Two-dimensional DNA Nanostructures and Their Applications in Biosensors and Nanomaterial Synthesis: A Survey

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Abstract

This survey paper explores the interdisciplinary field of DNA nanotechnology, focusing on the design and synthesis of two-dimensional DNA nanostructures, their metallization, and applications in biosensors and nanomaterials. The historical evolution of DNA nanostructures highlights significant advancements in molecular self-assembly and metallization techniques, which enhance their electronic properties, facilitating applications in nanoelectronics and biosensing. The integration of DNA with metals has led to innovative biosensors capable of detecting biological substances via colorimetric and electrochemical signals, with applications in diagnostics and environmental monitoring. The paper reviews scalable synthesis methods, including chemical vapor deposition and plasma-liquid interactions, for metallic nanosheets, emphasizing their potential in electronics and catalysis. Despite these advancements, challenges such as scalability, stability, and regulatory compliance persist. Addressing these limitations through interdisciplinary research and advanced simulation techniques is crucial for optimizing biosensor performance and expanding the industrial applications of DNA nanostructures. This comprehensive survey underscores the transformative potential of DNA nanotechnology in enhancing biosensor technology and nanomaterial synthesis, promising significant advancements in healthcare, electronics, and environmental sciences.

1 Introduction

1.1 Historical Context and Evolution

The evolution of DNA nanostructures reflects significant advancements in nanotechnology over recent decades. The field originated in the 1990s with the recognition of DNA's potential as a structural material, leading to the development of nanoscale architectures [1]. A pivotal milestone was the introduction of DNA metallization techniques in 1998, which enhanced the electronic properties of DNA structures, facilitating their integration into electronic and biosensing applications [2]. Progress in molecular self-assembly and an improved understanding of DNA behavior have enabled the synthesis of increasingly complex DNA nanostructures.

This evolution parallels the broader growth of nanotechnology, encompassing the synthesis, properties, and applications of diverse nanomaterials [3]. The significance of DNA nanostructures is underscored by their ability to address challenges in traditional synthesis methods and to open new avenues for innovation [4].

1.2 Interdisciplinary Nature of Research

Research in DNA nanostructures exemplifies a rich interdisciplinary integration of chemistry, biology, materials science, and engineering. This collaboration is crucial for advancing methodologies

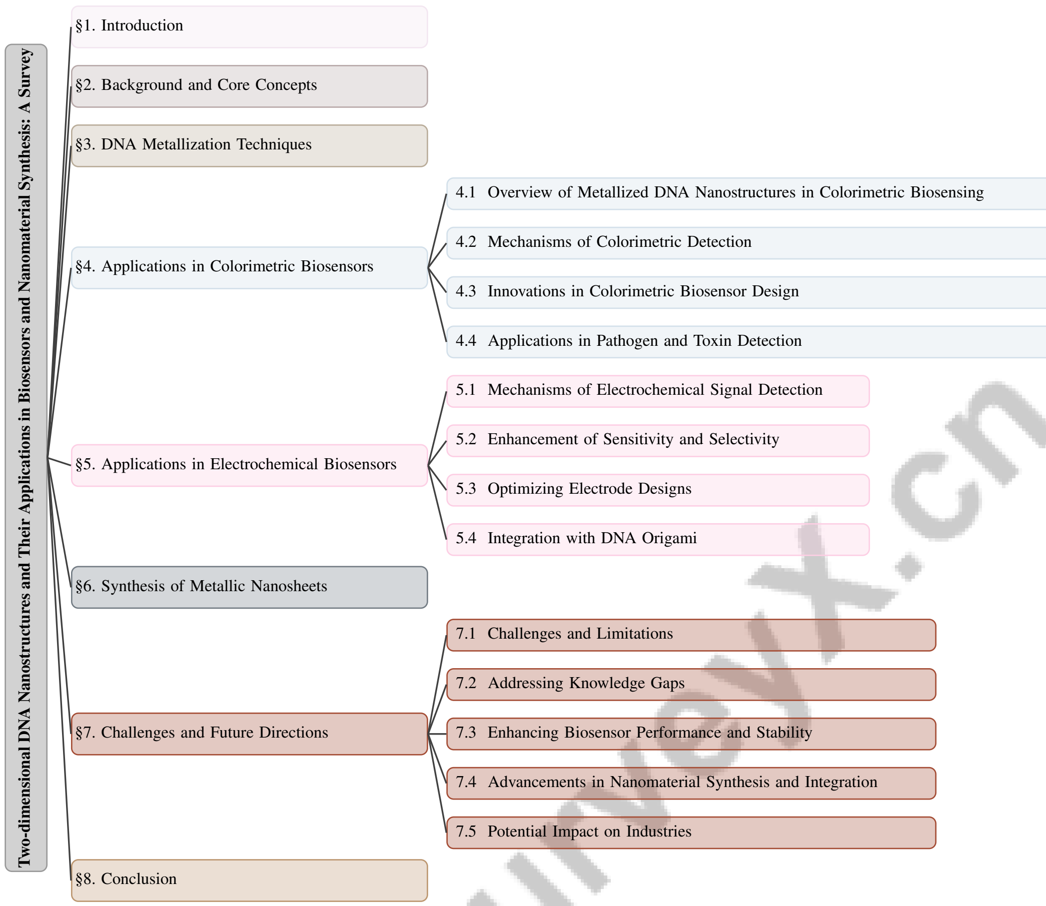


Figure 1: chapter structure

in DNA metallization and their applications in chemical catalysis, environmental sensing, and biomedical engineering [5]. The development of DNA nanostructures for nanoelectronics and drug delivery further emphasizes the need for cross-disciplinary expertise, as these applications require a comprehensive understanding of biological interactions and electronic properties.

In biosensing, the partnership between chemists and biologists has led to the creation of smart nanomaterials that mimic natural enzymes, improving colorimetric detection methods [5]. The synergy between materials science and analytical chemistry is evident in the integration of nanomaterials with optical and electrochemical technologies, enhancing arsenic detection techniques [5]. Additionally, DNA-guided metallization for synthesizing gold and silver nanoparticles demonstrates the biomedical potential of these interdisciplinary efforts, as these nanoparticles are pivotal in therapeutic and diagnostic applications.

Advanced computational techniques, including deep-learning algorithms for designing nanopillar arrays, illustrate the collaboration between data scientists and chemists aimed at optimizing the optical properties of nanostructures [5]. The integration of microfluidic technologies into molecular synthesis and detection processes further highlights the fusion of engineering principles with molecular biology, overcoming the limitations of traditional macro-scale methods and improving the precision of nanoscale manipulations. These collaborative efforts are vital for understanding the stability, design, and cellular uptake mechanisms of DNA nanostructures, essential for their effective biomedical applications [5].

1.3 Structure of the Survey

This survey paper is structured to explore critical aspects of two-dimensional DNA nanostructures and their applications. The introduction establishes the significance and interdisciplinary nature of DNA nanostructures in nanotechnology. Following this, the historical context and evolution of DNA nanostructures are discussed, emphasizing key milestones and advancements in the field. The interdisciplinary nature of research is examined, showcasing collaborative efforts across various scientific domains that propel innovation in DNA-based nanomaterials [5].

Subsequent sections provide a comprehensive overview of the fundamental principles, design, and synthesis techniques of DNA nanostructures, with a focus on DNA metallization and its role in enhancing electronic properties. The survey explores recent innovations and challenges in DNA metallization techniques.

Applications of metallized DNA nanostructures in biosensors are thoroughly analyzed, with dedicated sections addressing colorimetric and electrochemical biosensors, including detection mechanisms, innovations in sensor design, and specific applications in pathogen and toxin detection.

