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Bio-Memristors: The Convergence of Biological Computation and Artificial Cognition

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Abstract

The ever-growing demands of AI and data-driven computing expose the inefficiencies of conventional CMOS, HPC, and AI workloads (GPUs & TPUs), which suffer from the von Neumann bottleneck. Bio-memristors offer a transformative alternative, merging memory and computation for real-time, energy-efficient processing. Inspired by synaptic plasticity, they utilize Electrochemical Metallization (ECM) and Valence Change Mechanism (VCM) for adaptive, multi-level conductance, key to neuromorphic computing. Recent advances in biomaterial-based memristors—incorporating plantderived cellulose nanofibers, saccharide-based electrolytes, DNA-based switching, and protein-assisted charge transport—enhance sustainability and biocompatibility while replicating parallel processing and in-memory computing. Additionally, quantum conductance effects enable ultra-precise, low-power synaptic modulation, further bridging artificial and biological intelligence. This review explores memristor evolution, key switching mechanisms, and bio-inspired designs, categorizing bio-memristors based on their resistive switching behavior and highlighting applications in neuromorphic AI, neuroprosthetics, and energy-efficient IoT. Finally, it addresses challenges in scalability, integration, and ethical considerations, paving the way for computing systems that learn and evolve like the human brain.

Keywords: Bio-memristors, neuromorphic computing, synaptic plasticity, in-memory computing, resistive switching, biomaterials, quantum conductance

1. Introduction

The 21st century finds evidence of an unprecedented data explosion, with artificial intelligence (AI), quantum physics, and neuromorphic engineering transforming the underpinnings of computation. However traditional complementary metal-oxide-semiconductor (CMOS) circuits, high-performance computing (HPC), and AI computations based on Graphics Processing Units (GPUs) and Tensor Processing Units (TPUs) remain limited by the von Neumann bottleneck. Isolation between processing and memory results in high energy consumption, low bandwidth, and high latency, rendering real-time intelligent processing a continuous challenge [1].

In addition, the production of electronic chips to drive the Internet of Things (IoT), artificial intelligence, and fifth-generation mobile networks has grown exponentially, resulting in an increase in e-waste by many times.? The lifespan of electromagnetic products decreases. Global electronic waste will increase by 21% in 5 years, but its disposal through recycling does not match this rate [2]. Conventional semiconductor-based products are based on nonrenewable energy and toxic materials, such as toxic compounds and heavy metals, whose passing into the earth, water, and air causes pollution of natural ecosystems [3]. With the increasing computational requirements due to AI, cloud computing, and IoT, its ecological footprint has become unsustainable.

The hour of need is unmistakably obvious: we need to create a device that’s environmentally friendly and brain-like in its computation. The human brain works with unparalleled efficiency, carrying out trillions of calculations each second and using only a mere 20 watts of energy [4]. Evolution has developed biological intelligence through dynamic self-tuning neural networks constantly changing, learning, and memorizing with breathtaking accuracy. The failure of contemporary computing to match this biological efficiency leaves us with a profound and existential question: Can nature provide a roadmap to the future of computing?

Thus, by eliminating energy-intensive data shuttling associated with von Neumann architectures, memristors—electronic devices that combine memory and processing—provide a paradigm shift in computing [5]. Memristors, initially proposed by Leon Chua in 1971 and experimentally demonstrated by HP Labs in 2008, enable in-memory computing, considerably reducing computational overhead and energy consumption by processing data directly inside the storage unit [6]. They are also excellent candidates for neuromorphic computing, machine learning accelerations, and edge AI, where speed, energy efficiency, and real-time adaptability are paramount because of their resistive switching nature, controlled by charge transport and ion migration [7].

Yet, memristors are limited by those very materials that endow them with their valuable characteristics. Sequential and parallel processing to achieve brain-like computing is hampered by standard memristors based on inorganic metal oxides such as titanium dioxide or hafnium oxide. The rigid and crystalline nature of these oxides lacks biological plasticity to adapt to synapses [8]. The usual stochastic variability, limited tunability, and non-ideal switching of these inorganic materials restrict their usability in large-scale neuromorphic networks [9]. On the contrary, neurons modulate their synaptic weights dynamically through biochemical cascades.

In addition to computational limitations, the widespread deployment of memristive devices is constrained by fundamental issues of stability, reliability, and reproducibility [10]. Inorganic memristors frequently suffer from cycle-to-cycle and device-to-device variability arising from stochastic filament formation, uncontrolled ion migration, and interfacial defects. These effects lead to resistance drift, limited endurance, and poor retention, particularly under prolonged operation and large switching cycles. Moreover, the requirement for precise control over nanoscale conductive pathways makes large-area integration and uniform fabrication challenging.

To bridge this gap between artificial and biological intelligence, bio-memristors emerge as a revolutionary alternative**?** The flexible, dynamic biomolecules such as proteins, polypeptides, and even DNA utilized by the bio-memristors, as opposed to their rigid, inorganic based counterparts, enable synapse-like plasticity and authentic parallel and sequential processing of information similar to what the human brain accomplishes [11]. Their prospect of neuromorphic computing as well as real-time artificial intelligence applications are augmented by their ability to induce continuous, low-energy ionic modulations, simulating the biological learning process [12].

Aside from functionality, bio-memristors redefine sustainability. They cut down dramatically on the consumption of rare earth metals as well as toxic chemicals since they comprise renewable and biodegradable materials, reducing production costs and environmental harm [13]. Secondly, low power consumption matches necessities of large-scale, green computing with increasing AI loads and pervasive edge devices [14]. Bio-memristors harness the precision of electronics with the flexibility of biology to deliver a smarter and greener computing future [15].

This paper discusses recent progress in memristor technology, with an emphasis on its development toward bio memristors for use in neuromorphic hardware systems. It evaluates different biomolecules as active switching layers in bio memristors, ranging from proteins, DNA, those derived from plants, polymers, and saccharides, focusing on their neuromorphic applications.

2.Memristors

A memristor is a two-terminal device composed of a thin functional layer situated between two electrodes [16]. It stores data through the internal rearrangement of charged particles within this layer, allowing it to stabilize in various resistance states based on different external inputs [17]. Akin to a biological synapse, the top and bottom electrodes act as pre- and postsynaptic neurons, respectively, allowing charged particles to move from one electrode to another through conduction filament via quantum tunnelling. These electrodes are linked by a distinctive synaptic weight that enables the memristor to process information similarly to the human brain [18].

A memristor processes digital and analog signals in real time by adjusting its resistance states through the rearrangement of charged particles when voltage is applied [19]. This allows it to store and transmit information efficiently, enabling both binary data representation and continuous resistance changes for analogue signals [20].

The analog and digital memristors are distinguished by their switching properties [21]. Analog memristors exhibit a gradual, tunable change in resistance, making them ideal for modulation of synaptic weight in neuromorphic networks, as opposed to digital memristors which switch between discrete resistance states, typically classified as the low resistance state (LRS) and the High Resistance State (HRS) [22]. The transition from HRS to LRS is referred to as the set process, while the reverse transition from LRS to HRS is known as the reset
Process [23].

These switching characteristics determine the key performance parameters of the memristors, including the switching speed, endurance, resistance ratio, retention, and power consumption.

