TIU Transactions on Human Sciences (TTHS)

TIU Transactions on Human sciences

BIOLOGICAL CONDUCTORS: THE FUTURE BEYOND SILICON

*Arup Ratan Biswas [a], Sudip Kumar Ghosh [b], and Moumita Ghosh [c]

[a,b,c] Department of Chemistry, Techno India University, Kolkata-700091, West Bengal

Abstract

Biological conductors are being actively explored as alternatives to traditional semiconductors and, more specifically, as substitutes for silicon. Silicon has long been the pioneer material used in transistors due to its abundance and semiconducting properties. However, its limitations, such as inefficient electron transfer and high heat generation, have restricted its use as a source material in advanced semiconductor applications. This led to the development of hybrid nanomaterials combined with biological materials, as well as efforts to explore pure biological materials as replacements for both silicon and nanomaterials. Biological materials are particularly appealing due to their inherent flexibility and highly organized structures, which facilitate smooth electron transfer between adjacent molecules. Additionally, biological materials generate significantly less heat during operation, minimizing heat loss—a critical advantage over silicon. Their ability to self-assemble into organized structures further enhances their suitability for electrical conduction. This property has found key applications in the healthcare industry, where biological materials are used in devices that require high biocompatibility and environmentally friendly materials.

Examples of biological materials under investigation include DNA, melanin, and cytochromes, all of which exhibit favorable electron transfer properties through tunneling, hopping, or redox reactions, effectively overcoming energy barriers and facilitating efficient electrical conductivity. As research progresses, biological conductors may unlock new possibilities in sustainable and biocompatible electronics, offering a promising alternative to traditional semiconductor technologies.

Keywords: *Biological conduction, biological materials, DNA, Proteins, melanin, and cytochromes*

1. Introduction

The dominance of silicon in technology began with the invention of the transistor in 1947 by *John Bardeen* and *Walter Brattain* at bell labs [1]. Initially, germanium was the preferred material for transistors due to its effective semiconducting properties. However, germanium-based devices exhibited high leakage currents, which limited their performance in certain applications. This challenge prompted researchers to search for a more suitable material that could address these limitations. After years of research and development, silicon emerged as the material of choice. Its superior thermal stability, abundance, and lower leakage currents made it ideal for semiconductor applications. The adoption of silicon in transistors revolutionized semiconductor technology, laying the foundation for integrated circuits and microelectronics. Over time, silicon became synonymous with the semiconductor industry, earning its recognition as the cornerstone of modern technology and giving rise to the concept of the "silicon revolution" and the "Silicon Valley" hub of innovation.

The 1960s marked the advent of integrated circuit (IC) technology, which revolutionized the electronics industry and firmly established silicon's potential for microelectronics. During this period, transistors gradually became the dominant devices in computer logic circuitry, replacing vacuum tubes. The era from 1947, when the first transistor was invented, to the 1960s witnessed the evolution of silicon transistors, which began to dominate microprocessor chips due to their superior performance and reliability. The subsequent advancements in integrated circuit technology, including the development of Very Large Scale Integration (VLSI) in the 1970s and beyond, further cemented silicon's position as the material of choice for semiconductor technology [2]. These breakthroughs enabled the miniaturization of devices, increased computing power, and ushered in the era of modern microelectronics, solidifying silicon's unparalleled role in shaping the technological landscape.

In 1965, *Gordon Moore* made a groundbreaking observation, later known as Moore’s Law, predicting that the number of transistors in an integrated circuit would double approximately every 18 months. This trend, driven by relentless innovation, continued for decades and became the foundation for the exponential advancement of the microelectronics industry. The ability to integrate millions, and eventually billions, of components on single silicon chip revolutionized computing and electronics [**3**]. The rise in transistor density not only improved processing speed and energy efficiency but also made computers, mobile devices, and other electronic components more affordable and economically viable. These advancements fueled transformative changes in mobile technology and other industries, enabling the development of increasingly powerful, compact, and versatile devices that define the modern digital age [4].