The synthesis of metallic nanosheets using DNA templates is also investigated, exploring various techniques and their potential applications in medicine and electronics. The challenges and future directions section addresses current limitations and knowledge gaps, proposing strategies to enhance biosensor performance and stability while highlighting recent advancements in nanomaterial synthesis.

The findings underscore significant advancements in DNA nanostructure technology, emphasizing its transformative potential in enhancing biosensor capabilities and facilitating innovative nanomaterial synthesis. The review highlights the versatility of DNA as a template for constructing metal nanoarchitectures, leading to groundbreaking applications across fields such as chemical catalysis, environmental monitoring, and biomedical engineering. By leveraging DNA's unique properties, researchers can create well-ordered nanostructures exhibiting novel optical, electronic, and magnetic characteristics, paving the way for future developments in nanotechnology [2, 6, 5]. This structured approach offers a comprehensive roadmap for readers navigating the complex and multifaceted field of DNA nanostructures.The following sections are organized as shown in Figure 1.

2 Background and Core Concepts

2.1 Fundamentals of DNA Nanostructures

DNA nanostructures exploit DNA's molecular recognition and structural predictability to construct nanoscale architectures with precision and versatility [5]. The advent of DNA origami has revolutionized the field, enabling the efficient and cost-effective creation of complex nanostructures [1]. This innovation not only advances nanotechnology but also underpins the fabrication of metal nanoarchitectures crucial for next-generation electronic and optical devices [6].

The programmability, biocompatibility, and self-assembly of DNA nanostructures make them suitable for diverse applications, such as biocompatible carriers in drug delivery and diagnostics, leveraging their controlled interaction with biological systems [7]. Integrating DNA with biomolecules like antibodies leads to well-defined functional conjugates, expanding their biomedical applications [8]. In biosensing, DNA nanostructures facilitate the development of smart nanomaterials with peroxidase-like activity, used in colorimetric glucose biosensors [9], and aptamer-based biosensors for arsenic detection, addressing significant environmental challenges [10]. Their ability to engineer precise metal structures at the nanoscale is vital for optical metamaterials, which rely on DNA nanostructures for specific optical properties [11].

The intersection of DNA nanostructures with computational advancements, such as neural networks for optimizing design parameters, enhances their application in nanoscale devices, including HfO2 nanopillars for color generation [12]. Understanding charge density's influence on catalytic activities, especially in the hydrogen evolution reaction (HER), highlights the broader implications of DNA nanostructures in energy applications [13]. A key challenge remains the integration of optical and electrochemical sensing techniques on a unified platform to enhance biosensing capabilities [14]. Controlling the morphology and properties of metallic nanomaterials during synthesis is crucial for their biomedical applications [4]. Ongoing research focuses on developing dynamic DNA structures capable of complex transformations and efficient information relay at the nanoscale [15]. Mastery of these principles is essential for maximizing the potential of DNA nanostructures across various scientific and industrial applications.

2.2 Design and Synthesis of DNA Nanostructures

The design and synthesis of DNA nanostructures leverage DNA's molecular recognition and predictable structural properties to create complex nanoscale architectures. DNA origami, a pivotal technique, involves folding long single-stranded DNA into specific shapes using short staple strands, serving as a scaffold for further functionalization and metallization [15].

Innovative synthesis methods, such as DNA–pAsp conjugates, enhance guided mineralization within DNA frameworks, allowing precise control over mineral deposition and improving the structural complexity and functional adaptability of nanomaterials for drug delivery, biosensing, and biomimetic mineralization for tissue regeneration [6, 5, 16, 4]. DNA-mediated metal nanoparticle formation, as outlined by Ijiro et al., is crucial for fabricating conductive nanowires and enabling sequence-selective metal deposition, essential for advancing nanoscale electronic devices.

Aptasensor design demonstrates the application of DNA nanostructures in biosensing, utilizing DNA's specificity and sensitivity to enhance detection capabilities for various analytes, including neurotransmitters, pathogens, and environmental contaminants, thus advancing clinical diagnostics and point-of-care testing [17, 18, 19]. Photocrosslinkable protein G variants as adapters allow for site-specific conjugation of antibodies and Fc-fusion proteins to oligonucleotides, expanding the functional scope of DNA nanostructures in biomedical applications.

Metallization techniques, particularly involving low-valence metal ions like Cu^2 and Ag, enable precise control over selective condensation and metallization of DNA strands, facilitating the creation of multimetallic nanopatterns on DNA origami with a resolution of 10 nanometers. This method exploits DNA hybridization specificity and the coordination of metal ions with DNA bases, supporting site-specific reactions without affecting the surrounding origami structure. Consequently, this approach simplifies the fabrication of complex nanomaterials and opens new avenues for applications in nanoelectronics and nanophotonics [20, 4].

The functionalization of nanoseeds with DNA and subsequent DNA-guided nanoparticle growth are critical stages in synthesizing DNA-based nanomaterials, as highlighted in recent surveys. The evolution of DNA nanostructures has led to significant advancements in methodologies vital for biosensing, bioimaging, and therapeutic interventions. These innovative strategies utilize DNA's programmable base-pairing and structural versatility to create highly organized nanomaterials, proving indispensable across various scientific and industrial fields, including chemical catalysis, environmental monitoring, and biomedical engineering [6, 5]. Additionally, integrating surface plasmon polaritons (SPPs) with electrochemical methods presents a novel framework for enhancing biosensing capabilities, offering complementary approaches to improve the sensitivity and selectivity of DNA-based sensors.

The methodologies and techniques employed in designing and synthesizing DNA nanostructures underscore the interdisciplinary nature of this field, merging principles from chemistry, biology, and materials science. This synergy allows for precise control over nanomaterial morphology through DNA-guided metallization, facilitating the creation of metallic nanoparticles with tailored shapes and sizes. Such strategies leverage DNA's programmable characteristics, enabling the assembly of versatile nanoscale materials applicable in areas ranging from nanoelectronics to drug delivery, thereby highlighting the innovative potential of DNA nanotechnology in advancing various scientific domains [4, 5].

2.3 Principles of DNA Metallization

DNA metallization is a transformative process that enhances the electronic properties of DNA nanostructures, facilitating their use in advanced photonic and electronic applications. This process involves using DNA as a template to guide metal deposition, creating conductive pathways or metallic coatings on DNA frameworks [2]. Such precision in metal patterning is crucial for developing nanoscale devices with essential electronic and optical functionalities.

A core challenge in DNA metallization is achieving efficient, low-cost, and scalable methods for sub-10 nm nanolithography [1]. Controlling metal deposition at such fine scales is vital for integrating DNA nanostructures into solid-state devices, necessitating a comprehensive understanding of the kinetics and mechanisms involved in the metallization process, particularly in bulk films, where dynamics can significantly impact the quality and functionality of metallized structures [21].

DNA metallization approaches are broadly categorized into top-down and bottom-up methods. Top-down approaches typically involve photochemical metallization, where metal ions like silver are reduced to their metallic state directly on DNA templates via UV light activation [11]. This method allows precise control over metal placement, particularly for creating intricate metal patterns on DNA origami structures.

Conversely, bottom-up approaches rely on DNA's inherent molecular recognition and self-assembly properties to guide metal deposition. These methods often utilize low-valence metal ions that selectively condense on DNA strands, facilitating the formation of continuous metal coatings. The thermodynamic stability of DNA structures, driven by base-stacking interactions, supports these energy-efficient transformations, ensuring uniform metal coverage [15].

