiency of biological catalysts and enzymes or whole microorganisms to drive energy conversion processes. In these hybrid systems, DNA hydrogels serve dual roles as biocompatible electrolyte matrices and as programmable scaffolds for organizing biological components, enabling the development of living energy systems that combine the selectivity of biological catalysis with the reliability of electrochemical energy storage.

DNA origami nanostructures into microbial fuel cells (MFCs) to boost electron transfer processes. One such strategy involved anchoring methylene blue (MB), a redox-active mediator, onto DNA origami and applying this composite to carbon felt electrodes in an *E. coli*-driven MFC. This design improved the mediator's loading capacity, supported bacterial attachment, and accelerated electron movement at the anode.[76] The modified system maintained stable performance across repeated cycles without requiring a fresh nutrient supply, emphasizing the promise of DNA-based nanostructures as biocompatible and efficient platforms for enhancing bioelectrocatalytic energy systems.

5. Advantages of DNA hydrogels for energy storage applications

DNA hydrogel's unique physicochemical characteristics make them attractive candidates for use in next-generation energy storage systems. These hydrogels, which are made of hybrid networks of DNA and other biocompatible polymers or cross-linked DNA strands, have a flexible three-dimensional (3D) structure that facilitates effective ion transport, high water retention, and remarkable ionic conductivity. In contrast to traditional hydrogel electrolytes, DNA hydrogels have special benefits such as variable mechanical strength, molecular programmability by sequence-specific hybridization, and inherent biocompatibility. In the context of sustainable materials development, their renewable origin and ecologically benign

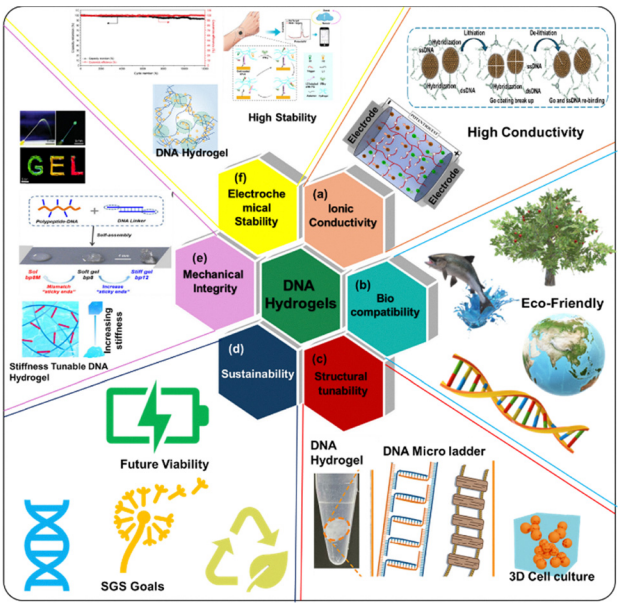

Fig. 5 Multifunctional properties and potential applications of DNA hydrogels in advanced materials and energy systems. (a) Ionic conductivity[60,78] adapted from ref. 78 with permission from American Chemical Society, Copyright 2018, (b) biocompatibility, (c) structural tunability,[79] adapted from ref. 79, Hanif *et al.*, *APL Bioengineering*, 2023, CC BY 4.0. (d) sustainability, (e) mechanical integrity[80–82] adapted from ref. 80 with permission from John Wiley and Sons, Copyright 2022, adapted from ref. 81 with permission from John Wiley and Sons, Copyright 2017, adapted from ref. 82 with permission from John Wiley and Sons, Copyright 2024, and (f) electrochemical stability,[71] adapted from ref. 71 with permission from John Wiley and Sons, Copyright 2022. The tunable molecular architecture of DNA and its ability to self-assemble enable the design of hydrogels with application-specific functionalities, positioning them as a versatile platform for next-generation energy storage systems.

character further increase their attractiveness. DNA hydrogels can function as efficient solid or quasi-solid electrolytes in energy storage devices like batteries and supercapacitors. Without the use of hazardous or volatile solvents, their negatively charged phosphate backbones improve ionic conductivity by facilitating cation migration (*e.g.*, Li^+, Na^+, Zn^{2+}).[77] Additionally, DNA's programmable nature allows for fine structural control at the nanoscale, which may be used to incorporate functional components like conductive nanoparticles or redox-active species and customize electrochemical performance. These characteristics make DNA hydrogels an ideal foundation for creating safe, effective, and long-lasting energy storage solutions (Fig. 5).