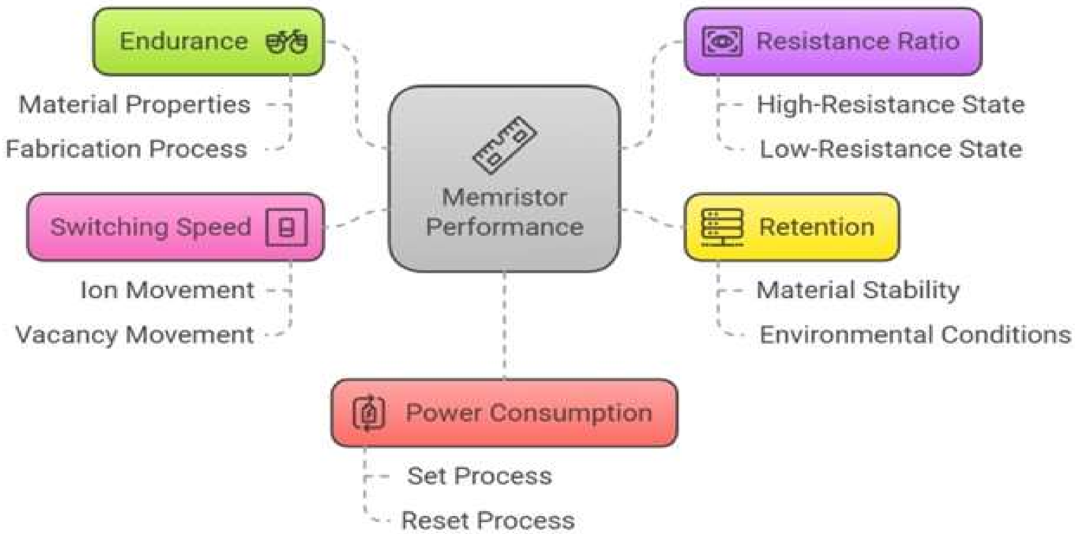

Figure 1. Overview of Critical Performance Parameters in Memristor Technology for Neuromorphic and Computing Applications.

Endurance: Device endurance depends on its stability across several cycles of switching. Memristor endurance is characterized by its ability to withstand a certain number of set/reset cycles prior to degradation. The endurance of a memristor depends on intrinsic characteristics such as material and fabrication process variations, as well as extrinsic characteristics such as electrical stress due to circuit operation. Conversion between LRS and HRS involves applying a signal with correct polarity, either creating or breaking down the conduction filament, thus changing the resistance state of the device. The number of times this cycling can withstand until permanent breakdown characterizes its endurance property. A high endurance level is crucial in memory applications, where repeated read and write operations should not fail.[?]

Resistance Ratio: The resistance ratio refers to the ratio between device resistance in high-resistance state (HRS) and low-resistance state (LRS). The higher the resistance ratio, the greater the clarity of state differentiation, with higher ease in differentiating among memory states. The differentiation is very important in order to achieve high accuracy in data storage as well as in execution of logical operations. The higher resistance ratio decreases read errors, increases signal-to-noise ratio, and enables more efficient multi-level cell (MLC) storage, with intermediate resistance used to store multiple bits of data into each memristor [24].

Retention: Retention describes the memristor's property of preserving its resistance state (LRS or HSR) with no power applied over a period of time. The retention time over which a memristor can store a state is measured by observing the resistance drift under zero-bias conditions [25]. Long retention times are specifically crucial in non-volatile memory as data needs to stay stable even when turned off. Retention also depends upon stability of materials, defect migration, and external environment, with designs aiming to achieve optimum retention times equal to years or even decades to compete with conventional flash memory [26].

Switching speed: The switching speed of a memristor refers to how long it takes to switch between LRS and HRS [27]. It is regulated by charged species (ions or vacancy) movement in the functional layer. The set process creates a conductive path, whereas the reset process disturbs it. Higher switching speeds improve high-speed computing and memory performance, but high speeds beyond certain levels may lead to structural instability, cutting down on endurance [28].

Power Consumption: On application of a voltage, the device runs at a certain level of power as measured by the setting or resetting process. The level of power at which the device becomes set or reset represents the energy needed to create or destroy a state in the device [29].

3. Bio-inspired memristors

Bio-memristors are a category of memristive devices based on biological or bio-mimetic materials, including proteins, DNA, polysaccharides, and other biomolecules, used to realize electrical resistance switching [30]. As opposed to traditional metal-oxide memristors, based on inorganic materials, bio-memristors take advantage of electrochemical and ionic characteristics of biomolecules to provide memory and processing operations. Development was based on investigation into using biocompatible and renewable substitutes for neuromorphic computing [31].

Theoretical basics of bio-memristors date back to research on conduction in biological systems as well as in organic electronics. The earliest of theories backing bio-memristors come from Leon Chua's memristor hypothesis (1971), where it was hypothesized that a memoryresistor was possible. This was followed by Strukov et al.'s (2008) first experimental evidence of a memristor in nanoscale [32].

Recent advances in materials science, including protein-based resistive switching (e.g., silk fibroin and ferritin), showed the potential of energy-efficient and biocompatible computing with bio-memristors [33]. With these advancements, bio-memristors are well-placed as a prime enabling technology in bridging artificial intelligence with green electronics [34].

3.1 Biological Inspiration Behind Bio-Memristors

The efficiency and adaptability of the human brain have long inspired researchers in the pursuit of next-generation computing architectures [35]. Unlike traditional digital systems, which rely on rigid logic gates and fixed memory-storage separation, the brain exhibits highly efficient, parallel, and self-learning capabilities due to its synaptic network. The foundation of this adaptability lies in synaptic plasticity, a biological mechanism that allows neurons to modify their connectivity based on activity patterns. Bio-memristors are designed to emulate these biological processes, offering a hardware-based alternative to artificial synapses, capable of adaptive learning, real-time information processing, and ultra-low power consumption [36].

3.1.1 Synaptic Plasticity and Biological Learning Mechanisms

Synaptic plasticity is the brain's ability to strengthen or weaken neuronal connections in response to stimuli, forming the basis of learning and memory. This adaptability occurs through two primary mechanisms:

- **Short-Term Plasticity (STP):** Temporary changes in synaptic strength, occurring over milliseconds to minutes. STP is responsible for transient information retention and immediate neural responses.
- **Long-Term Plasticity (LTP & LTD):** More permanent modifications in synaptic weight, occurring over minutes to hours, enabling long-term learning and memory formation.

– **Long-Term Potentiation (LTP):** Strengthening of synaptic connections after repeated activation [37].

– **Long-Term Depression (LTD):** Weakening of synapses when activity decreases, optimizing neural efficiency [38].

These mechanisms ensure that frequently used neural pathways become stronger, while less used connections weaken or disappear, allowing for adaptive and efficient memory storage.

In computational terms, this behaviour is crucial for neuromorphic computing, where systems must dynamically adjust their memory states based on past inputs without explicit reprogramming [39].