The implications of DNA metallization extend beyond structural modifications; it significantly enhances the electronic properties of DNA nanostructures. Metallized DNA frameworks exhibit improved conductivity and can support plasmonic and photonic activities, essential for applications in biosensing, nanoelectronics, and optical devices. The introduction of narrow-band Fano-type resonances, as observed in dielectric metasurfaces, exemplifies the potential of these metallized structures for achieving high-quality color generation and enhanced optical responses [12].

In recent years, the exploration of DNA metallization techniques has garnered significant attention within the scientific community. These techniques can be broadly categorized into hierarchical structures that encompass both top-down and bottom-up approaches, as well as chemical and physical processes. The advancements in this field not only demonstrate the versatility of DNA as a scaffold for metal integration but also highlight its potential applications across various domains, including electronics, photonics, and biosensing.

To illustrate this categorization more clearly, Figure 2 presents a comprehensive overview of the hierarchical framework of DNA metallization techniques. This figure effectively encapsulates the integration of DNA with metal ions and other nanomaterials, emphasizing the innovative advancements that have emerged in recent years. By visualizing these relationships, we can better appreciate the intricate interplay between different methodologies and their respective applications, thereby enhancing our understanding of the field's current landscape and future directions.

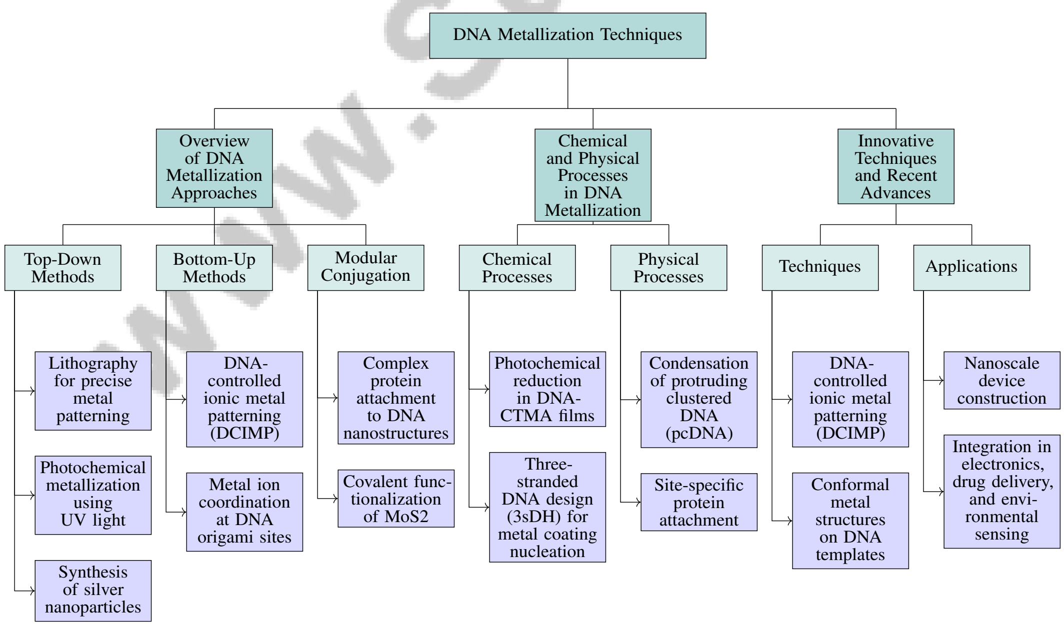


Figure 2: This figure illustrates the hierarchical categorization of DNA metallization techniques, including top-down and bottom-up approaches, chemical and physical processes, and innovative advancements. It highlights the integration of DNA with metal ions and other nanomaterials, showcasing applications in electronics, photonics, and biosensing.

3 DNA Metallization Techniques

3.1 Overview of DNA Metallization Approaches

DNA metallization leverages DNA's molecular recognition and programmability to craft conductive nanomaterials. Techniques range from top-down methods like lithography, which precisely pattern metals onto DNA templates, to bottom-up approaches that exploit DNA's self-assembly for metal deposition. Photochemical metallization, utilizing UV light to grow metallic structures, exemplifies top-down strategies, enabling the synthesis of structures such as silver nanoparticles, critical for optical storage and catalysis [6, 5, 21, 4]. Bottom-up methods, including DNA-controlled ionic metal patterning (DCIMP), enable precise metal ion coordination at DNA origami sites, fostering applications in nanoelectronics and nanophotonics [20, 4, 22, 11].

Modular conjugation enhances metallization versatility, allowing complex protein attachment to DNA nanostructures, thus expanding their functional potential [8]. Innovations like covalent functionalization of MoS2, while maintaining metallic properties, illustrate the integration of metallized DNA with other nanomaterials [13]. These diverse approaches underscore DNA's adaptability as a template for advanced nanomaterials, crucial for developing nanoscale devices in electronics, photonics, and biosensing [5].

3.2 Chemical and Physical Processes in DNA Metallization

DNA metallization transforms DNA into a functional nanomaterial with enhanced electronic properties through intricate chemical and physical processes. Photochemical reduction, such as silver ion reduction in DNA-CTMA films, exemplifies fundamental chemical processes, embedding nanoparticles within DNA matrices [21]. The three-stranded DNA design (3sDH) achieves controlled mineral-inducing group spacing, promoting metal coating nucleation on DNA templates [16].

Physical processes include the condensation of protruding clustered DNA (pcDNA) on origami templates, serving as nucleation sites for precise metal plating [22, 11]. Site-specific protein attachment ensures functional integrity during metallization, essential for applications requiring biological activity and enhanced electronic properties [8]. These processes enable multifunctional material transformation, facilitating applications in catalysis, sensing, and biomedical engineering through precise nanoparticle morphology control [4, 21, 5].

Figure 3 illustrates the categorization of chemical and physical processes in DNA metallization, highlighting the key methods and their applications in various fields. This visual representation effectively complements the preceding discussion, providing a clearer understanding of how these processes interact and contribute to the overall functionality of metallized DNA structures.

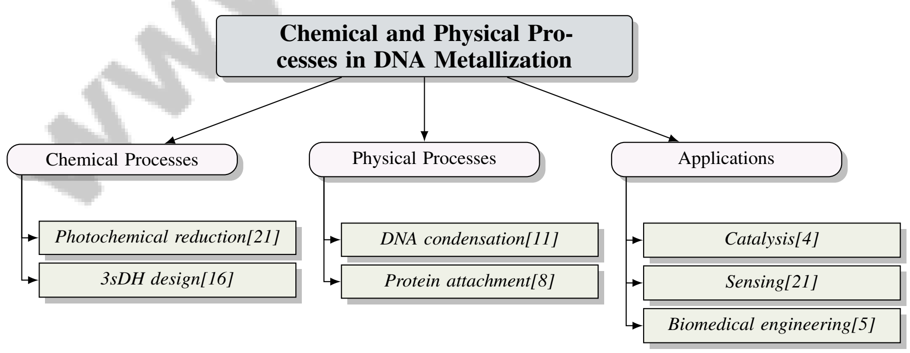


Figure 3: This figure illustrates the categorization of chemical and physical processes in DNA metallization, highlighting the key methods and their applications in various fields.