5.1. High ionic conductivity

Despite the unique chemical structure of DNA, DNA hydrogels exhibit remarkably high ionic conductivity, a crucial characteristic for energy storage devices. The porous nature of the hydrogel enhances this feature by allowing ions to flow easily, thereby lowering internal resistance and increasing charge–discharge efficiency. In contrast to many conventional hydrogel electrolytes, a DNA-based hybrid hydrogel, such as one made with sodium alginate, has an ionic conductivity of

73.27 mS cm^{-1}. For supercapacitors to achieve high power density and batteries to be able to charge quickly, rapid ion diffusion is made possible by this high conductivity. DNA is a reliable option for energy storage applications because of its capacity to coordinate with ions, which guarantees consistent electrolyte performance under a range of electrochemical circumstances. The practical uses of DNA hydrogels in flexible and wearable electronics are further enhanced by their excellent ionic conductivity. DNA-based hydrogels have shown that strong ionic conductivity in supercapacitors can result in enhanced specific capacitance and energy density, with specific capacitances of up to 420 F g^{-1} at 0.5 A g^{-1}.[77] This performance is explained by the hydrogel's capacity to support both faradaic and non-faradaic charge storage processes, which effectively move ions to electrode surfaces. Furthermore, ion mobility is improved by the hydrogel's water-rich environment in comparison to solid-state electrolytes, which lowers energy losses during charge–discharge cycles. DNA hydrogels naturally have this feature because of their biological nature, unlike synthetic polymer hydrogels which can need further doping to get similar conductivity. However, challenges such as maintaining conductivity under extreme temperatures or long-term cycling need further exploration to optimize their performance in real-world energy storage systems.[69]

5.2 Biocompatibility and biodegradability

DNA hydrogels are safe and non-toxic for use in wearable or implanted energy storage devices because they are extremely biocompatible and made from natural sources, such as salmon sperm or other biological DNA. Due to DNA's function as a basic biological molecule, they are biocompatible, meaning that it will not react negatively when it comes into contact with human tissues.[61,69] For next-generation devices, such as bio-integrated supercapacitors or batteries used in medical implants, where materials must live with biological systems without generating toxicity or inflammation, this characteristic is very beneficial. DNA hydrogels are made even more suitable for these kinds of applications by their ability to be integrated with other biocompatible polymers, including chitosan or alginate, which creates a stable and secure electrolyte matrix.[61,83] The increasing need for physiologically and ecologically acceptable materials in energy storage systems is met by biocompatibility. The biodegradability of DNA hydrogels, which tackles the environmental issues caused by synthetic materials in energy storage devices that do not decompose, is equally significant. The natural breakdown of DNA hydrogels into harmless components lowers electrical waste and promotes environmentally friendly production methods. For example, unlike petroleum-based polymers like polyvinyl alcohol (PVA), which can linger in the environment, DNA derived from industrial wastes like fish sperm can be completely broken down by natural processes.[83] As the worldwide push for green technology heats up and rules favor materials with the least amount of ecological damage, this biodegradability becomes even more important.[84] However, because early deterioration might impair performance, the biodegradation process needs to be carefully regulated to maintain the device's lifetime during operating life. DNA hydrogels are a viable option for environmentally friendly energy storage solutions because of advancements in crosslinking methods, such as mixing DNA with polysaccharides, which assist balance durability and biodegradability.

5.3 Structural tunability and programmability

DNA hydrogels have structural tunability due to sequence-specific base-pairing, which allows for fine control over the hydrogel's architecture at the molecular level. This programmability allows for the creation of hydrogels with controlled porosity, crosslink density, and mechanical characteristics, hence enhancing their performance as electrolytes in energy storage devices. DNA strands, for example, may be designed to build interconnected porosity networks that enhance ion transport and electrolyte–electrode interactions, increasing supercapacitor and battery efficiency.[69] Additionally, the negative charges on DNA hydrogels provide an ideal substrate for assembling functional materials through electrostatic interactions, enabling the integration of conductive polymers or nanoparticles to further tune electrochemical properties.[79,85] For instance, DNA hydrogels have been used as templates for the assembly of carbon nanotubes (CNTs) and polyaniline, resulting in hybrid supercapacitor electrodes with enhanced specific capacitance and cycling stability. The DNA hydrogel's structure allows for the systematic deposition of conductive layers, and its mechanical and electrochemical properties can be modulated by varying the DNA building blocks or the number of deposition cycles.[32] Moreover, DNA hydrogels can be hybridized with other polymers or nanomaterials (such as graphene, alginate, or synthetic polyelectrolytes) to further customize their flexibility, surface area, and ionic conductivity, making them suitable for flexible and wearable energy storage devices.[61,83]