While silicon has revolutionized the microelectronics industry, it faces growing challenges as transistors continue to shrink. As the physical dimensions of transistors approach their limits, silicon's ability to scale efficiently becomes a significant limitation. In response, ongoing research is exploring alternative materials to overcome these challenges. For example, materials such as high-k gate insulators are being investigated to address issues like leakage currents and performance degradation in integrated circuits and transistors [5] [6]. Additionally, biological materials are emerging as potential replacements for silicon in certain applications. These materials show promise, particularly in the medical industry, where their unique properties could be leveraged for innovative devices and treatments, offering new possibilities beyond traditional silicon-based technologies.

1.1 The need for alternative material

The development of alternative materials to replace silicon arises from the growing demand for faster, more efficient, and sustainable technologies. Over the last few decades, the semiconductor industry has faced mounting challenges as silicon approaches its physical limits. Factors such as miniaturization limits, energy inefficiency, heat generation, and the environmental impact of silicon-based components have hindered progress. This has prompted the rise of various post-silicon alternatives, which present both material and conceptual breakthroughs pushing the boundaries of electronics and computing. Moore's Law, a predictive model suggests that the number of transistors on a chip would double approximately every two years, has been the backbone of semiconductor innovation for decades. However, as transistor sizes approach atomic scales, fundamental physical limitations make it increasingly difficult to sustain this pace of progress [7] [8] [9]. The difficulties in maintaining Moore's Law have led researchers and companies to explore new materials and approaches to continue scaling electronic performances. In particular, the limitations of silicon in areas like heat dissipation, quantum effects at smaller sizes, and energy consumption have driven the search for materials that can deliver higher efficiency and performance at the nanoscale [10] [11] [12].

In response to these challenges, alternative nanomaterials have emerged, offering potential replacements for silicon.

1.2. Alternative nanomaterials replacing silicon

Some of the most promising candidates include

1.2.1 Carbon-Based Nanomaterials

Materials like graphene and carbon Nanotubes (CNTs) are leading the charge. These nanomaterials exhibit remarkable electrical conductivity, high strength, and unique properties that allow them to outperform silicon in certain applications, especially at smaller scales [13] [14] [**15**]. For instance, graphene’s 2D structure enables incredibly fast electron mobility, which could lead to faster processors and more efficient electronics. The most prominent carbon based nanomaterials are as listed.

a) Graphene: A single layer of carbon atoms arranged in a two-dimensional lattice, graphene has remarkable electrical, thermal, and mechanical properties. Its high conductivity and flexibility make it an appealing candidate for future electronics, particularly in flexible and wearable devices [16].

b) Carbon Nanotubes (CNTs): Cylindrical molecules made of carbon atoms, exhibits high electrical conductivity and have been explored as potential replacements for silicon in transistors. Their small size, strength, and ability to carry electrical current without significant resistance make them a highly promising material for next-generation electronics [17].

1.2.2 Quantum Computing Materials

As traditional silicon-based transistors struggle with scalability, quantum computing offers a paradigm shift. Material such as quantum dot, topological insulator, and superconducting possess faster and efficient computation. These materials leverage the principles of quantum mechanics, allowing for operations that are far beyond the reach of classical silicon-based computers. Following quantum computing materials as cited.

a) Quantum Dots: Nanoscale semiconductor particles that have unique electronic properties due to quantum mechanics. They are used in quantum computing to store and manipulate information at speeds far beyond what current silicon-based processors can achieve [18].

b) Topological Insulators: Materials that have insulating bulk properties but conductive surface states, which can lead to ultra-low-energy devices and potentially solve issues related to power consumption in electronic devices [19].

c) Superconductors: Certain materials that exhibit zero electrical resistance at low temperatures. Quantum computing leverages superconducting quantum bits for faster, more efficient computations, presenting an exciting alternative to classical silicon chips [20].