Essentially, synaptic plasticity in bio-memristors is analogous to the adaptive learning processes of the human brain. These devices emulate synaptic plasticity by modulating their resistive states in response to electrical stimuli. Instead of fixed ON/OFF states like conventional transistors, bio-memristors exhibit gradual, analog-like conductance changes, closely mirroring biological synapses [40]. Their resistance is altered through mechanisms such as ion migration, redox reactions, and charge trapping, allowing them to mimic STP and LTP/LTD in the following ways:

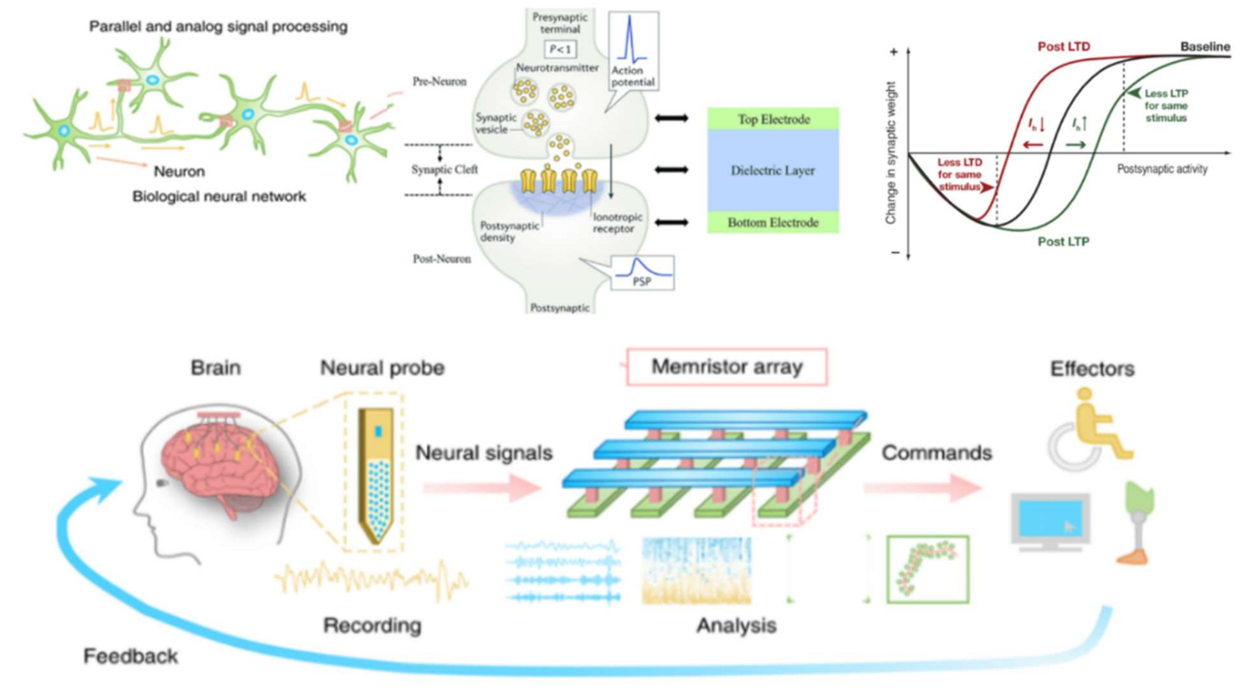

Figure 2. This schematic illustrates bio-memristors mimicking synaptic plasticity for neuromorphic systems. (Top left) Biological neural networks process signals via synapses. (Top middle) A synapse and its bio-memristor equivalent, featuring electrodes and a dielectric layer. (Top right) A synaptic plasticity curve showing LTP and LTD, essential for learning. (Bottom) A neuromorphic interface using neural signals and memristors for adaptive control of prosthetics and interfaces.

- **Short-Term Memory (STP in Bio-Memristors):**

– Low-amplitude voltage pulses induce transient resistive changes, similar to neurotransmitter release in biological synapses.

– Resistance gradually returns to its original state, mimicking the short-lived memory retention seen in neural circuits.

– Used for temporary buffering of information and rapid signal processing [41].

- **Long-Term Memory (LTP & LTD in Bio-Memristors):**

– Higher or repeated voltage stimuli induce cumulative and lasting changes in resistance, akin to synaptic weight adjustments in long-term memory formation [42].

– Just like in biological neurons, the ”stronger” or ”weaker” connections persist, allowing information to be retained over extended periods.

– Essential for learning-based AI systems, neuromorphic processors, and real-time decision-making applications.

These characteristics position bio-memristors as a hardware-based alternative to software trained artificial neural networks, enabling real-time learning and cognitive processing with significantly lower energy consumption [43].

3.1.2 Neurotransmitter-Like Switching in Resistive Memory

Biological synapses are based on neurotransmitters—chemical messengers like glutamate and acetylcholine—to change synapse strength [44]. Neurotransmitters interact with postsynaptic neuron receptors, controlling ion channel function, changing electrical conductivity, and facilitating proper signal transfer. Drawing an analogy, bio-memristors depend on neurotransmitter-like mechanisms like ion transport, redox processes, and molecular switching to change resistance states [45].

Proton-conducting biomemristors function by harnessing cation chelation and ion transport mechanisms in protein or biopolymer films [46]. Hydrogen-bond networks or amino acid residues present in such films can conduct protons by the proton hopping mechanism, whereby protons are passed between sites. Cationic chelation in addition stabilizes intermediate transport states and thereby increases the mobility of protons [47]. Dynamic transport of ions leads to resistance modulation, simulating ionic currents in biological systems' synaptic clefts. Through these mechanisms, these devices mimic synaptic plasticity, facilitating information processing and storage [48]. Ultra-low power operation modes and biocompatibility make them excellent candidates for usage in biocompatible electronics, especially wearable and implantable medical devices. The systems are going to change the integration of electronic and biological interfaces forever [49].

Moreover, one of the major phenomena accountable for switching in oxide-based biomemristors is oxygen vacancy migration. It refers to the movement of oxygen vacancies in the active region of the device under an applied electrical field. Oxygen vacancies are lattice defects and are charge carriers. They are accountable for interfacial modulation. Redistribution of oxygen vacancies between interlayers in the material changes local electronic structure, and this changes device's conductivity [50]. The

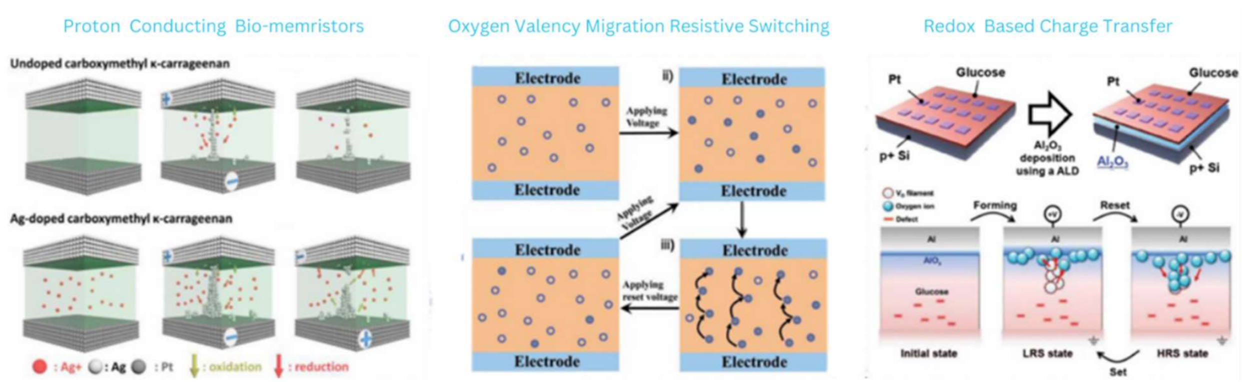

Figure 3. Overview of emerging resistive switching mechanisms in bio-inspired and oxide-based memristors: (Left) Proton-conducting bio-memristors using carboxymethyl κcarrageenan, (Middle) Oxygen valency migration-driven resistive switching, and (Right) Redox-based charge transfer in glucose-assisted memristors.

modulation is similar to biological synaptic plasticity, where neurotransmitters and ions regulate synaptic strength. Oxygen vacancy migration also creates or dissolves conducting filaments, and this offers another mechanism of controlling resistance. Devices based on these are especially valuable in nonvolatile memory, where data are stored even in the absence of supply of power, and in neuromorphic computing, where device's adaptive characteristics are exploited to simulate brain-like processing [51].