The programmability of DNA hydrogels also enables dynamic responses to environmental stimuli, such as pH or ionic strength, which can be leveraged to create smart, self-regulating energy storage systems.[77] This level of structural control is unmatched by most synthetic hydrogels, which typically rely on less precise chemical modifications. Unlike conventional hydrogels made from natural or synthetic polymers, DNA hydrogels leverage the addressability and sequence specificity of DNA to precisely control structure, mechanical properties, and stimulus responsiveness at both nano- and macroscopic scales.[86,87] DNA hydrogels represent a versatile platform for engineering biomaterials with precisely tunable mechanical, biochemical, and responsive properties. Their programmability at the molecular level, combined with emerging hybrid and nanocomposite strategies, opens new avenues for advanced tissue engineering, smart drug delivery, and integrated biomedical devices.[88]

DNA hydrogels are broadly categorized into two types based on their composition, pure DNA hydrogels, and hybrid DNA hydrogels. The pure DNA hydrogels, comprised entirely of DNA oligonucleotides, forming a network through physical

entanglement, enzymatic ligation, or sequence-directed self-assembly.[87,88]

Whereas hybrid DNA hydrogels integrate DNA with synthetic polymers or natural polymers, using DNA as dynamic crosslinkers or functional units. These hybrids combine the mechanical robustness of polymers with the programmability and responsiveness of DNA. Linear dsDNA, Y-, X-, T-, pentamer, and hexamer junctions are common, with branched structures offering greater valency and network density. Enzymatically assembled DNA ligase or polymerase hydrogels can covalently link DNA building blocks for permanent networks or use strand displacement for reversible gelation.[86,87,89] The mechanical properties as pure DNA hydrogels typically exhibit low stiffness, though this can be tuned by altering linker flexibility, junction valency, and DNA concentration, whereas hybrid DNA hydrogels can offer precise customization of structure and mechanical properties, biodegradability, self-healing, and other additional functionalities.

DNA hydrogels can be employed in stimulus responsive systems as their stimulus-responsiveness is high due to its unique properties, it can response to variety of stimuli, such as pH, temperature, light, biomolecule sensing, and enzymes.[90–95] With integration with nanoparticles and functionalization which is an important property of the DNA hydrogel programmability, as they can be used in nanoparticle-crosslinked hydrogels, where DNA is functionalized with nanoparticles such as CNTs, graphene, gold which serve as crosslinkers, which introduce new mechanical, optical, magnetic and catalytic properties to the hydrogel network. With their unique structural and functional characteristics, DNA hydrogels serve as a versatile foundation for developing advanced, multifunctional electrolytes and electrodes tailored to next-generation energy storage needs.

5.4 Sustainability

DNA hydrogels are at the forefront of sustainable material innovation for energy storage, offering a unique combination of renewable sourcing, green manufacturing, and eco-friendly end-of-life characteristics. Their sustainability begins with material sourcing: DNA can be extracted from abundant, renewable, and often waste-derived sources such as fish sperm, agricultural byproducts, or microbial biomass. This not only diverts biological waste from landfills but also creates a high-value feedstock for advanced energy applications, directly supporting circular economy principles and the United Nations Sustainable Development Goals (SDGs).[35,77] The extraction and processing of DNA for hydrogel synthesis are typically water-based and do not require harsh chemicals or high energy input, contrasting sharply with the synthesis of petroleum-based polymers. For example, recent advances have shown that microbial systems can be engineered to produce DNA hydrogels in a self-sustaining and scalable manner, further reducing the environmental footprint of production and enabling continuous, low-impact material supply.[96] These strategies are becoming more important as the world's requirement for energy storage materials is expected to grow significantly, requiring millions of tons per year in the future.

DNA hydrogels also excel in lifecycle sustainability. Their inherent biodegradability ensures that, after serving as electrolytes or structural matrices in supercapacitors and batteries, they can be broken down by natural enzymes and microorganisms into harmless nucleotides and other small molecules. This rapid degradation stands in stark contrast to synthetic hydrogels like polyvinyl alcohol (PVA) or polyacrylamide, which persist for decades and contribute to environmental pollution.[35,97] Moreover, the degradation products of DNA hydrogels are nontoxic, reducing the risk of ecological harm at end-of-life disposal.[98] The environmental advantages of DNA hydrogels extend to their manufacturing and operational phases. Green chemistry principles are often employed in their synthesis, using aqueous-based crosslinking and avoiding toxic solvents or byproducts. This results in lower energy consumption and a reduced carbon footprint compared to traditional polymer processing.[97] Furthermore, DNA hydrogels can be hybridized with other bio-based materials, such as cellulose or lignin, to further enhance their mechanical, electrochemical, and environmental performance. For instance, cellulose-DNA hybrid hydrogels have demonstrated both high mechanical strength and cost-effectiveness, with production costs significantly lower than many conventional materials, making them attractive for large-scale deployment in energy storage and environmental remediation.[98,99] The scalability and economic feasibility of DNA hydrogels have also improved. Recent techno-economic analyses indicate that the plant-gate cost of synthesizing DNA-based hydrogels can be orders of magnitude lower than that of traditional immobilized enzyme systems, especially when using waste-derived DNA and green processing methods.[98] This cost advantage, combined with their recyclability and high performance, positions DNA hydrogels as a leading candidate for sustainable energy storage solutions. Despite these advances, challenges remain. Scaling up DNA extraction and hydrogel fabrication to industrial levels requires further optimization to ensure consistency, cost-effectiveness, and supply chain resilience. Collaborative efforts between academia, industry, and biotechnology sectors are essential to develop robust, large-scale production methods and to integrate DNA hydrogels into commercial energy storage devices.[96] Additionally, continued research into hybridization strategies, lifecycle analysis, and end-of-life management will help maximize the sustainability benefits of DNA hydrogels.