1.2.3 Organic Electronics

Conductive polymers and organic light-emitting diodes (OLEDs) are already in use in displays and lighting. The development of organic semiconductors holds promise for creating flexible, low-cost electronics. Organic materials can be produced through printing or casting processes, potentially revolutionizing the way we manufacture electronics, especially for wearable or biodegradable devices. Promising organic electronics that may be the future alternative to the traditional source material are as:

a) Conductive Polymers: Polymers that can conduct electricity are another potential alternative to silicon. These materials can be processed at lower temperature, which makes them suitable for flexible, lightweight, and large-area electronics such as organic solar cells, displays, and sensors [21].

b) Organic Light-Emitting Diodes (OLEDs): OLED technology has already found applications in displays, and organic semiconductors are being researched for use in transistors and other electronic devices [22].

The advantages of various source materials alternative to silicon are represented in ***Table 1.***

1.2.4 Biological Conductors

The most novel and bio-inspired of these alternatives, biological conductors include natural materials like proteins, DNA, and biomolecules that conduct electricity through mechanisms such as electron transfer. The integration of biological materials into electronics could lead to more energy-efficient, self-healing, and biocompatible systems [23]. Researchers are exploring how to leverage bioelectronics for applications in medical devices, biosensors, and more. The rise of these post-silicon materials not only offers new avenues for improving the performance and sustainability of electronic systems but also holds the promise of fundamentally changing how devices are conceived, designed, and built. As the semiconductor industry faces the limitations of silicon, innovations in nanomaterials prepared from biological systems represent an exciting future for computing, electronics, and other high-tech fields [24].

2. Biological conductor as a suitable replacement.

The microelectronics industry is undergoing a materials revolution. While silicon has been the cornerstone of semiconductor technology, its limitations have prompted a search for alternatives. Nanomaterials initially emerged as promising candidates due to their exceptional properties. However, challenges such as scalability, uniformity, and integration with existing systems have hindered their widespread adoption [25]. This has led to a shift toward biologically-based materials, particularly for applications in healthcare. These materials offer unique advantages, including compatibility with biological systems, positioning them as attractive candidates for the next generation of semiconductors.

Organic electronics have also gained attention by addressing some challenges posed by nanomaterials. Organic semiconductors are cost-effective, flexible, and capable of covering large areas. However, their structural instability, deformities under electrical input, and poor integration with microelectronic chips remain significant obstacles. Additionally, achieving uniform layers of organic molecules with functional groups embedded in a solid matrix continues to be a technical challenge. This evolving landscape highlights the ongoing search for materials that balance performance, scalability, and integration, paving the way for innovative solutions in semiconductor technology [26] [27] [28].

Bioelectronics, DNA computing, conductive proteins, and nanowires are collectively categorized under biologically-based semiconductor devices, utilizing various biological matrices. Biological materials such as proteins, DNA, and peptides (biopolymers) are emerging as competitive alternatives to silicon in this domain. Often referred to as bioelectronics, these materials possess the remarkable ability to transfer electrons and conduct electricity with minimal heat dissipation and high efficiency [29] [30].

What makes these biological materials particularly promising is their inherent ability to self-assemble and adapt seamlessly to biological environments. These properties position them as an exciting and viable post-silicon alternative for next-generation semiconductor technologies.

Table 1: Various source materials alternative to silicon and their advantage

Source material types	**Examples**	**Advantages**
Carbon based Nanomaterials	Graphene	High electrical conductivity High thermal conductivity High control on functionalisation
Carbon based Nanomaterials	Carbon Nanotubes	High tensile strength Special electronic structures High chemical stability High thermal stability
Quantum computing materials	Quantum Dots	Superior optical properties Photoluminescence Optical nonlinearity
Quantum computing materials	Topological Insulators	Bulk band gap Odd number of relativistic Dirac fermions on surface
Quantum computing materials	Superconductors	Strong and stable magnetic field Efficient energy storage Minimal energy loss Long-distance electricity transmission
Organic Electronics	Conductive Polymers	Light weight Robust Low cost Easy manufacturing Environment friendly Less toxic
Organic Electronics	Organic Light-Emitting Diodes (OLEDs)	High contrast ratio Better viewing angles Scalable large-area fabrication Flexible substrates

DNA (Deoxy-Ribo-Nucleic acid), a nucleic acid is considered a highly promising material for Bioelectronics due to its unique structural and electronic properties. Its double-helix structure enables efficient charge transfer along its strands, making it suitable for conducting electrical signals. Additionally, DNA's programmability through sequence-specific base pairing allows for precise Self-assembly into nanostructures, facilitating the design of highly organized and complex systems. DNA's biocompatibility and ability to operate in aqueous and biological environments make it an ideal candidate for integrating electronics with living systems, such as in biosensors, bio-computing devices, and medical applications [31] [32]. Moreover, DNA can be chemically modified or hybridized with other nanomaterials, such as metals or carbon-based materials, to enhance its conductivity and functionality, paving the way for innovative applications in bio-nanoelectronics.