3.3 Innovative Techniques and Recent Advances

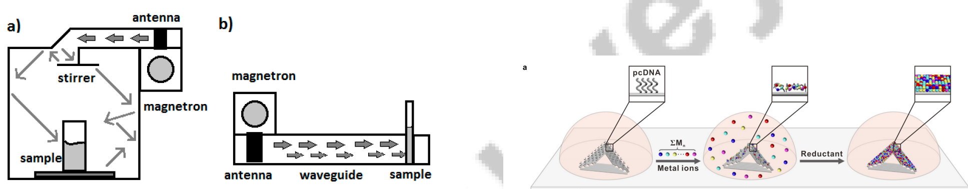
Advancements in DNA metallization have expanded the capabilities of DNA nanostructures, particularly in solid-state device development. Techniques like DNA-controlled ionic metal patterning (DCIMP) eliminate the need for nanoparticle anchoring, enabling direct, efficient metallization on

Method Name	Technological Innovations	Application Domains	Material Properties
DCIMP[20]	High-resolution Metallization	Nanoelectronics And Nanophotonics	High-resolution Metallic
PM[11]	Dna Origami Templates	Optical Metamaterials	Precise Control
DCIMP[22]	Dna Origami Templates	Nanoelectronics And Catalysis	Controlled Morphology

Table 1: Overview of DNA Metallization Techniques, Technological Innovations, and Their Applications in Nanotechnology. The table summarizes various methods, highlighting their technological advancements, application domains, and material properties, emphasizing the role of DNA-controlled ionic metal patterning (DCIMP) and DNA origami templates in enhancing nanoscale device fabrication.

DNA origami with high resolution, crucial for nanoscale device construction [20]. Recent methods offer advantages such as conformal metal structures on DNA templates, precise control, and minimal defects, enhancing electronic properties critical for nanoelectronics and optical devices [11]. Table 1 provides a comprehensive overview of recent advancements in DNA metallization techniques, detailing the technological innovations, application domains, and material properties associated with each method.

These innovations in DNA metallization techniques are revolutionizing nanotechnology by providing new methods for high-performance nanoscale material fabrication. They address existing challenges and pave the way for integrating DNA-based nanostructures into fields like electronics, drug delivery, and environmental sensing. By leveraging DNA's programmable properties, researchers create ordered nanomaterials with unique characteristics for innovative applications across disciplines [4, 6, 5].



(a) Magnetic resonance imaging (MRI) systems[23]

(b) Metal-Wrapped DNA: A Novel Approach for DNA Assembly and Assembly Control[22]

Figure 4: Examples of Innovative Techniques and Recent Advances

As illustrated in Figure 4, DNA metallization techniques offer innovative pathways for molecular assembly and control. Metal-wrapped DNA (mDNA) exemplifies this progress, with plasmid DNA (pcDNA) binding metal ions to form complexes reduced to mDNA, showcasing precise DNA assembly potential. This technique opens new avenues for nanotechnology and bioengineering applications. The juxtaposition of MRI systems highlights technological innovations' transformative impact in medical imaging and molecular engineering, illustrating the dynamic intersection of biology and technology for future breakthroughs in DNA manipulation and diagnostics [23, 22].

4 Applications in Colorimetric Biosensors

Exploring the transformative role of metallized DNA nanostructures in colorimetric biosensing reveals their foundational characteristics and functionalities. This section elucidates how these nanostructures enhance biosensor performance through improved stability, catalytic activity, and signal transduction. By examining their unique properties, this discussion underscores the significance of metallized DNA nanostructures in advancing colorimetric detection technologies.

4.1 Overview of Metallized DNA Nanostructures in Colorimetric Biosensing

Metallized DNA nanostructures are pivotal in advancing colorimetric biosensing technologies due to their enhanced stability, tunable catalytic activities, and effective signal transduction capabilities. These nanostructures provide a robust platform for biosensors that detect biological substances via visible color changes, offering a straightforward and economical diagnostic approach. Incorporating metallic elements into DNA frameworks enhances catalytic properties, enabling high sensitivity and rapid detection of analytes like glucose, while also driving advancements in chemical catalysis, environmental monitoring, and biomedical engineering [2, 24, 25].

A key strategy involves using gold nanoparticles (AuNPs) as colorimetric reporters, which exhibit distinct optical properties such as visible color change upon aggregation, triggered by specific analytes. This characteristic is utilized in biosensors for detecting toxins like saxitoxin (STX) through aptamer-functionalized AuNPs, where aptamer binding induces a measurable color shift [11, 5, 22, 2, 4].

In pathogen detection, metallized nanostructures in paper-based analytical devices (PADs) offer high-throughput, low-cost solutions for identifying pathogens in clinical and environmental samples [19]. The incorporation of aptamers enhances specificity and sensitivity, exemplified by aptamer-based colorimetric biosensors for arsenic detection, which outperform traditional methods [10].

Challenges such as low sensitivity and accuracy in paper-based colorimetric biosensors persist due to the lack of signal amplification techniques [26]. Addressing these involves optimizing the design and functionalization of metallized DNA nanostructures. Recent studies highlight the potential of aptamer and dsDNA-SYBR Green I complexes in high-throughput colorimetric biosensors for pathogen detection, as demonstrated with Staphylococcus aureus [27].

Innovative applications include using non-aggregated Au@Ag core-shell nanoparticles modified with DNA probes for illicit drug detection [28], and a paper-based colorimetric biosensor utilizing chitosan for enhanced glucose detection in tear samples [29].

Metallized DNA nanostructures are crucial for advancing colorimetric biosensors by enabling innovative detection methodologies that leverage DNA's unique properties for the synthesis and assembly of metallic nanoparticles. This technique allows precise control over nanomaterial morphology and size, facilitating applications across biomedical engineering, environmental monitoring, and chemical catalysis [2, 4]. Ongoing research continues to expand these applications, promising significant advancements in clinical diagnostics and environmental monitoring.

4.2 Mechanisms of Colorimetric Detection

Colorimetric biosensors detect biological substances via visible color changes, offering a straightforward method for biosensing applications. Integrated with nanomaterials and paper-based platforms, these sensors enhance sensitivity and signal stability. For instance, the interaction between horseradish peroxidase (HRP) and chromogenic substrates like 3,3',5,5'-tetramethylbenzidine (TMB) amplifies colorimetric signals, making them suitable for rapid pathogen detection in point-of-care settings, thereby simplifying detection and improving accuracy [30, 26, 19].

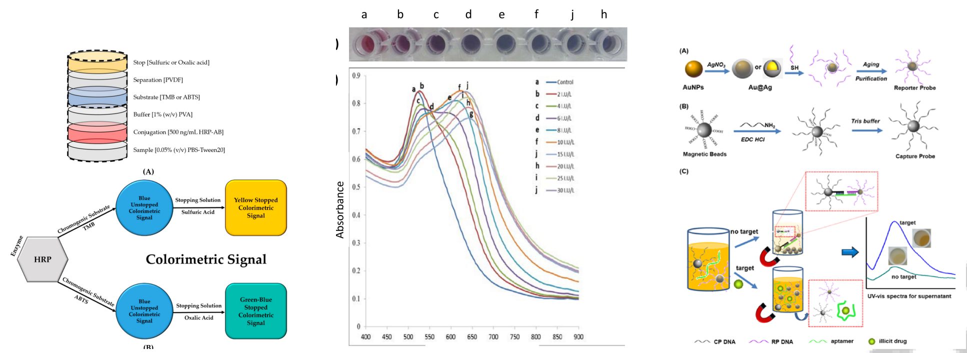
A fundamental mechanism is the localized surface plasmon resonance (LSPR) of AuNPs, resulting in distinct color changes upon aggregation. This property is utilized in detecting specific analytes, such as toxins and pathogens, where target molecule binding to aptamer-functionalized AuNPs induces aggregation and a corresponding color shift.

The oxidation of substrates like TMB catalyzed by peroxidase-like nanozymes is another mechanism in colorimetric detection. Nanozymes mimic natural enzymes, facilitating the conversion of colorless substrates into colored products, allowing analyte quantification such as glucose. The color change intensity is directly proportional to the target analyte concentration, enabling sensitive and quantitative measurements [31].