5.5 Mechanical integrity

DNA hydrogels have emerged as a next-generation material for energy storage devices, offering a unique combination of mechanical integrity, tunable structure, and high electrochemical performance. Their mechanical excellence is rooted in the robust crosslinking between DNA strands and other polymers, such as polysaccharides (*e.g.*, agarose, alginate, lignin), which together form a stable, elastic, and highly porous network.[77] This hybrid network not only withstands significant deformation, including stretching, bending, and compression,

but also maintains its structural integrity and ionic conductivity under repeated mechanical and electrochemical cycling, which is critical for flexible and wearable supercapacitors and batteries.[61] A recent landmark study demonstrated that bio species-derived genomic DNA hybrid gel electrolytes, fabricated by combining DNA with polysaccharides, achieved outstanding mechanical properties: a mechanical strength of 6.98 MPa and elongation at a break of 997.42%.[77] These values far surpass those of many traditional hydrogels, such as gelatin-based gels, which often lack sufficient strength for demanding energy storage applications. The DNA hybrid hydrogel's stable polymer network, high porosity, and interconnected pore structure ensure efficient ion transport and rapid charge/discharge cycles, even under physical stress. The adaptability of DNA hydrogels is another key advantage. Mechanical properties can be precisely tuned by adjusting the DNA concentration, crosslinking density, or by hybridizing with functional materials like graphene oxide.[61,83] Such modifications further enhance toughness, elasticity, and electrochemical stability, making these hydrogels suitable for high-performance, portable, and flexible devices. The water-rich nature of DNA hydrogels also contributes to their flexibility and prevents brittleness during repeated mechanical cycles, a common challenge for conventional hydrogels. From a materials science perspective, the synergy between DNA's negatively charged phosphate backbone and the hydroxyl-rich polysaccharides creates a 3D porous polymer network with dynamic conductive ion channels. This architecture not only supports rapid ion migration but also promotes water retention and swelling, which are vital for maintaining high ionic conductivity and mechanical robustness over extended use. Additionally, the integration of DNA with other biopolymers lowers material costs and enhances the overall sustainability of the hydrogel, as both components can be sourced from renewable or waste-derived feedstocks.[83,100] Despite these advances, challenges remain-especially regarding long-term mechanical stability under harsh electrochemical conditions, such as high voltages or extreme temperatures. Ongoing research is focused on optimizing composite formulations and crosslinking strategies to address these issues, ensuring that DNA hydrogels can consistently deliver high performance in next-generation energy storage systems.