DNA offers unparalleled advantages, including ultra-dense data storage and the capability for highly parallel processing—features that surpass the limitations of silicon-based systems. Its inherent molecular structure allows for encoding digital information in the form of nucleotide sequences, enabling immense data storage capacity in a minuscule volume. Additionally, DNA's ability to self-assemble and perform biochemical reactions makes it a prime candidate for biological computing, opening new frontiers in computational efficiency and data processing.

Natural proteins like cytochromes, melanin, as well as protein based nanowires are being explored by the researcher as an alternative to be used as a bio-inspired circuits and sensors, which are expected to be more energy-efficient, adaptable, and sustainable than traditional silicon systems [33].

Bio-hybrids are emerging as a compelling alternative to nanomaterials in the microelectronics industry. The combination of biological materials such as DNA, proteins, cytochromes, and melanin with nanomaterials offers an innovative pathway to surpass the limitations of silicon. These hybrid systems leverage the best properties of both biological and synthetic materials, enabling the creation of highly efficient, adaptable devices [34].

The concept of bio-inspired engineering has also become a pivotal achievement in the post-silicon era. By mimicking biological processes and structures, a principle known as bio-inspiration, researchers are developing new electronic systems that are compatible with human biology and hold great promise for healthcare applications.

Recent advancements include the exploration of synthetic enzymes and receptors as sustainable and efficient alternatives for microelectronics and human health systems. These innovations are not only enhancing device performance but are also paving the way for more sustainable and biologically integrated technologies in the post-silicon landscape.

3. Fundamentals of Biological Conductors

Biological conductors are unique in their ability to transfer electricity through biological materials such as DNA, proteins, and melanin. Unlike conventional silicon semiconductors, these materials offer alternative electron transfer mechanisms, making them promising candidates for next-generation electronic systems. One key mechanism is *hopping conduction*, where electrons move in a stepwise manner between adjacent molecules or functional groups. This is exemplified by *melanin*, which facilitates localized charge transport through its structure. Another important mechanism is *quantum tunneling*, which is particularly evident in biological polymers like DNA. Despite its insulating properties, DNA enables charge transfer over significant distances by allowing electrons to tunnel through its helical structure.

Additionally, proteins involved in the electron transport chain, such as cytochromes, play a vital role in localized electron transfer. These proteins facilitate electron flow via redox reactions, where charge carriers are generated through oxidation and reduction processes. This property of proteins further enhances their potential as biological conductors, challenging the dominance of traditional silicon-based systems.

By harnessing these unique mechanisms, biological conductors not only provide efficient electron transfer but also offer a sustainable and versatile alternative to silicon, paving the way for advanced bioelectronics applications.

4. Advantage of considering biological based materials as semiconductor over traditional silicon based semiconductor.

The structural properties of biologically-based materials make them unique candidates for semiconductor applications. These materials can naturally organize into nanoscale structures, enabling efficient electrical conduction. This ability is encapsulated in the term self-assembly, which is a key characteristic of biological materials. Additionally, biological materials contain functional groups such as amines and hydroxyls, which enhance electron tunneling across distant junctions by facilitating structural modifications. These properties enable more efficient charge transfer, further distinguishing biological conductors from traditional semiconductors. Moreover, the inherent flexibility of biological structures provides a significant advantage, particularly for applications in stretchable devices. This flexibility allows for the development of electronics that can bend and stretch without compromising performance, opening up new possibilities for wearable and flexible electronics.
Some of the key advantages of biological semiconductors include the followings:

4.1 Sustainability: Biological conductors are environmentally sustainable and help maintain ecological balance, making them an eco-friendly alternative to traditional materials.