Additionally, dsDNA-SYBR Green I complexes in biosensors exemplify nucleic acid-based detection strategies. Under photo-irradiation, these complexes catalyze TMB oxidation, resulting in a measurable color change used to detect pathogens like Staphylococcus aureus [27]. This approach highlights colorimetric biosensors' versatility in leveraging various catalytic mechanisms for effective detection.

Paper-based biosensors enhance colorimetric detection by providing a platform for point-of-care testing, utilizing capillary action and colorimetric reactions to detect analytes in samples like tears, where color change correlates with glucose concentration [29]. However, challenges in achieving high sensitivity and accuracy necessitate strategies such as generating stopped colorimetric signals to improve detection precision [26].

The mechanisms of colorimetric detection in biosensors are diverse, encompassing metallic nanoparticles, enzyme-mimicking nanozymes, and nucleic acid complexes. These mechanisms enable the development of rapid, cost-effective, and sensitive biosensing technologies for various applications, including pathogen detection in global health crises [19].



(a) Enzyme-Linked Immunosorbent Assay (ELISA) Method for Protein Detection[26]

(b) Absorbance Spectra of Different Concentrations of a Sample[30]

(c) Synthesis and Application of Magnetic Nanoparticles for Targeted Drug Delivery[28]

Figure 5: Examples of Mechanisms of Colorimetric Detection

As shown in Figure 5, various mechanisms enhance colorimetric detection capabilities, offering significant applications in medical diagnostics and drug delivery. This section introduces three exemplary methods illustrating diverse approaches to colorimetric detection. The Enzyme-Linked Immunosorbent Assay (ELISA) method is highlighted for protein detection efficacy through a structured schematic diagram. The absorbance spectra of different sample concentrations demonstrate how variations in concentration can be visually and quantitatively assessed using absorbance values plotted against wavelength. Lastly, the synthesis and application of magnetic nanoparticles for targeted drug delivery focus on the innovative use of AuNPs to enhance precision and efficacy. These examples underscore the versatility and potential of colorimetric detection methods in advancing biosensor technology [26, 30, 28].

4.3 Innovations in Colorimetric Biosensor Design

Recent innovations in colorimetric biosensor design have significantly enhanced sensitivity, specificity, and applicability, especially in point-of-care settings. A notable advancement is integrating a stopping solution to stabilize and enhance the colorimetric signal. This approach, effective with substrates like TMB and ABTS on a PVDF membrane, ensures reliable and consistent signal outputs, improving detection accuracy [26].

Integrating nanomaterials into paper-based analytical devices (PADs) represents another significant innovation, demonstrating substantial improvements in pathogen detection sensitivity and specificity by enhancing signal amplification. This allows for more effective biosensors capable of rapid and accurate detection, crucial in clinical diagnostics and environmental monitoring [19].

Additionally, using non-aggregated Au@Ag core-shell nanoparticles has improved detection sensitivity compared to traditional gold nanoparticle-based methods. This innovation addresses aggregation-induced signal variability, providing a stable and reliable platform for colorimetric detection [28].

The combination of wax-printed microfluidic devices with chitosan modification marks a significant advancement in biosensor design, enhancing sensitivity and reliability for detecting analytes like glucose in biological samples [29]. Chitosan improves mechanical stability and facilitates better interaction between the analyte and sensing elements.

These innovations underscore ongoing efforts to refine colorimetric biosensor technologies, making them more accessible and effective for applications ranging from medical diagnostics to environmental analysis. Advancements in signal stabilization, nanomaterial integration, and device design continue to push the boundaries of rapid, point-of-care biosensing [30].

4.4 Applications in Pathogen and Toxin Detection

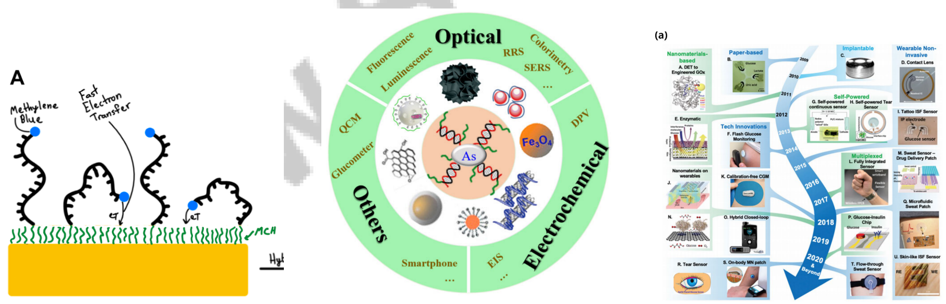
Colorimetric biosensors utilizing metallized DNA nanostructures show immense potential in pathogen and toxin detection, providing a rapid, cost-effective, and user-friendly diagnostics platform. These biosensors leverage metallic nanoparticles' unique optical properties, such as AuNPs, which exhibit distinct color changes upon specific analyte interaction. This feature is advantageous for detecting pathogens and toxins, allowing straightforward visual identification of target substances [19].

In pathogen detection, aptamer-functionalized nanostructures significantly enhance biosensors' specificity and sensitivity. Aptamers, short single-stranded DNA or RNA molecules with high affinity for specific targets, enable selective pathogen recognition, minimizing false positives and improving diagnostic accuracy. These aptamer-based biosensors effectively detect various pathogens, including bacteria and viruses, in clinical and environmental samples [19].

The detection of toxins, such as saxitoxin (STX), benefits from colorimetric biosensors. Specific aptamer binding to STX induces a color change, providing a visual indication of the toxin's presence. This approach offers rapid and reliable detection, crucial for food safety and environmental health monitoring [19].

Despite advancements, challenges remain in the widespread application of colorimetric biosensors for pathogen and toxin detection. Key issues include standardizing detection protocols to ensure consistent and reliable results across settings. Additionally, addressing the scalability of production methods for PADs is essential for large-scale deployment. Integrating multiplex detection capabilities, allowing simultaneous monitoring of multiple pathogens, requires further development to enhance utility in complex diagnostic scenarios [19].

Overall, applying colorimetric biosensors in pathogen and toxin detection represents a significant advancement in diagnostic technology. Ongoing research and development in electrochemical biosensors focus on addressing limitations such as sensitivity and detection range, critical for early disease diagnosis. By integrating advanced materials like nanomaterials, enzymes, and biomolecules, these efforts aim to enhance biosensors' capabilities to detect low concentrations of disease biomarkers in real-time. This progress is expected to significantly contribute to public health and safety by enabling rapid and accurate disease detection, improving food safety monitoring, and facilitating point-of-care diagnostics [32, 33, 34, 35, 25].



(a) Electron Transfer in a Membrane[36]

(b) Optical and Electrochemical Applications of As[10]

(c) Progress in Wearable and Implantable Sensors: A Timeline Overview[35]

Figure 6: Examples of Applications in Pathogen and Toxin Detection

As shown in Figure 6, colorimetric biosensors play a pivotal role in pathogen and toxin detection, illustrated by images encapsulating diverse methodologies and advancements. "Electron Transfer in a Membrane" offers insight into electron transfer processes, with Methylene Blue as a key component. "Optical and Electrochemical Applications of As" presents a circular diagram categorizing optical and electrochemical arsenic detection approaches, highlighting fluorescence and luminescence. Lastly, "Progress in Wearable and Implantable Sensors: A Timeline Overview" provides a chronological depiction of sensor technology evolution, showcasing significant strides in developing paper-based, implantable, and other sensor types. These images testify to innovative strategies in biosensor development for pathogen and toxin detection, reflecting the complexity and potential of these technologies in advancing public health and safety [36, 10, 35].