5.6 Electrical conductance of DNA molecules

Beyond their structural programmability, mechanical integrity and biocompatibility, DNA molecules exhibit intriguing electrical conductance properties that are highly relevant for their prospective role in energy storage systems.[101,102] The electrical conductance of DNA has become a significant area of research, revealing the molecule's ability to transport charge over long distances through its π-stacked base pairs. This property is highly dependent on a variety of factors, including sequence, conformation, and environmental conditions.[103,104] Extensive experimental and computational efforts have sought to unravel the mechanisms underlying electron and hole migration along the π-stacked base pairs.[105] The transport of charge through DNA is generally understood to occur through two primary mechanisms, Coherent Super exchange (Tunnelling), Incoherent Hopping and the Intermediate Regime. Tunnelling is the concept that, at short distances, electrons or holes can tunnel directly from a donor to an acceptor through the DNA bridge. This process is highly dependent on the electronic coupling between the donor, acceptor, and the intervening DNA bases, and its efficiency decreases exponentially with distance.[52] Whereas, Incoherent Hopping over longer distances, a multi-step hopping mechanism dominates. In this model, charge carriers (typically holes) move between discrete, localized sites along the DNA strand. Guanine bases, having the lowest ionization potential, often serve as these hopping sites.[106] Recent evidence points to an intermediate regime where coherent and incoherent processes coexist. This is described as a partially coherent hopping mechanism, where charge moves between delocalized domains spanning 2–3 base pairs.[107] Several key factors modulate the electrical conductance of DNA, such as sequence dependence, where the sequence of nucleobases significantly impacts conductance, and guanine-rich sequences are more conductive than those with alternating G–C pairs or A–T-rich regions. This is due to the stronger electronic coupling and lower ionization potential of guanine, facilitating hole transport.[107] The integrity of the base-pair stack is paramount. A single base mismatch can increase the resistance of a DNA duplex by over 300-fold. Similarly, structural disruptions caused by mechanical stretching can lead to an abrupt decrease in conductance due to the breaking of hydrogen bonds at the ends of the duplex.[106,108] The molecular backbone and the chemical linkers used to connect DNA to electrodes also affect conductance. Studies comparing DNA with peptide nucleic acids (PNA), which have a different backbone, show that the more flexible aeg-PNA backbone leads to a 10-fold higher conductance than DNA or the more rigid γ-PNA. The type of linker used to attach the DNA to electrodes can also increase the overall conductance by an order of magnitude by improving charge injection into the base stack.[109] The conductance of DNA can be modulated by the interaction with other molecules. For instance, intercalating metal complexes can enhance charge transport, while the adsorption of DNA onto metal oxides like Mn_3O_4 is being explored for biosensor and energy storage applications.[103,110] For energy storage applications, the significance lies not in DNA serving as a bulk conductor, but rather as a bio-nanoionics scaffold where localized electronic interactions may synergize with ionic conductivity. Understanding and harnessing DNA conductance thus broadens the scope of DNA hydrogels as they may serve not only as ion-conductive matrices but also as platforms where electron–ion interplay can be tailored at the molecular scale. Beyond fundamental insights, the ability of DNA to support tunable charge transport provides opportunities for enhancing electrode–electrolyte interfacial kinetics, hybrid electrode design, and sustainable multifunctional scaffolds in next-generation batteries and supercapacitors

5.7 Electrochemical stability

DNA hydrogels demonstrate remarkable electrochemical stability, enabling long-term performance in energy storage devices

such as supercapacitors and batteries. This stability is primarily attributed to the robust chemical structure of DNA, which resists degradation under repeated charge–discharge cycles and maintains a stable hydrogel matrix. For example, bio species-derived genomic DNA hybrid gel electrolytes have enabled supercapacitors to achieve a capacitance retention rate of 93.8% after approximately 200 000 cycles, along with high ionic conductivity and stable energy and power densities performance that sets a new benchmark among hydrogel-based supercapacitors.[77,111] The hydrogel's ability to maintain a strong electrolyte–electrode interface minimizes side reactions such as electrolyte decomposition, ensuring efficient ion transport and consistent device performance over extended operation. The electrochemical stability of DNA hydrogels is further enhanced by their compatibility with various electrode materials, including carbon-based and metal oxide electrodes, which support both electric double-layer capacitance (EDLC) and pseudocapacitance mechanisms. Integrating DNA with other functional materials, such as graphene or ionic liquids, can further improve the hydrogel's resilience and performance under diverse operating conditions, including high voltages and mechanical deformation. For instance, DNA–carbon nanotubes composite hydrogels have demonstrated stable charge storage and mechanical robustness, making them attractive for flexible and high-energy-density energy storage systems.[32] Moreover, the interconnected porous structure of DNA hybrid hydrogels, along with abundant functional groups from both DNA and polysaccharide components, allows for rapid ion migration and consistent capacitance over extended cycling. The water retention and swelling properties of these hydrogels also contribute to their electrochemical stability by maintaining ionic conductivity and structural integrity during repeated use.[112] DNA hydrogels have also shown excellent performance in physiological and biofluid environments, maintaining cycling stability and charge–discharge efficiency even under challenging conditions.[69] While DNA hydrogels have shown excellent performance under standard conditions, ongoing research is focused on optimizing their stability in extreme pH or temperature environments to ensure viability across a wider range of energy storage applications[61,112] (Table 1).

6. The challenges and limitations of DNA hydrogels

DNA hydrogels are attracting attention as a promising material for energy storage systems due to their distinctive characteristics, like biocompatibility and structural adaptability. Still, their future hasn't been realized yet. Numerous challenges hold back their extensive adoption, including concerns about scalability, long-term stability, and cost-effectiveness.