4.2 *Low Heat Dissipation*: Biological semiconductors exhibit minimal heat dissipation, which makes them an attractive option for researchers looking to replace conventional nanomaterials or silicon-based semiconductors. This unique property ensures higher efficiency and reduced energy loss in devices.

4.3 *Biocompatibility:* Semiconductors derived from biological materials are highly biocompatible, making them ideal for use in healthcare devices and bioelectronics. Their compatibility with living systems enables seamless integration into medical technologies.

4.4 Self-Assembly and Nanoscale Organization

The biological materials have the unique property of self assembling within its structures to an organized structure thereby facilitating the smooth electron transport between the adjacent molecules or functional groups increasing the electrical conduction property. Self assembly means the spontaneous organization of molecules into nanoscale or hierarchical structures. The organized structures thus formed due to the self assembling property of the biological materials results in a well defined conduction pathway with less or no hindrance to the flow of electron and thereby increasing the electron density to be transported among the adjacent molecules or functional groups. Biological materials like that of DNA undergo self assembling into highly ordered nanostructures thereby allowing the conduction to occur smoothly. Proteins and peptides can form conductive nanowires. Biological pigment *melanin* exhibits spontaneous assembly in to an organized structure thereby permitting the electron flow between the adjacent molecules facilitating the electrical conduction.

The advantage of using biological system is its unique property of getting self assembly into organized structures that simplifies device fabrication and allows the creation of nanoscale systems without the need for complex manufacturing processes.

4.5 Flexibility and Environmental Adaptability

Flexibility of biological structures and environmental adaptability makes it a unique source material for the electron transfer and thereby increasing the electrical conduction. It helps to maintain the conductivity when subjected to mechanical stress, bending and stretching. Flexible biological polymers like proteins and DNA are ideal for developing stretchable electronics and wearable devices. Their adaptability to aqueous or physiological environments ensures stable operation in bioelectronics.

5. Mechanism of Biological Conduction

Biological conduction is the process by which electrical charges are transported through biological materials such as DNA, proteins, melanin, and other biomolecules. Unlike traditional silicon-based semiconductors, which rely on band gap-based conduction, biological conductors operate through a combination of unique mechanisms that are rooted in the molecular and structural characteristics of these materials [35]. Below are the primary mechanisms that govern biological conduction:

5.1 Hopping Conduction Mechanism

It is a stepwise mechanism in which electrons move between adjacent molecules or functional groups. This type of conduction is primarily exhibited by biological materials that possess localized charge carriers. One prominent example is *melanin*, a natural skin pigment. Melanin demonstrates hopping conduction by enabling electrons to transfer in a stepwise manner between its adjacent functional groups, thereby facilitating efficient electron flow across its polymeric structure [36] [37].

The principle behind electron hopping lies in the transfer of electrons between closely spaced energy states within molecules or functional groups. This process is most effective when the distance between adjacent molecules or functional groups is minimal, as shorter distances reduce energy barriers and enhance the likelihood of electron transfer.

A notable advantage of hopping conduction is that it does not require a crystalline structure for electrons to migrate. Unlike conventional semiconductors that rely on ordered lattices, materials like melanin can exhibit effective electron transport even in amorphous or disordered forms. This unique property makes hopping conduction particularly advantageous in biological materials.

5.2 Quantum Tunneling Mechanism

It refers to the movement of electrons through an insulating barrier by penetrating the barrier rather than overcoming it. Unlike classical conduction, where electrons require sufficient energy to move over a barrier, tunneling allows electrons to "pass through" the barrier due to their wave-like nature [38]. This process is probabilistic and depends on factors such as the thickness of the insulating barrier and the energy levels of the system.