Redox-mediated charge transfer represents another vital mechanism, with redox transformations between organic molecules or bio-inspired molecules initiating changes in conductance. Redox processes are characterized by electron transfer, resulting in valence state switching of the active material [52]. For example, an increase in oxidation state provides higher conductivity, and reduction provides lower conductivity. The redox reaction dynamics underlies filament growth, or paths of high-conductance, inside the material. The

Table 1. Representative biomaterial-based memristors categorized by material class (protein, DNA, plant, and saccharide), device architecture, dominant switching mechanism, and key performance metrics including ON/OFF ratio, endurance (cycle number), and retention time

Material	Device Structure	Mechanism	OFF/ON Ratio	Cycle Number	Retention (s)
Protein Based Memristors					
Ferritin	Au/Ferritin/Au	Charge trapping	$\sim 10^4$	$> 10^5$	$\sim 10^7$
Silk fibroin	ITO/Silk fibroin/Ag	Proton conduction	$\sim 10^3$	$> 10^4$	$\sim 10^5$
Egg albumen (EA)	Ag/EA/Ag	Ionic transport	$\sim 10^3$	$> 10^4$	$\sim 10^7$
Hybrid EA-protein	Au/EA-protein/Ag	Mixed valence	$\sim 10^3$	$> 10^4$	$\sim 10^7$
Catalase enzyme	Pt/Catalase/Ti	Charge tuning	$\sim 10^3$	$> 10^4$	$\sim 10^7$
Lysozyme enzyme	Au/Lysozyme/Ag	Proton hopping	$\sim 10^3$	$> 10^5$	$\sim 10^8$
Peroxidase-functionalized	Ag/Peroxidase/Au	Biochemical redox	$\sim 10^4$	$> 10^5$	$\sim 10^8$
Bacteriorhodopsin	ITO/Bacteriorhodopsin/Ag	Photo-driven switching	$\sim 10^3$	$> 10^4$	$\sim 10^6$
Genetically modified bacteriorhodopsin	Au/GM Bacteriorhodopsin/Ag	Optoelectronic response	$> 10^4$	$> 10^5$	$\sim 10^7$
Prion-like protein	Au/Prion-like protein/Ag	Conformational change	$> 10^2$	$> 10^4$	$\sim 10^6$
Amyloid fibril	Pt/Amyloid fibril/Au	Electron tunneling	$> 10^3$	$> 10^5$	$\sim 10^7$
Hemoglobin	ITO/Hemoglobin/Ag	Charge transport	$> 10^3$	$> 10^5$	$\sim 10^7$
DNA Based Memristors					
DNA-templated Au nanowires	Au/DNA-Au nanowires/Au	Electron transport	$\sim 10^4$	$> 10^5$	$\sim 10^8$
Metal-ion-doped DNA	Pt/DNA-Metal ion/Ag	Redox	$\sim 10^3$	$> 10^4$	$\sim 10^7$
G-quadruplex DNA	Au/G4-DNA/Au	Charge transport	$\sim 10^3$	$\sim 10^4$	$\sim 10^6$
DNA-intercalator	Ag/DNA-Intercalator/Ag	Charge transfer	$\sim 10^4$	$> 10^5$	$\sim 10^7$
DNA origami	ITO/DNA Origami/Ag	Programmable resistance	$\sim 10^3$	$\sim 10^5$	$\sim 10^7$
Silver-ion DNA conduction	Ag/DNA-Ag^+/Ag	Ion transport	$\sim 10^3$	$\sim 10^4$	$\sim 10^7$
Copper-doped DNA	Cu/DNA-Cu^{2+}/Ag	Conductive filaments	$\sim 10^4$	$\sim 10^5$	$\sim 10^7$
Graphene-DNA hybrid	Graphene/DNA/Ag	Charge trapping	$\sim 10^3$	$> 10^4$	$\sim 10^7$
Plant Based Memristors					
CNF-based	ITO/CNF/Ag	Ionic transport	$\sim 10^3$	$\sim 10^4$	$\sim 10^7$
CNC-based	Pt/CNC/Au	Dielectric polarization	$\sim 10^3$	$> 10^4$	$\sim 10^7$
Bacterial cellulose	Ag/Bacterial Cellulose/Ag	Ionic drift	$\sim 10^3$	$\sim 10^5$	$\sim 10^7$
CMC-doped	Au/CMC/Ag	Redox	$\sim 10^4$	$> 10^5$	$\sim 10^8$
Cellulose acetate	ITO/Cellulose Acetate/Ag	Resistive switching	$\sim 10^3$	$> 10^4$	$\sim 10^7$
Lignin-carbon nanodot	Au/Lignin-CND/Au	Conductive pathways	$\sim 10^4$	$> 10^5$	$\sim 10^7$
Lignosulfonate	Pt/Lignosulfonate/Ag	Proton hopping	$\sim 10^3$	$\sim 10^4$	$\sim 10^7$
Polydopamine-lignin	Ag/PD-Lignin/Ag	Electron tunneling	$\sim 10^3$	$\sim 10^5$	$\sim 10^7$
Enzymatically processed lignin	ITO/Lignin/Ag	Redox modulation	$\sim 10^3$	$\sim 10^4$	$\sim 10^7$
Saccharide Based Memristors					
Starch-AgNP	Ag/Starch-AgNP/Ag	Charge trapping	$\sim 10^3$	$> 10^4$	$\sim 10^7$
Corn starch	ITO/Corn Starch/Ag	Ionic conduction	$\sim 10^3$	$\sim 10^4$	$\sim 10^6$
CNF-doped starch	Au/Starch-CNF/Ag	Electron hopping	$\sim 10^4$	$\sim 10^5$	$\sim 10^7$
Metal oxide-starch	Pt/Starch-MO/Ag	Conductive filaments	$\sim 10^3$	$> 10^4$	$\sim 10^7$
Hydrogel starch	Au/Starch-Hydrogel/Ag	Ionic drift	$\sim 10^3$	$\sim 10^4$	$\sim 10^6$
Chitosan	Ag/Chitosan/Ag	Ion diffusion	$\sim 10^3$	$> 10^4$	$\sim 10^7$
Xanthan gum	Au/Xanthan/Ag	Ionic migration	$\sim 10^3$	$> 10^4$	$\sim 10^7$
Alginate	Pt/Alginate/Ag	Biodegradable switching	$\sim 10^3$	$> 10^4$	$\sim 10^7$
Potato starch composite	ITO/Potato-Starch/Ag	Resistive switching	$\sim 10^4$	$\sim 10^5$	$\sim 10^7$
Gelatin-starch blend	Au/Starch-Gelatin/Ag	Electron transport	$\sim 10^3$	$> 10^4$	$\sim 10^7$
Carrageenan-based starch	Pt/Starch-Carrageenan/Ag	Ionic redistribution	$\sim 10^3$	$\sim 10^4$	$\sim 10^6$

filaments facilitate regulated and reversible resistance adjustability, replicating biological synapse's chemical communication processes. The end product is an architecture with multi-level storage, with different resistance state correspondence to respective quantities of stored data. The high densities of these devices and their energy consumption result in them being suited to high-density storage as well as energy-efficient computing architectures [53].

3.3 Bio-molecules for active switching layers in bio-memristors

Bio-materials and bio-inspired materials are pivotal to bio-memristors due to their provision of biocompatibility, elasticity, and energy-efficient switching characteristics. They comprise protein-based systems (e.g., silk proteins, bacteriorhodopsin), conducting architectures based on DNA and peptides, and tunable electronic property organic polymers [54]. Their ability to self-assemble naturally and transport ions allows them to exhibit synaptic-like characteristics, rendering them suitable for neuromorphic applications. Bio-hybrid composites also provide stability and high conductivity, leading towards environmentally friendly, next-generation memory and computation technologies [55].