6.1. Scalability challenges

Another challenge that comes with DNA hydrogels is boosting their manufacturing. While they perform well in lab settings, turning these materials into something that can be made on an

Table 1 Property comparison between DNA hydrogels and traditional polymer hydrogel materials in various applications

Property	DNA hydrogels	Conventional hydrogels	Advantage	Ref.
Ionic conductivity (mS cm^{-1})	73.27	1–40	Enhanced by DNA's dense anionic backbone and porosity	79, 113–118
Specific capacitance (F g^{-1})	425	Typically, 50–350	DNA hydrogel supports better capacitance *via* faster ion transport	79, 119–124
Cycling stability (% retention)	>90% over 100 000 cycles	Moderate to lower retention over higher cycles	DNA hydrogels dynamic crosslinking aids longevity	125–130
Mechanical stretchability (%)	>700% elongation	Typically, 100–500%	High programmability allows precise tunability of mechanical properties	131–137
Young's modulus (MPa)	0.1–5 MPa (tunable)	0.1–5 MPa	DNA sequence and density can help control the thickness and improve the mechanical properties	138–144
Thermal stability (°C)	Up to ~100 °C	Variable	DNA helices are more thermally stable than some polymers	142, 145, 146
Water retention (%)	>90%	70–95%	DNA's phosphate groups bind water strongly	147–149
Biodegradability	Fully biodegradable	Variable, depends on the polymer	DNA hydrogels are highly eco-friendly	150, 151
Biocompatibility	High	Good to excellent, yet can be harmful	DNA hydrogels are widely used in biomedical devices	150, 151
Voltage	~2–2.5 V	~2–2.5 V	DNA requires conductive additives for electrodes	152–155
Synthesis complexity	Moderate to high, depending on the source and processing	Established, generally moderate	DNA cost and handling still challenge scalability	
Cost of raw materials	Higher, but reducing with natural waste sources	Lower	Economic barriers remain for DNA	
Environmental impact	Low carbon footprint, biodegradable	Variable	DNA hydrogels are more sustainable	
Surface functionalization	Highly tunable *via* sequence design and chemistry	Moderate-high	DNA programmable binding sites promote functionalization, such as π–π interactions	
Compatibility with nanomaterials	Excellent binding properties	Variable	DNA used in scaffolds, templates, and binders	

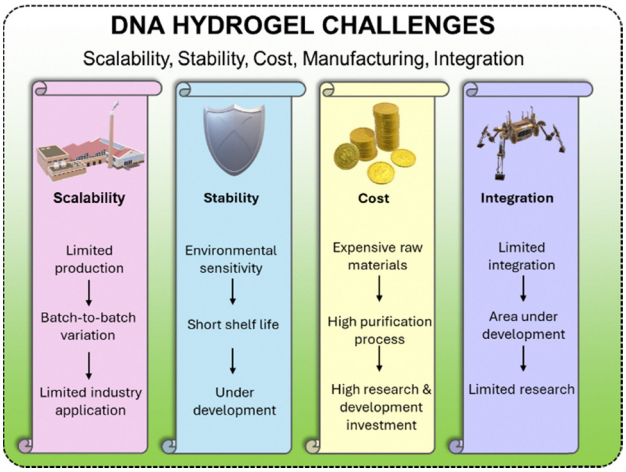

Fig. 6 Challenges and limitations of DNA hydrogels.

industrial scale has proven difficult. The main roadblocks are the complicated synthesis process and the high cost of DNA materials. So far, large-scale production of DNA hydrogels has not been achieved, and the potential for integrating their multiple functions together in one system hasn't been fully explored. On top of that, the high costs and challenges in mass production remain key obstacles to making DNA hydrogels practical for real-world applications.[156]

To reduce costs and cut down on this process, researchers have modified DNA from more readily available sources, such as salmon fish sperm DNA. This choice is much more economical than using fully fabricated DNA. While these natural sources can contribute large amounts of material at a cheaper price, they still need to develop purification and standardization for consistency. However, ensuring quality control and reproducibility continues to limit the ability to scale up production for practical energy storage applications (Fig. 6).

6.2 Stability challenges

Environmental factors like pH can demand the steadiness of DNA hydrogels in energy storage applications,[157] temperature, and UV[158] susceptibility. To deal with this, researchers have created various strategies to boost the mechanical properties and stability of DNA hydrogels, which include varying mechanical properties and utilizing hybrid materials.

A few material engineering strategies have been introduced to overcome this unpredictability. One perspective implies chemical crosslinking or the formation of double-network hydrogels. Moreover, the development of double-network hydrogels, which consist of two interpenetrating polymer networks, improves the mechanical strength and ability of hydrogels. These structures can better resist mechanical stress and maintain their integrity over extended periods, making them more suitable for energy storage applications.[159]

6.3 Cost limitations

The overpricing of synthetic DNA is a substantial hurdle to the universal adoption of DNA hydrogels in energy storage. The migration of DNA with conductive filters, such as carbon nanotubes or metal nanoparticles, to a greater extent, increases the fabrication costs and initiates variability in performance. The commonly used 1 : 1 identification strategy in DNA-based systems repeatedly requires numerous responsive elements, rapidly increasing design complexity, and material use in DNA hydrogels.[160]