One biological example that supports quantum tunneling is DNA, a natural polymer known for its ability to conduct electrons across insulating barriers. Despite having an insulating backbone, DNA facilitates quantum tunneling through its helical structure, enabling charge transfer over significant distances. The arrangement of DNA's base pairs—purines (adenine and guanine) and pyrimidines (cytosine and thymine)—plays a critical role in tunneling efficiency. Certain sequences of base pairs can enhance the tunneling process, as the molecular structure of purines, being larger and more electron-rich than pyrimidines, may favor electron transfer [39].

Consequently, DNA sequences with a higher proportion of purines are more likely to support efficient tunneling. This unique property of quantum tunneling in DNA allows for long-range conduction across large gaps or insulating regions. By leveraging the natural arrangement of base pairs and the helical structure, DNA provides a promising mechanism for efficient charge transfer in biological systems. This phenomenon makes DNA a valuable material in the field of bioelectronics, where its quantum tunneling capabilities can enable novel applications in nanoscale devices.

5.3 Redox-based Conduction Mechanism

The process described involves oxidation and reduction reactions that take place within the electron transport chain (ETC), a critical component of cellular respiration. In this system, substrates are oxidized sequentially, releasing electrons that are subsequently captured by downstream substrates. These downstream molecules are reduced as they accept the electrons. This cascade of redox reactions continues until the electrons are ultimately transferred out of the system, typically to a final electron acceptor such as oxygen in aerobic organisms. A key player in this process is the cytochrome, a protein integral to the electron transport chain. Cytochromes contain a heme group, which includes an iron atom capable of reversible oxidation and reduction. This property allows cytochromes to efficiently facilitate the transfer of electrons between adjacent molecules in the chain. The presence of the heme group accelerates the rate of electron transfer, ensuring the rapid and efficient progression of the redox cascade.

Cytochromes are particularly suited for short-distance electron transfer due to their highly efficient and continuous operation, even under conditions requiring sustained electron flow. This makes them indispensable for maintaining the proper functioning of the ETC, where precise electron transfer is essential for the production of ATP, the energy currency of the cell [40]. Beyond their biological role, cytochromes have the potential for applications in bioelectronics systems. By leveraging their inherent capacity for electron transfer, cytochromes could serve as components in the development of biological conductors. These conductors could enable the flow of electrons in systems designed to mimic or integrate with biological processes. Moreover, cytochromes can mitigate electron deficiencies in such systems by maintaining a continuous supply of electrons, ensuring reliable performance in environments that demand consistent electron flow. The unique combination of efficiency, specificity, and adaptability of cytochromes highlights their significance not only in biological systems but also in advancing innovations in bio-inspired electrical conduction technologies.

5.4 Modulating the functional groups

The functional groups like that of amines, hydroxyls, carboxyl**,** and thiols present in biopolymer play a significant role in enhancing electron transfer property. These groups facilitate electron transfer between adjacent functional groups of the same type by acting as electron donors or acceptors, depending on their chemical properties. The presence of these functional groups, particularly thiols**,** amines**,** and hydroxyls, significantly modifies the electronic properties of the biological matrix [41]. These modifications can influence the carrier mobility potential, altering the movement of charge carriers, and can also impact the energy levels or energy barriers within the system. Such changes can either facilitate or impede electron flow, depending on the configuration and density of the functional groups. An increase in the number of functional groups within a biological matrix correlates with improved electrical conduction and enhanced electron transfer between adjacent functional entities. This is primarily due to the increased electron tunneling activity, where electrons are able to move efficiently across short distances even in the absence of a direct physical pathway. This phenomenon enhances both short- and long-distance electron transfers, leading to improved electrical conduction efficiency within the biological system.

By truncating or modulating the functional groups in a biological matrix, it is possible to tailor the electronic properties of biopolymers for specific applications. Such modifications are particularly relevant in the field of bioelectronics, where designing sustainable, biocompatible materials is critical. These tailored biopolymers hold great promise for use in healthcare industries, where they can enable advanced technologies such as biosensors, bio-integrated devices, and implantable electronics [42]. Thus the mechanisms of biological conduction, includes the hopping conduction, quantum tunneling, redox-based transfer, and functional group modulation. Biological conduction utilizes inherent structural and chemical properties of biological materials. These mechanisms, combined with the self-assembly and flexibility of biomolecules, position biological conductors as a unique and promising alternative to traditional semiconductors. Their ability to operate efficiently in dynamic and biological environments makes them particularly valuable for emerging applications in bioelectronics, healthcare devices, and sustainable technologies.