3.3.1 Protein-Based Memristors

Protein-based memristors are revolutionizing the next-generation memory device paradigm by providing inherent charge transport mechanisms, spontaneous assembly properties, and adjustable resistive switching. Unlike rigid silicon-based architectures, these biomolecular components provide flexible, dynamic, and biocompatible information processing and are therefore extremely promising for environmentally friendly and neuromorphic electronics [56]. One of the key advancements here is the ability of some

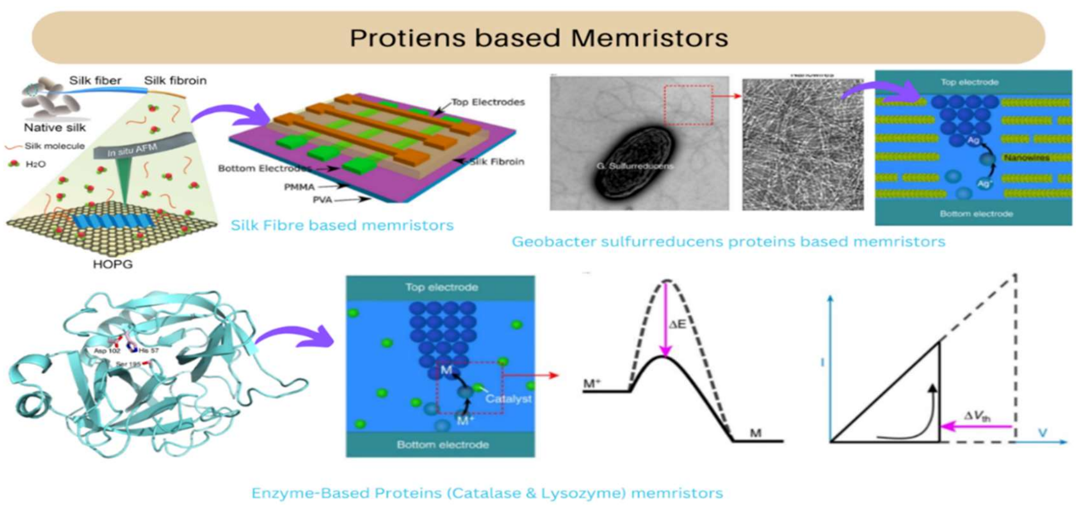

Figure 4. Overview of Protein-Based Memristors: Silk fiber-based memristors (top left) utilize silk fibroin for resistive switching. Geobacter sulfurreducens protein-based memristors (top right) leverage conductive bacterial nanowires for charge transport. Enzyme-based memristors (bottom) incorporate catalase and lysozyme to enable ionic modulation and resistive switching, demonstrating the potential of biological materials in neuromorphic computing.

proteins to enable redox reactions and ionic transport and perform resistive switching at the nanoscale. Geobacter sulfurreducens proteins, for instance, enable electron transfer and filament stabilization, accelerating synapse-like conductivity [57]. In ferritin, an iron-storage protein, there are multi-level states of resistivity, allowing high-density encoding of memory through charge trapping. Recent research has shown that programmable resistance changes are possible by altering the oxidation state of ferritin, opening up the possibility of nonvolatile energy-efficient memory systems [58].

Besides metal interactions, biopolymer protein silk fibroin from Bombyx mori has demonstrated enormous potential toward flexible, transparent, and biodegradable memristors and opening the way toward wearable and bio-integrated computing [59]. Further, egg albumen (EA) is also gaining popularity due to cost and stable switching performance. In an interesting turn of events, researchers at the National University of Singapore recently found that they can create stable nanoscale conducting filaments using a hybrid EA-protein network, significantly enhancing endurance and reliability compared to regular organic memristors [60]. One of the emerging frontiers of protein-based memristors includes the study of charge dynamics enabled by enzymes. Proteins from enzymes like catalase and lysozyme introduce biochemical tunability to memristor operations [61]. For example, catalase was shown to catalyze hydrogen peroxide degradation while tuning local charge distribution, effectively regulating resistive states. In one foundational study, scientists created a peroxidase-functionalized memristor that is capable of responding to extrinsic biochemical signals, paving the way toward neuromorphic circuits that can dynamically adapt to biological environments [62]. In addition, bacteriorhodopsin, a photoreceptor protein, is demonstrated to display photoresponsive resistive switching, and this makes it possible to develop optically driven memory architectures [63]. Synthetic biology advancements enabled the genetic modulation of bacteriorhodopsin's chromophore dynamics, and this can be programmed through pulses of light to develop memristors [64]. This innovation opens up possibilities of energy-efficient, optogenetically driven neuromorphic computing. One of the fronts that remain untouched is the use of prion-like proteins, having the shared ability to alter their shape. MIT scientists recently examined the potential of using prion domains in artificial peptides and discovered that their metastable states can be exploited to store multi-bit memory [65]. The observation that prion-like sequences can be made to exhibit controllable resistive switching reveals an entire class of bioelectronic devices that can store information in protein folding states [66]. Using protein conformation dynamics and biochemical reactivity, researchers are extending the boundaries of molecular-scale memory, bridging the gap between organic intelligence and artificial computation. The application of protein-based memristors to neuromorphic circuits, brain-machine interfaces, and self-learning AI hardware is a paradigm-changing step toward bio-inspired computing paradigms as efficient and adaptive as those of nature [67]. As the technology progresses, the potential of self-assembling, self-healing, and even selfevolving memristor networks may revolutionize the boundaries of artificial intelligence and sustainable electronics [68].

3.3.2 DNA and Peptide-Based Memristors

DNA and peptides, the biological building blocks, are emerging as flexible platforms for biomemristors, offering an unparalleled combination of molecular recognition, self-assembly, and tunable conductivity [69]. Relative to conventional inorganic compounds, these biomolecules offer nanoscale charge transport with high accuracy, utilizing their structural pliability and chemical programmability toward next-generation memory [70]. One of the most promising aspects of DNA-based memristors is their ability to facilitate electron and ion transport by means of π-stacking interactions and metal-ion doping. Using conductive metal nanoparticles or intercalating redox-active molecules, DNA strands can be induced to exhibit resistive switching behavior, mimicking synaptic plasticity [71]. In addition, G-quadruplex DNA