5 Applications in Electrochemical Biosensors

Understanding electrochemical biosensors' applications necessitates exploring the mechanisms that convert biochemical interactions into electrical signals. This foundational knowledge is crucial for appreciating how these biosensors utilize redox reactions and biocatalytic elements to enhance performance, as discussed in the following subsection.

5.1 Mechanisms of Electrochemical Signal Detection

Electrochemical biosensors transform biochemical interactions into measurable electrical signals, significantly enhanced by nanomaterials and advanced electrode designs. These sensors primarily utilize redox reactions, with enzymes facilitating analyte conversion into detectable signals [37]. Despite the effectiveness of traditional enzyme-based biosensors, they often struggle with sensitivity, selectivity, and stability. Incorporating metal and metal oxide nanoparticles enhances electron transfer and provides robust biosensing platforms [18].

Screen-printed carbon electrodes, modified with compounds like 1-pyrenebutyric acid-N-hydroxysuccinimide ester (PANHS), improve sensitivity and selectivity. For example, electrodes modified with PANHS and anti-hCG antibodies effectively detect human chorionic gonadotropin (hCG), demonstrating potential in clinical diagnostics [38].

Nanogap electrodes enhance sensitivity and selectivity, though optimizing their design remains challenging due to numerical simulation complexities and precise fabrication needs [25]. DNA origami frameworks improve biosensor specificity and sensitivity, using DNA's programmability to create functionalized surfaces [33].

Electrochemical biosensors employ amperometric, potentiometric, and impedimetric methods for analyte quantification, advantageous for on-site testing due to rapid response, low cost, and miniaturization potential [32]. Adaptations like using microcentrifuge tubes as electrochemical cells enhance point-of-care testing feasibility [25].

Advancements in nanomaterial integration, electrode design, and analytical methodologies drive the evolution of electrochemical signal detection in biosensors, crucial for detecting low-concentration disease biomarkers for early diagnosis and monitoring [39].

As illustrated in Figure 7, which depicts the hierarchical structure of electrochemical signal detection mechanisms, the integration of nanomaterials, advanced electrode designs, and various analytical methods collectively enhances the sensitivity, selectivity, and stability of biosensors for effective disease biomarker detection and monitoring. The schematic of an electronic network with resistors, capacitors, and inductors highlights the complexity in biosensor circuitry [40]. Square wave voltammetry data analysis is crucial for identifying analytes through current peaks [36]. Finally, the use of a nanocomposite for detecting Escherichia coli O157:H7 demonstrates advanced material integration for enhanced sensitivity and specificity [34].

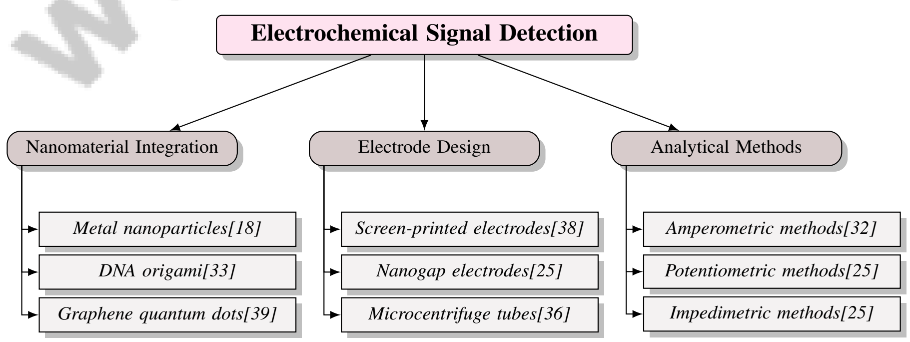


Figure 7: This figure illustrates the hierarchical structure of electrochemical signal detection mechanisms, highlighting the integration of nanomaterials, advanced electrode designs, and various analytical methods. These components collectively enhance the sensitivity, selectivity, and stability of biosensors for effective disease biomarker detection and monitoring.

5.2 Enhancement of Sensitivity and Selectivity

Enhancing electrochemical biosensors' sensitivity and selectivity is vital for detecting low-concentration biomarkers in complex samples. Nanomaterial integration improves electron transfer and robustness, but requires careful selection and optimization [41]. Advanced modeling techniques, inspired by electronic circuit optimization, address non-linear kinetics and species diffusion, enabling accurate sensor behavior predictions [40].

DNA origami offers a programmable framework for creating functionalized surfaces, enhancing biosensor sensitivity and selectivity while withstanding biofluid interference [42]. Novel antimicrobial glucose biosensors demonstrate high sensitivity, selectivity, and stability, ideal for real-time monitoring [43].

Adapting biosensor setups to minimize sample loss, reduce costs, and simplify use broadens accessibility, allowing experiments without extensive training [36]. Micro-electrodes enhance sensitivity and specificity, crucial for effective biomarker detection [38].

Challenges include achieving high sensitivity and specificity, ensuring stability and reproducibility, and simplifying fabrication and integration [25]. Addressing these is essential for practical diagnostic applications, particularly in detecting disease biomarkers [33]. The real-time, portable, and cost-effective detection capabilities of electrochemical biosensors are crucial for timely responses to infectious disease outbreaks [34].

5.3 Optimizing Electrode Designs

Optimizing electrode designs is crucial for enhancing electrochemical biosensors' sensitivity, selectivity, and efficacy. Advanced simulation schemes, such as those mapping diffusion problems to circuit elements, enable electrode configuration optimization through electronic circuit-inspired methodologies [40]. This approach fine-tunes electrode parameters, improving electrochemical response and signal transduction efficiency.

Nanostructured materials in electrode designs significantly enhance performance. For instance, TiO_2 nanotubes modified with AgO and Prussian blue offer a robust platform for glucose oxidase immobilization, improving glucose detection sensitivity and selectivity [43]. Controlled environments in cyclic voltammetry and chronoamperometry ensure reliable measurements, highlighting material choice and experimental conditions' importance in optimization.

Electrode design and fabrication stages include fluidic manipulation, signal amplification, and data processing, emphasizing efficacy, usability, and cost-effectiveness for real-world implementation [25]. Microfluidic systems with optimized electrode designs enhance small sample volume manipulation, boosting biosensor detection capabilities.

User-friendly methods for detecting biomolecular binding events enhance sensitivity and selectivity, utilizing small analyte volumes for practical applications [36]. Optimizing electrode designs involves integrating advanced simulation techniques, nanomaterials, and practical design factors to develop portable and wearable biosensors for health monitoring and diagnostics. This approach addresses numerical complexities and aims to improve sensing accuracy, integrating biosensors into digital healthcare pathways [14, 40, 25]. These efforts advance electrochemical biosensors' capabilities for clinical diagnostics, environmental monitoring, and pathogen detection.

5.4 Integration with DNA Origami

Integrating DNA origami with electrochemical biosensors enhances functionality, offering a versatile platform for precise analyte detection. DNA origami's programmability and structural precision create ordered, functionalized surfaces that improve biosensor sensitivity and selectivity [42]. This integration involves designing DNA origami structures tailored to specific analytes, functionalizing them with binding sites, and incorporating them into electrochemical platforms.

DNA origami enables intricate three-dimensional structures accommodating diverse functional components, enhancing real-time molecular sensing capabilities. This innovative approach leverages DNA origami's properties for precise nanoscale object assembly, advancing biosensing technologies [20, 42, 36, 11]. These structures serve as scaffolds for efficient electron transfer and improved biosensor performance. DNA origami's programmability allows customizable binding sites for selective target detection in complex samples.