6. Application of Biological Conductor

The application of biological conductor centers on analyzing and interpreting biological data, especially in genomics and bioinformatics. Below are some detailed applications across biological and biomedical research fields:

6.1 Genomics Research

Biological conductor is essential for analyzing and interpreting large-scale genomic datasets in the view of analyzing the DNA sequence analysis, genome annotation and comparative genomics. The DNA sequencing analysis mainly involve the mutations spot identification, SNPs (single nucleotide polymorphisms), and structural variations. Biological conductor is also applied in the field of genome annotation in the sense that it helps in mapping the genes to the exact genome locations, functional annotations and finding regulatory elements. It is also applied in the field of comparative genomics where it is primarily used for the identifying the similarities and difference between genomes of different organisms.

6.2 Transcriptomics and Gene Expression Analysis

Biological conductor facilitates the analysis of transcriptomics data by RNA-sequence analysis, microarray data analysis, and single-cell RNA sequence (scRNA-Seq) analysis. The RNA sequence analysis involves the identification of differentially expressed genes (DEGs) and alternative splicing events. The application of biological conductor in analyzing cell heterogeneity and identifying the cell subpopulations in tissues as a part of the study belonging to single cell RNA sequence (scRNA-Seq) is highly useful.

6.3 Epigenomics

Biological conductor has the huge application in the field of ChIP sequence data analysis, DNA methylation analysis, and ATAC sequence analysis. The ChIP sequence data analysis involves the investigation of the interaction occurring between the DNA and the transcription factors. The involvement of the biological conductor is being explored to study the epigenetic changes linked to disease set of condition in particular community. Studying the chromatin accessibility and to investigate the role of chromatin in the gene regulation has been possible with the use of biological conductor.

6.4 Proteomics and Metabolomics

Biological conductor is useful in protein quantification in the sense that it is being explored to be used for analyzing the data of peptide mass fingerprints obtained from mass spectrometry. Biological conductors are also being explored to be used for differential protein expression and analysis between the experimental and control, as well as have being explored for the metabolic pathway analysis as a part of the drug discovery platform.

6.5 Functional Genomics

Biological conductors are useful in gene ontology (GO) enrichment that is the understanding biological processes, cellular components, and molecular functions associated with the gene sets. It finds its application in the pathway analysis that is investigating the pathways associated with specific conditions or treatment. Understanding the over expression of a particular gene set in a data also use the application of biological conductor the study which is grouped under gene set enrichment analysis.

6.6 Multi-Omics Data Integration

Biological conductor application is found in integration of data of combining genomics, transcriptomics, and proteomics all together compiled to be as multi-omics. It helps in building comprehensive and holistic biological networks and is also useful in the identification of the biomarker of disease.

6.7 Cancer Research

Biological conductor finds it application in the cancer research mainly in tumor heterogeneity analysis study which involves single cell data to understand tumor evolution and cell populations. Mutation identification also finds the useful application of biological conductor that correctly suggests the genetic changes occurring with high accuracy that may be possibly a initiation and progression of metastasis. A drug sensitivity and multidrug resistance study also involves the usage of biological conductors for understanding the various drug response and resistance in the cancer patients.

7. Conclusion

Biological conductors, with their efficient electron transfer potential, are emerging as a promising alternative to traditional semiconductor materials like silicon. While the development of fully functional biological conductors capable of replacing silicon remains in its infancy, global research efforts in this area have made it a hot topic in the scientific community. These materials hold immense promise due to their potential sustainability, biocompatibility, and unique properties, which could revolutionize fields like bioelectronics and green technology. However, the journey to establish biological conductors as a viable replacement for traditional semiconductors is still a long way off. Despite ongoing studies by various research groups, no conclusive data has yet confirmed their practical use as a full-fledged alternative to silicon. Nonetheless, the growing interest and rapid advancements in this field highlight its potential to reshape the future of electronics.

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