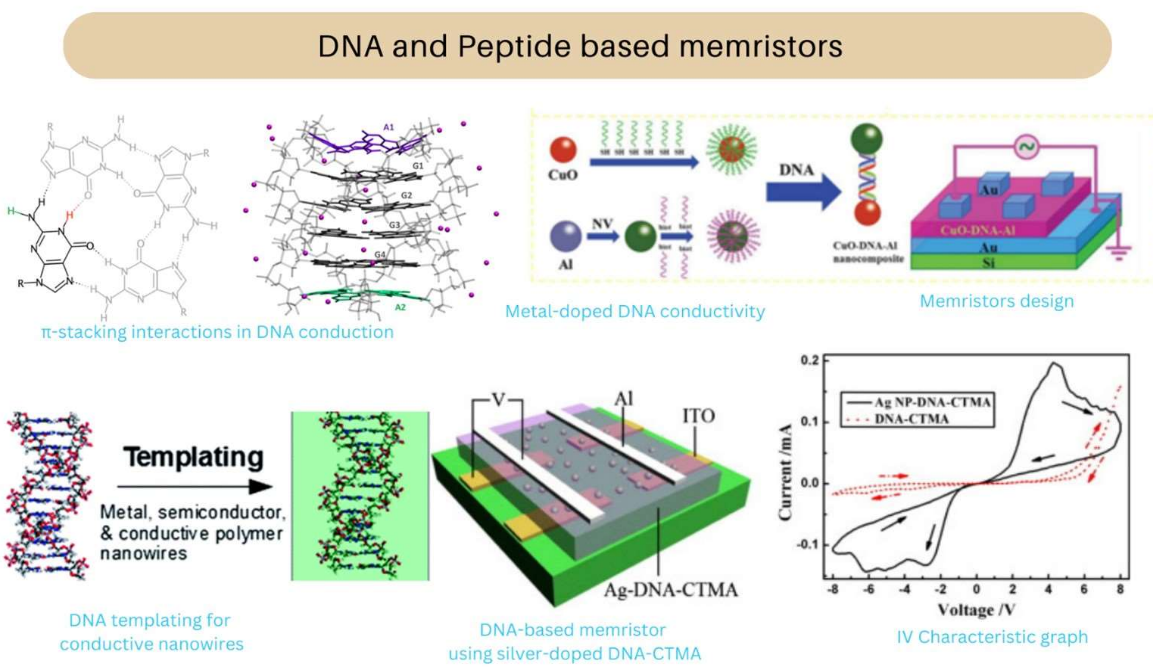

Figure 5. Concepts in DNA and Peptide-Based Memristors: π-stacking interactions in DNA facilitate conduction (top left), while metal-doped DNA enhances electrical properties (top center). Memristor design using DNA nanocomposites (top right) demonstrates practical applications. DNA templating enables the formation of conductive nanowires (bottom left), and silver-doped DNA-CTMA is used in memristor fabrication (bottom center). The IV characteristic graph (bottom right) illustrates the electrical behaviour of DNA-based memristors, highlighting their resistive switching capabilities.

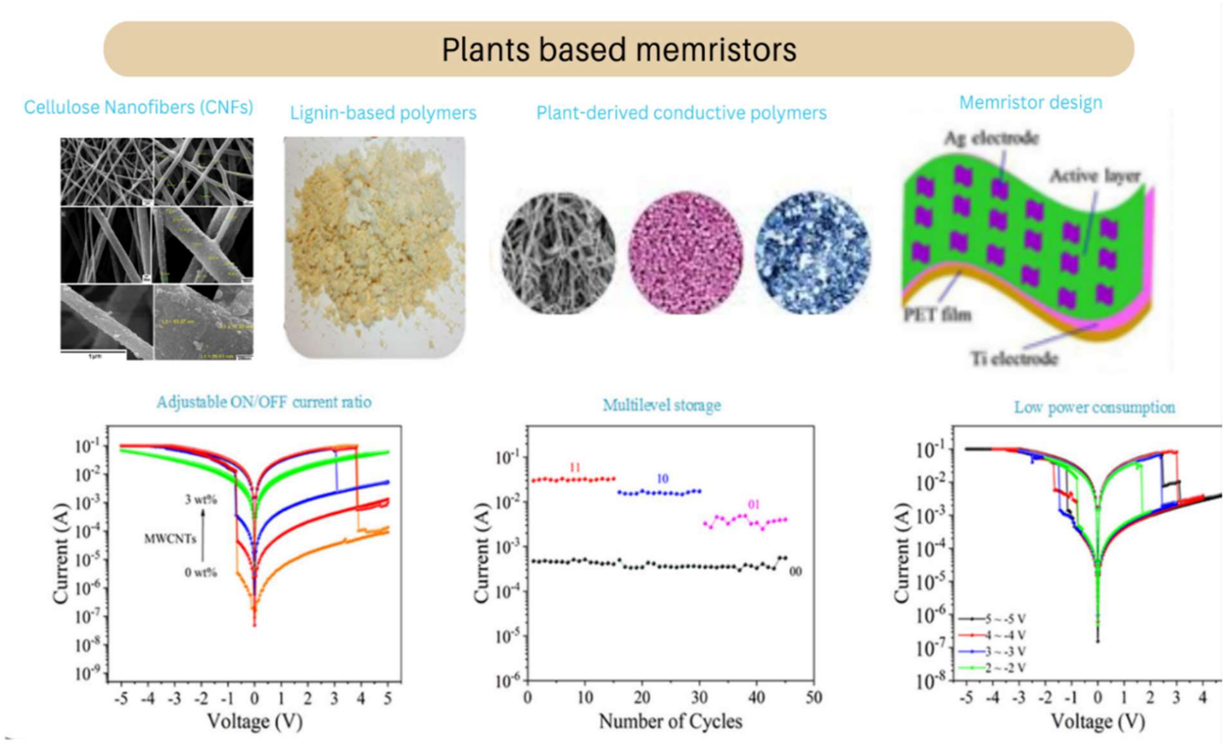

Figure 6. Cellulose nanofibers (CNFs) (top left), lignin-based polymers (top center), and plant-derived conductive polymers (top right) serve as bio-materials for resistive switching applications. A flexible memristor design (top far right demonstrates the integration of this materials [80]. The bottom graphs illustrate key performance characteristics: adjustable ON/OFF current ratio (bottom left), multilevel data storage (bottom center), and low power consumption (bottom right), showcasing the potential of plant-based materials for sustainable and efficient memory devices.[81]

architectures, distinguished by high electrical conductivity and stability, are examined as natural templates for multi-state storage and neuromorphic processing. Such biomolecules, when paired with structural versatility, provide prospects for ultra-low-power, adaptive, and biodegradable computing systems [72]. Groundbreaking research has confirmed the revolutionary promise of DNA-based memristors. Scientists at Chalmers University of Technology (Sweden) synthesized DNA-templated arrays of gold nanowires, having precise resistive switching through π-stacking interactions and stable electron transport [73]. Scientists at Tel Aviv University studied metal-ion-doped DNA strands, and metal ions including silver and copper ions facilitated improved charge transport, an alternative contender for ultra-lowpower neuromorphic circuits [74]. Stanford University advancements focused on G-quadruplex

DNA devices, where DNA architectures folded create natural conductivity, enabling multi-level states of resistance to be stored, perfect for high-density memory [75]. Parallel to this, researchers at the National University of Singapore (NUS) incorporated redox-active intercalators into DNA to achieve stable switching by charge transfer mechanisms that are reminiscent of enzymatic reactions. Concurrently, MIT researchers created programmable DNA origami memristors by exploiting the structural programmability of DNA to construct nanoscale architectures that modulate resistive states directly and provide unmatched control over memory behavior [76]. Besides DNA, peptides are also possible bio-memristor prospects. Scientists at ETH Zurich were able to successfully demonstrate peptide-based conducting films that display adaptive electrical properties reminiscent of those observed in synaptic plasticity. Amyloid fibrils and silk fibroin peptides, among several others, are among those that have demonstrated high potential to enable flexible, biodegradable, and transparent wearable and implantable devices [77]. Embracing sequence-directed self-organization, charge transport by π-stacking and metal-ion coordination, and structural dynamics of DNA and peptides, bio-memristors provide a paradigm shift in memory technology [78]. Their integration into neuromorphic hardware, bio-sensing platforms, and in vivo memory systems is a revolutionary step toward computing architectures compatible with biological environments. Bridging the gap between organic intelligence and artificial computation, these advancements demonstrate the feasibility of an adaptive, sustainable future of electronics [79].

3.3.3 Plant-Based Memristors

Plant-based composites and bio-hybrid polymers are some of the advanced next-generation memristor technologies that take advantage of the biocompatibility, structural variability, and environmental friendliness of plant-based materials,[82] Through the use of naturally occurring organic components whose electronic properties are controllable, these materials offer an alternative to the use of conventional synthetic and inorganic semiconductors, particularly where applications require flexible, low-power, and biodegradable memory devices.