Advanced simulation techniques, mapping diffusion equations to equivalent circuit elements, optimize DNA origami integration with biosensors. Electronic design automation tools fine-tune electrochemical properties, ensuring optimal performance [40]. These tools help explore parameter space and identify configurations maximizing sensitivity and selectivity.

Integrating DNA origami with electrochemical biosensors enhances detection capabilities, crucial for addressing health threats like infectious diseases. It broadens applications in clinical diagnostics, environmental monitoring, and pathogen detection, improving public health outcomes [34, 19]. Ongoing research continues to push DNA-based nanotechnology's boundaries, promising significant biosensor technology advancements.

6 Synthesis of Metallic Nanosheets

Recent advancements in metallic nanosheet synthesis have focused on developing innovative, scalable, and sustainable methods to meet the demand for high-quality nanomaterials. This section outlines key synthesis techniques that enhance the scalability and quality of metallic nanosheets for diverse applications.

6.1 Scalable Synthesis Techniques

Scalable synthesis techniques are essential for producing metallic nanosheets with superior electrical properties, crucial for electronics and energy storage. Chemical vapor deposition (CVD) stands out as a leading method, enabling the controlled growth of nanosheets with precise thickness and uniformity. This method has successfully produced high-quality VS2 nanosheets with exceptional electrical properties, making them suitable for next-generation electronic devices [44]. CVD's scalability is due to its ability to generate large-area nanosheets with high purity and crystallinity, characterized by sub-10 nm thickness and large domain sizes [45, 44, 6]. Process parameters such as temperature, pressure, and precursor concentration are tunable to optimize growth conditions for desired material characteristics.

Other scalable techniques include liquid-phase exfoliation and electrochemical deposition. Liquid-phase exfoliation involves dispersing bulk materials in a solvent and using sonication or mechanical agitation to separate layers into nanosheets, offering simplicity and large-scale production potential. Electrochemical deposition uses an electric field to reduce metal ions onto a substrate, allowing for tailored nanosheet shapes and sizes [45, 4, 44]. These methods are crucial for producing transition metal dichalcogenides like vanadium disulfide and molybdenum disulfide, which are critical for high-performance electronics and efficient energy storage systems [39, 3, 44, 13].

6.2 DNA-Template Synthesis

DNA-template synthesis leverages DNA's structural properties to guide the formation of metallic nanosheets. This method uses DNA's chemical functionality and programmable base-pairing interactions as scaffolds for metal ion deposition, allowing precise modulation of nanosheet morphology and functionality [4, 6]. Ambient-pressure CVD, adapted for synthesizing sub-10 nm thick VS2 nanosheets, exemplifies this technique's effectiveness [44]. DNA-template synthesis simplifies fabrication processes and enables the creation of complex nanostructures tailored for applications in catalysis, bio-sensing, and drug delivery [6, 5, 22, 4]. The use of DNA as a template marks a significant breakthrough in nanomaterial fabrication, enabling cost-effective and efficient synthesis compared to traditional methods.

6.3 Microwave Reactor Technology

Microwave reactor technology has revolutionized metallic nanosheet synthesis by providing rapid and uniform heating, enhancing growth control. This method, highlighted by Dkabrowska et al., emphasizes efficiency in achieving precise temperature control and reduced reaction times [23]. Microwave reactors facilitate chemical reactions leading to metallic layer formation, optimizing configurations and materials for improved outcomes [45, 23, 3]. The rapid heating reduces synthesis time and energy consumption, aligning with sustainability goals. This technology allows fine-tuning of reaction conditions, crucial for enhancing the performance of materials like molybdenum disulfide and vanadium disulfide in catalysis and multifunctional electrodes [23, 44, 39, 18, 13].

6.4 Chemical Vapor Deposition (CVD)

CVD is fundamental for synthesizing metallic nanosheets, such as vanadium disulfide (VS), essential for next-generation electronic and energy-storage applications. This method offers precise control over material properties, producing crystalline nanosheets with sub-10 nm thickness and significant domain sizes, exhibiting excellent electrical conductivities (3×10^{3} S cm^{1}) [4, 44]. The CVD process involves vapor-phase deposition of metal precursors onto a substrate, resulting in high-quality nanosheets with uniform thickness and crystallinity [3, 44]. CVD's versatility allows for synthesizing various metallic nanosheets, including transition metal dichalcogenides, facilitating advancements in energy storage, transparent electrodes, and electronic devices [23, 3, 44, 39, 45].

6.5 Green Synthesis Methods

Green synthesis methods focus on environmentally friendly approaches that minimize hazardous chemicals and energy consumption. Microwave reactor technology exemplifies this, demonstrating efficiency in producing high-quality nanomaterials with controlled properties [23]. Plasma-liquid interactions represent another innovative approach, leveraging plasma's unique properties to induce chemical reactions in liquid environments, facilitating nanosheet formation under mild conditions [45]. Advancing green synthesis methods is vital for sustainable nanotechnology, as these approaches minimize environmental impact and leverage renewable resources for producing advanced nanomaterials needed in energy storage and environmental remediation [23, 3, 44, 39].

6.6 Plasma-Liquid Interactions

Plasma-liquid interactions (PLIs) are a cutting-edge approach in synthesizing metallic nanosheets, combining physical and chemical processes under mild conditions. The interaction between plasma and liquid phases generates reactive species that promote nucleation and growth of nanosheets at the plasma-liquid interface [45]. Research on nanomaterial synthesis via PLIs emphasizes understanding the plasma-liquid interface, crucial for controlling nanosheet size, morphology, and composition [23, 3]. PLIs align with green chemistry principles by reducing reliance on toxic solvents and harsh conditions. The synthesis of high-purity nanosheets using PLIs is advantageous for applications in electronics, catalysis, and energy storage, where material integrity is critical [3, 44, 39, 13, 45]. As research progresses, integrating PLIs into nanomaterial synthesis enhances scalability and supports environmentally friendly technologies [23, 3, 44, 13, 45].

7 Challenges and Future Directions

7.1 Challenges and Limitations

The development of DNA nanostructures faces significant challenges that impede their practical application. Key issues include variability in experimental conditions and the lack of standardized methods, which compromise reproducibility and scalability [7]. The complexity of fabricating synthetic DNA structures limits their length and intricacy, restricting deployment [24]. Concerns about the reproducibility and stability of nanomaterial-based biosensors persist, with challenges in achieving consistent results and long-term performance [37]. Additionally, DNA damage during metallization, particularly in photochemical methods, raises concerns about structural integrity, although some studies report no significant changes [13].

Integrating functional materials into DNA nanostructures presents additional challenges, such as interference from biological matrices and the need for optimization to enhance sensitivity [30]. The complexity of biosensor fabrication, biomolecule stability issues, and the requirement for sophisticated detection equipment further complicate biosensing applications [33]. The sensitivity of reflectance spectra to fabrication imperfections can undermine the quality of colorimetric biosensors, necessitating precise manufacturing techniques [14].

Environmental and regulatory concerns also pose significant hurdles. The toxicity and environmental impact of nanomaterials, alongside compliance with regulatory standards, are particularly relevant in applications like arsenic detection, where selectivity and sensitivity challenges persist in complex samples [32]. Existing methods in clinical diagnostics, such as HPLC and ELISA, are often complex and costly, limiting their applicability for real-time monitoring of toxins like saxitoxin (STX) in water [46].