The material expenses of DNA hydrogels also require a specialized synthesis infrastructure, including temperature systems, nucleic acid purification tools, and possibly enzyme-mediated reactions, all of which contribute to elevated production costs. While hybridization and self-modular assembly reduce labor intensity, they do not yet achieve the cost efficiency required for commercial energy applications. Efforts to decrease cost by using new tools for cost-effective DNA synthesis[161] include sourcing DNA from natural materials, such as salmon sperm DNA, DNA extracted from food waste,[162] Chicken blood,[163] flowers,[164] and plants,[165] *etc.*, which can lower the overall cost of DNA with a synergistic effect[77] (Table 2).

Recent efforts to reduce the cost and improve the commercial viability of DNA hydrogels for energy storage applications have made remarkable progress through several innovative strategies.

Central to these advances is the focus on utilizing biowaste-derived DNA sources, such as salmon sperm and other fishery byproducts, which significantly lower raw material costs compared to expensive synthetic oligonucleotides. This approach not only reduces expenses to below $10 per g but also aligns sustainable, circular economic principles by valorizing waste streams.

Complementing this, biotechnological production methods are being developed to synthesize DNA at scale using microbial fermentation or enzymatic assembly, targeting kilogram-scale continuous manufacturing. These methods offer the potential for customizable sequences while enhancing yield and purity, thus bridging the gap between laboratory feasibility and industrial scalability.

Additionally, combining DNA with low-cost biopolymers like agarose, alginate, or lignin results in hybrid hydrogels that maintain desirable electrochemical and mechanical properties while significantly lowering the overall material cost. These composites benefit from synergistic effects, improving ionic conductivity, mechanical robustness, and cycle stability beyond what pristine DNA hydrogels achieve.

Process innovations include developing milder, scalable purification and functionalization protocols that minimize reagent use and disposal challenges, thereby reducing production cost and environmental footprint. Moreover, device-level innovations such as separator-free configurations utilizing DNA hydrogels simplify architecture and manufacturing, further driving down costs and improving device reliability.

Together, these developments highlight a dynamic research landscape driving DNA hydrogel from expensive, niche laboratory materials toward competitively priced, sustainable solutions poised for commercial energy storage applications.

Table 2 Quantitative challenges comparison between DNA hydrogels and traditional polymer hydrogel materials

Challenge	Description	Quantitative data/examples	Comparative insight	Ref.
Cost	High cost of raw materials and purification	Synthetic DNA: >$1000 per g high purity; salmon sperm DNA: <$10 per g Research & development expenses remain high	Conventional polymer electrolytes: <$100 per kg DNA hydrogels face substantially higher upfront costs	
Scalability	Limited industrial-scale synthesis Batch-to-batch variability	Current production scale: gram/day; target: kg-scale bioreactors Variability in DNA extraction, batch purity affects performance	Synthetic polymer mass production offers high reproducibility High programmability allows precise tunability of mechanical properties	166
Stability	Environmental sensitivity and chemical degradation Shelf-life limitations	DNA hydrogels: capacitance retention >90% after 10 000 cycles DNA hydrogels, Shelf life is currently under improvement	Commercial supercapacitors show >95% retention over 100 000 cycles Limited shelf life	167
Integration	Challenges interfacing with other device components	Limited commercialisation integration with flexible substrates is still under research	Conventional electrodes/electrolytes have mature integration techniques	
Functional performance	Ionic conductivity, charge storage abilities	Good ionic conductivity, energy storage abilities	Commercial electrolytes generally offer higher conductivities but less biocompatibility	
Mechanical properties	Modulus and durability under mechanical stress	DNA hydrogels can be engineered with tunable properties	Synthetic polymers show a wide modulus range but often lack biodegradability	
Environmental impact	Sustainability and biodegradability	DNA sourced from biowaste offers significant sustainability advantages over petroleum-based polymers	Few synthetic polymers are mostly non-biodegradable	168

Continued optimisation of these strategies will be crucial to unlocking widespread adoption and realising the full technological and environmental benefits of DNA-based energy devices.

7. Future perspectives

7.1 Transformative research directions

The future of DNA hydrogel technology will be to re-engineer the role of biological materials in electrochemical devices. Rather than passive binders or structural matrices, next-generation DNA hydrogels could be active ionic conductors, charge transporters, or even energy-harvesting interfaces. Although synthetic DNA and DNA origami have been widely used in developing programmable hydrogels, future advancements are expected to come from naturally occurring genomic DNA. Sources such as salmon sperm DNA, DNA extracted from chicken blood, and other genomic DNA derived from biological waste offer promising alternatives for constructing hydrogels that are not only cost-effective but also environmentally sustainable. These naturally sourced DNAs possess unique features such as structural diversity, tunable lengths, and rich biochemical content that can be tailored to improve the structural, mechanical, and electrochemical properties of the hydrogels for energy applications.