With environmental concerns and energy consumption on the rise, eco-friendly neuromorphic computing systems are increasingly being made possible by plant-based memristors [83]. Among all the cellulosic polymers, cellulose stands out due to its mechanical strength, high dielectric strength, and tunable ionic conductivity [84]. There are several forms of cellulose that were examined as potential applications when it comes to resistive switching devices, and these are cellulose nanofibers (CNFs), cellulose nanocrystals (CNCs), and bacterial cellulose (BC). They are all nanostructured materials that are extremely flexible and are therefore best suited to wearable computing systems and flexible electronics [85]. One of the main mechanisms of cellulose-based memristors is the use of intrinsic hydroxyl (-OH) groups to facilitate hydrogen bonding and redox interactions, important for resistive switching behavior [86]. Recently, it was demonstrated that cellulose nanofibers, when functionalized by conducting nanoparticles, are capable of exhibiting stable bipolar resistive switching, indicative of their application potential as low-power memory. Additionally, bacterial cellulose, having its highly interconnected and porous network of nanofibers, presents an ionic transport scaffold, facilitating better tunability of switching properties [87]. Derivatives of cellulose, carboxymethyl cellulose (CMC), and cellulose acetate, among others, have been studied because they show improved conductivity and structural stability. Doping cellulose with conducting bio-based fillers like tannins, flavonoids, or even graphene analogs from plants has been demonstrated to significantly improve its electronic properties [88]. A recent breakthrough along these directions was the application of blends of CNC along with conducting plant extracts to fabricate ultra-low switching voltage memristive films, paving the way to energy-efficient neuromorphic hardware [89]. One of the aromatic complex polymers found within the cell wall of plants is lignin, another possible candidate for bio-based memristors. Unlike cellulose, whose primary role is structural support, lignin is redox active due to the presence of numerous phenolic and quinone functional groups. Such functional moieties are able to support charge transfer reactions, enabling non-volatile memory storage with enhanced environmental stability [90].

Recent studies on lignin electronics demonstrated that carbon nanodots from lignin are functional additives that can be utilized to increase conductivity and optimize switching performance of organic memristors. Experiments confirmed that lignosulfonates, soluble lignin derivatives, can be incorporated into bio-composite films to enable controlled resistive switching through proton-coupled electron transfer [91]. A breakthrough experiment here was the blending of lignin and conducting polymer from plants, including polydopamine, and this achieved stable memory storage up to thousands of switching cycles, an important step toward practical applications [92]. Furthermore, enzymatically processed lignin was also explored as a bio-template semiconductor wherein redox cycling generates reversible resistance changes. Lignin-polyphenol conjugates were also successfully engineered by scientists to exhibit multi-state resistive switching, an essential property of artificial synapses in neuromorphic computing [93]. Such advancements are crucial toward the development of bio-memristors capable of mimicking human brain synaptic plasticity. Aside from cellulose and lignin, polyphenols from plants, flavonoids, and tannins are also being considered due to their electronic properties. These naturally occurring molecules commonly found in tea, cocoa, and grapes possess redox properties that are ideal for use in resistive switching devices. Researchers were able to create bio-memristors from catechin-functionalized nanocellulose films and prove the existence of multi-level states of resistance that are crucial to high-end memory architectures [93]. One of the innovative solutions is the use of plant-based conducting biopolymers like melanin, a naturally found pigment in various plants. Melanin is intrinsically electronically conducting and possesses proton mobility, and hence it is one of the best candidate materials for memristor applications. Research on melanin-coated cellulose membranes demonstrated their ability to be used as low-power, biodegradable electronic memories, opening up further possibilities of eco-friendly computing material. Cellulosebased materials, including cellulose nanofibers (CNFs), cellulose nanocrystals (CNCs), and bacterial cellulose (BC), exhibit excellent mechanical flexibility, high dielectric strength, and tunable ionic conductivity [94]. Their intrinsic hydroxyl groups facilitate hydrogen bonding and redox interactions, enabling resistive switching behaviour crucial for neuromorphic significant advantages over traditional synthetic and inorganic semiconductors, particularly for applications in low-power, flexible, and biodegradable memory devices computing [95]. Modified cellulose derivatives, such as carboxymethyl cellulose (CMC) and cellulose acetate, further enhance conductivity and structural stability, expanding their applicability in flexible memory architectures.

3.3.3 Saccharide-Based Memristors

Saccharide-based memristors have immense brain-like computing potential brain-like computing because of their tunable resistive switching mechanisms, biocompatibility, and flexibility. Being naturally occurring polysaccharides, these compounds already possess inherent ionic conductivity, structural plasticity, and suitability to incorporate conductive fillers to augment charge transport [96]. They are attractive candidates for applications in neuromorphic computing, flexible electronics, and green memory storage due to their potential to achieve ion transport and electrochemical redox processes. Natural polysaccharide

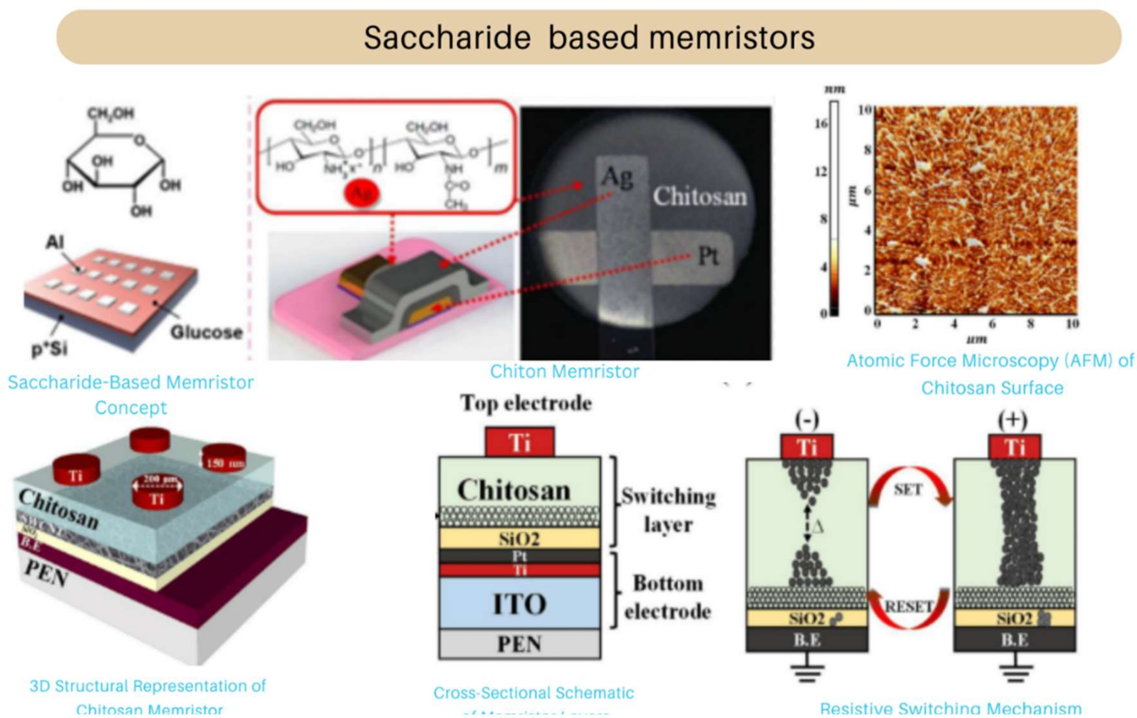

Figure 7. Chitosan-based materials (top left) serve as the active layer for resistive switching, with a detailed device structure (top center) and surface morphology analysis (top right). A flexible memristor design (top far right) demonstrates the integration of these bio-materials. The bottom section presents key performance metrics: tunable ON/OFF current ratio (bottom left), multilevel data storage capability (bottom center), and energy-efficient switching behavior (bottom right), highlighting the potential of saccharide-based memristors for sustainable memory applications.