Future studies should aim to modify natural genomic DNA through strategies such as controlled depolymerization, chemical crosslinking, and integration with conductive or redox-active materials. These approaches can help preserve the inherent biological structure of DNA while significantly improving its electrical conductivity, ionic transport, and mechanical strength. Transitioning from fully synthetic sequences to biologically derived DNA sources open the door to developing a new generation of versatile, multifunctional, and structurally diverse hydrogels suitable for advanced energy storage technologies.

7.2 Integration with digital and smart technologies

Beyond the scope of material development, integrating DNA hydrogels with intelligent technologies opens novel pathways for innovation. In future energy systems, smart batteries and supercapacitors could incorporate DNA-based materials that offer real-time feedback, enabling AI-driven systems to dynamically optimize performance or identify degradation at an early stage. Additionally, DNA itself could act as a molecular memory unit, capable of recording operational events or environmental changes, which can later be retrieved through sequencing.

Moreover, combining these systems with IoT frameworks makes DNA hydrogel-powered devices at the core of autonomous, self-healing energy networks. Especially, suited for challenging environments such as deep-sea monitoring, remote sensing, or even space applications. In such scenarios, one could imagine DNA-driven sensors capable of autonomously collecting and transmitting environmental information, repairing structural damage, and interacting wirelessly with AI-guided control units all functioning independently, without the need for human oversight.

7.3 Driving sustainable innovation

As climate concerns deepen, the use of waste derived DNA from food, agriculture, and biomedical industries represents a transformative step toward truly sustainable energy storage. Unlike synthetic polymers or inorganic materials, genomic DNA sourced from industrial byproducts or natural ecosystems is renewable, biodegradable, and often available on a large scale.

Developing low energy extraction and purification techniques, combined with green synthesis pathways, could make DNA hydrogels not just sustainable, but carbon negative.

Further, researchers can investigate the biodegradability and soil-recyclability of these DNA hydrogels, envisioning zero-waste energy storage systems that degrade harmlessly or even enrich soil post-disposal. Coupling this with microbial biosynthesis or cell-free DNA production platforms may ultimately lead to decentralized, on-demand manufacturing of DNA-based energy materials. Additionally, the end-of-life strategy for such materials could be radically different, employing enzymatic degradation, composting, or recycling through biological cascades. Moreover, aligning DNA hydrogel development with global frameworks like the EU Green Deal or Net Zero 2050 strategies will require interdisciplinary metrics not just electrochemical performance, but also bioethics, environmental justice, and ecosystem compatibility.

7.4 Towards intelligent, living energy systems

In the future, natural DNA hydrogels could be combined with living cells, bioelectronic components, and AI-based control systems to create smart energy devices that can sense, respond, and adapt to their surroundings. Instead of just acting as support material or templating, DNA could be used for its unique features, like genetic memory, reactive sequences, or even the ability to control biological functions. This idea fits with the growing interest in living materials, where energy systems are designed not only to store energy, but also to communicate, grow, or repair themselves based on changing conditions.

8. Conclusions

DNA hydrogels, created by assembling DNA macromolecules are gaining attention as eco-friendly and renewable materials for energy storage. These hydrogels capitalize on DNA's natural benefits biodegradability, widespread availability, and affordability while providing exceptional structural flexibility through their 3D network design. The DNA framework, packed with functional groups and ion-attracting sites, enables seamless interaction with various electroactive components, making them ideal for use in systems like lithium-ion batteries, supercapacitors, and fuel cells. Their capacity to hold water, facilitate ion movement, and allow molecular customization drives improved performance across diverse energy storage platforms. As research progresses, DNA hydrogels are set to become key materials in developing future sustainable, high-efficiency energy storage solutions.

Author contributions

Samanth Kokkiligadda: conceptualization, investigation, data curation, writing – original draft. Surya Kiran Ampasala: conceptualisation, data curation. Soong Ho Um: supervision, resources, funding acquisition, writing – review & editing.

Conflicts of interest

There are no conflicts to declare.

Data availability

This review article does not present any original experimental data. No new research findings, datasets, software, or code were generated or analysed during the preparation of this manuscript. All data and information discussed herein, including those shown in figures and tables, are sourced from previously published literature. These sources are properly cited throughout the text and fully listed in the reference section. Where relevant, specific dataset identifiers (*e.g.*, DOIs) are included in figure captions, table notes, or within the main discussion. Any computational models or parameters mentioned are described in detail in the corresponding cited publications.

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