starch, comprising amylose and amylopectin, has demonstrated great promise in resistive switching because of its semi-crystalline nature, high dielectrics, and property to establish stable ionic networks. Through the addition of conducting fillers like carbon nanofibers (CNFs), graphene oxide, or metal nanoparticles, scientists have successfully used starch-based composites to achieve tunable resistance states with characteristics similar to synaptic plasticity [97]. Researchers at Tsinghua University made a major breakthrough with starch-based memristive films after doping starch with silver nanoparticles (AgNPs). The composite architecture allowed metal filament formation under applied voltages, causing non-volatile resistive switching and more than two memory states [98]. The fact that starch is bio-derived also allowed it to exhibit biodegradability, a quality well suited to transient electronics and environmentally friendly computing systems. Additionally, corn starch-based memristors, created in Zhejiang University, had humidity-sensitive conductivity, enabling tunable switching characteristics depending on environmental humidity levels. The property is very desirable in sensor applications and bio-interfacing systems where external stimuli are used to modulate the performance of a memristor [99]. The hydrogel-forming property of starch also offers a path towards flexible and stretchable electronic device design with preserved functionality under mechanical stress conditions. Chitosan, a chitin-derived biopolymer, represents another saccharide-based material with immense potential to exhibit memristive characteristics. Chitosan, with its proton-conducting nature and metal cation chelating ability, exhibits memristors based on chitosan with mechanisms of operation based on ionic migration, rendering them appropriate for applications in neurosynaptic and neuromorphic circuits and also in sensors [100]. Researchers at Yonsei University created resistive memory devices based on chitosan, where an analogue memory function was observed with the polymer matrix facilitating the creation and destruction of mobile silver- or copper-based conductive filaments. Chitosan-based memristors are also investigated as low-power, biocompatible computing platforms due to their proton transport functionality, with them proving to be well-suited as implantable neural interfaces as a result of this property [101]. More recent breakthroughs with saccharide-based memristors went beyond starch and chitosan to incorporate cellulose, another ubiquitous polysaccharide with remarkable mechanical resistance and stability. Researchers in Cambridge created cellulose nanofiber-based memristors using gold nanoclusters to improve charge transport and storage characteristics [102]. The memristors showed multilevel resistive switching, opening up high-density energy-saving memory arrays. Moreover, a pioneering technique at MIT used xanthan gum, a viscoelastic exopolysaccharide, to create self-healable memristors. Ionic liquid electrolytes were incorporated into xanthan gum matrices to achieve dynamic resistive switching with recovery after mechanical deformation, presenting opportunities for self-healable, long-lasting electronics [103].

3.4 Neuromorphic Application of Bio-memristors

Bio-memristors represent a paradigm shift in neuromorphic engineering and biomedical technology, leveraging intrinsic biocompatibility and ionic dynamics to emulate the core functions of biological synapses. In neuroprosthetics and brain-machine interfaces (BMIs), these devices can mediate communication between artificial circuits and living neural networks, enabling adaptive connectivity across damaged pathways to restore motor or sensory function in patients with paralysis or neurotrauma [104]. Their analog, stochastic, and activity-dependent conductance modulation mirrors synaptic plasticity, supporting real-time, bidirectional interaction between neurons and prosthetic devices, and allowing more naturalistic control of prosthetic limbs, exoskeletons, and sensory substitution systems [105].

Beyond BMIs, bio-memristors hold transformative potential for bioelectronic therapeutics. Implantable or wearable neuromodulation devices incorporating bio-memristors could provide closed-loop, adaptive stimulation for neurodegenerative diseases such as Parkinson's and Alzheimer's [106]. Unlike conventional rigid stimulation protocols, bio-memristor-based systems can dynamically modulate electrical patterns in response to neural activity, enhancing efficacy while minimizing side effects. Their long-term, non-volatile information storage at the ionic level further enables learning-enabled implants that adapt autonomously to disease progression or patient-specific neural signatures.

At the molecular and cellular scale, bio-memristors offer new avenues in biosensing. By transducing biochemical signals into modifiable electrical states, they can detect enzymatic reactions, metabolite fluctuations, or neurotransmitter concentrations with high temporal resolution [107]. Integrated into implantable or wearable platforms, these devices enable continuous monitoring of biomarkers such as glucose, cardiac metabolites, or amyloid-beta levels, providing immediate feedback or triggering autonomous therapeutic interventions [108]. Their low-energy, non-volatile operation makes them ideal for self-powered, real-time diagnostic systems.

In neuromorphic computing, bio-memristors support short- and long-term synaptic plasticity, spike-timing-dependent plasticity (STDP), and homeostatic scaling, making them suitable for in-memory computing, online learning, and energy-efficient pattern recognition. They can power cognitive neuroprosthetics that learn patient-specific neural patterns to improve rehabilitation after stroke or traumatic brain injury, serve as hybrid bio-electronic chips for low-power AI and pattern recognition, enable dynamic sensory encoding in artificial vision, audition, or tactile feedback systems, and facilitate smart pharmacological interfaces that modulate drug delivery or neuromodulation in real time, effectively merging diagnostics, computing, and therapy.

Despite their promise, the long-term deployment of bio-memristors in biomedical systems remains constrained by challenges in material stability, reproducibility, and degradation under physiological conditions.

Biomaterials used in memristive devices—such as proteins, polysaccharides, and biopolymers—are susceptible to hydration-driven structural rearrangements, ionic drift, enzymatic degradation, and fatigue over repeated switching cycles, which can lead to variability in conductance states and device-to-device inconsistency. Ensuring stable synaptic emulation over clinically relevant timescales therefore requires precise control over material composition, encapsulation strategies, and interface engineering to mitigate degradation while preserving biofunctionality. Addressing these limitations is critical for translating bio-memristors from proof-of-concept demonstrations to reliable, implantable neuromorphic systems.

4. Conclusion

In conclusion, this review assesses biomaterial-based memristors from an angle that focuses on their neuromorphic functionality, rather than attempting to classify them from an analogy-based comparison between biological systems and memristors. In theory, further developments from memristor-based systems towards utilizing biomaterials for neuromorphics opens doors for exploring ionic transport properties, redox processes, or biomaterial-based molecular conformation dynamics based on biological systems for systematic control of analog or stochastic resistive switching at lower voltages.

A function-based classification system of bio-memristors, which includes plant-derived polymers, proteins, nucleic acids, and saccharide biomolecules, is proposed to overcome the current disjointed state of the literature. By using a classification system, a wide range of bio-memristors with different chemistries are easily compared by correlating the physicochemical properties, which include ion mobility, hydrated transport, redox reversibility, and biomolecule flexibility, with the performance properties, which include endurance, resistance ratio, retention, switching times, and power dissipation. Based on the comparison with traditional inorganic memristors, the biomaterial devices have been shown to have lower operation voltages and better analog characteristics, although with the trade-offs in long-term endurance and reproducibility.

Importantly, the use of biomaterials in this regard enables additional functionality that transcends computation. Owing to their biocompatibility, ionic-electronic coupling in the absence of external stimuli, stochasticity inherent in the material's underlying processes and properties, and the flexibility of the material that makes possible the analogue representation of weights bio-memristors present a paradigmatic shift in neuroprosthetic interfaces and nanobiosensing applications.

Conflict of Interest: There is no conflict to declare.

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