Scalability issues with green synthesis methods and the need for comprehensive studies on the long-term stability of graphene quantum dots (GQDs) remain significant challenges [39]. Variability in electrode manufacturing complicates result reproducibility, while controlling synthesis processes due to diverse reactive species generated in plasma-liquid interfaces and preventing oxidation of reactive metals are key obstacles [45]. Addressing these challenges is crucial for advancing DNA nanostructures, enabling the development of highly programmable and versatile nanomaterials for applications in nanoelectronics, drug delivery, catalysis, environmental sensing, and biomedical engineering. Overcoming these obstacles will allow researchers to fully exploit the unique properties of DNA-based scaffolds for assembling metal nanoparticles and fabricating complex nanostructures, unlocking new functionalities and applications [6, 5].

7.2 Addressing Knowledge Gaps

Despite the potential of DNA nanostructures, critical knowledge gaps must be addressed to fully leverage their capabilities. One major uncertainty is the long-term stability and real-world applicability of biosensors under varying environmental and biological conditions. Developing standardized methodologies to validate sensor performance and reliability is imperative for broader adoption [41].

Further exploration is needed on the scalability and operational longevity of microwave reactors, essential for synthesizing metallic nanosheets. Establishing standardized protocols and conducting comprehensive studies on the scalability of these reactors for industrial applications are vital steps toward optimizing their use in large-scale nanomaterial production [23].

The mechanisms of cellular uptake of DNA nanostructures, their stability in serum conditions, and the impact of various modifications on their performance remain inadequately understood. These factors are critical for effective biomedical applications, necessitating detailed investigations to elucidate these mechanisms and enhance integration in biological systems [7].

Moreover, the selectivity and sensitivity of metal nanoparticle sensors warrant further exploration. Identifying optimal conditions for enhancing these properties, along with a deeper understanding of their catalytic mechanisms, is essential for improving sensor efficacy in detecting specific analytes [24].

The long-term stability and toxicity of nanomaterials in biological systems also present significant challenges. Developing improved methods to mitigate interference from biomolecules and conducting thorough toxicity assessments are crucial for ensuring safe and effective nanomaterial use [18]. Addressing these knowledge gaps through targeted research initiatives and interdisciplinary collaboration is vital for advancing DNA nanostructures and unlocking new opportunities in nanotechnology and biosensing. This approach will facilitate the development of innovative DNA-directed assembly methods, enhance the precision of metallic nanomaterial fabrication, and expand the application of DNA nanostructures across various domains, including nanoelectronics, drug delivery, environmental sensing, and biomedical engineering. Leveraging DNA's programmable base-pairing and addressability allows researchers to create organized nanomaterials with tailored functionalities, driving progress in both fundamental science and practical applications [6, 5, 16].

7.3 Enhancing Biosensor Performance and Stability

Enhancing the performance and stability of biosensors utilizing DNA nanostructures is crucial for advancing their practical applications. Future research should focus on optimizing the dynamic properties of DNA scaffolds to improve guided mineralization, essential for regenerating mineralized tissues. Refining the metallization process to enhance the quality and functionality of metal structures, potentially through other DNA-based templates, is essential [15]. Additionally, optimizing metal precursor combinations and exploring other metal complex anions in the metallization process could improve the uniformity and functionality of biosensors [22].

Integrating advanced numerical simulation techniques, such as electronic circuit-inspired optimization, can simplify complex simulations and enhance accessibility for experimental applications [38]. This approach aids in the precise design of biosensor components, ultimately improving sensitivity and specificity. Exploring alternative reagents for transformation and enhancing scalability could lead to the development of more intricate 3D structures, expanding biosensor functional capabilities [15].

Future research should also focus on improving fabrication techniques to minimize imperfections and exploring more complex metasurface designs to enhance color generation capabilities [12]. Simplifying biosensor designs and enhancing stability are crucial, particularly for food safety monitoring, where integrating biosensors with information communication technology could offer significant benefits [32].

Moreover, optimizing nanozyme formulations and conducting clinical trials to validate biosensor effectiveness in real-world applications are essential steps for advancing the field [31]. Investigating the relationship between functional group density and catalytic performance, such as in the hydrogen evolution reaction (HER), is necessary to optimize the balance between activity and stability [13].

Incorporating wearable technologies and improving real-time monitoring capabilities are vital for developing user-friendly, cost-effective, and scalable biosensors. Enhancing multiplexing capabilities and robustness in complex samples is critical for advancing practical applications, particularly in pathogen detection [32]. Optimizing nanomaterials for specific applications and integrating biosensors into portable devices for real-time monitoring are pivotal for advancing the field, especially in glucose monitoring, where real-time data collection can significantly impact patient care [31].

The strategies discussed emphasize the need for a comprehensive approach to enhance the performance and stability of DNA nanostructure-based biosensors. This multifaceted methodology is essential for ensuring effective applications across various scientific and industrial fields, particularly in real-time disease diagnosis and environmental monitoring, where sensitivity and specificity are paramount. By leveraging advancements in nanomaterials, electrochemical techniques, and aptamer technology, researchers can develop biosensors capable of detecting various biomarkers and analytes in complex biological samples, addressing critical health and environmental challenges [17, 42, 35, 36].

7.4 Advancements in Nanomaterial Synthesis and Integration

Recent advancements in synthesizing and integrating nanomaterials with DNA nanostructures have significantly broadened their applications across various scientific and industrial fields. A key focus has been on enhancing the scalability and robustness of DNA-directed assembly techniques, crucial for their adoption in nanomedicine and materials science [5]. This involves developing sophisticated modular designs easily adaptable for new targets, thereby increasing the versatility and applicability of DNA-based devices in real-world contexts [42].

Significant progress has been made in integrating nanomaterials with DNA nanostructures, particularly in biosensing. Enhancements in sensor designs aim to improve performance for real-time monitoring, explore new nanomaterials, and develop portable sensing devices for point-of-care applications [37]. Ongoing efforts to simplify fabrication processes and enhance biosensor stability focus on exploring new biomaterials and detection strategies to expand electrochemical biosensors' applicability [33].

In DNA-guided metallization, there is potential to produce nanomaterials with tailored properties for specific biomedical applications. However, further research is needed to address current limitations and improve the scalability and robustness of these techniques [4]. Investigating new materials for enhanced sensitivity and the role of energetic carriers in electrochemical reactions are critical areas for future research [14].

Applying machine learning to expand biosensor detection capabilities represents another promising research direction. By developing public datasets and applying machine learning to new analytes, researchers aim to advance the field and enhance the functionality of DNA-based sensors [47]. Continued exploration and refinement of nanomaterial synthesis and integration techniques hold significant promise for advancing DNA nanotechnology. These efforts are anticipated to yield groundbreaking solutions across diverse scientific and industrial fields, significantly improving the functionality and applications of DNA-based devices in critical areas such as clinical diagnostics, environmental monitoring, chemical catalysis, and biomedical engineering. Recent advancements in DNA metallization techniques have facilitated creating sophisticated nanostructures that serve as effective scaffolds for guided mineralization, enhancing the potential for innovative applications in biosensing and other disciplines [16].

7.5 Potential Impact on Industries

DNA nanostructures and their applications are poised to revolutionize various industries by offering innovative solutions and enhancing technological capabilities. In healthcare, integrating DNA nanostructures in biosensors promises to improve diagnostic accuracy and efficiency. The development of non-invasive, pain-free testing methods, such as rapid glucose monitoring at the point of care, exemplifies the potential of DNA-based technologies to enhance patient care and streamline clinical workflows [29]. Furthermore, advancing high-throughput chip-based platforms for multiplex detection of toxins could transform environmental monitoring and food safety testing, providing rapid and reliable assessments crucial for public health [46].

In electronics, DNA-guided synthesis techniques are revolutionizing material science by enabling precise control over the morphology and composition of metallic nanomaterials. This advancement is anticipated to facilitate developing next-generation electronic devices with enhanced performance characteristics, as these techniques allow for creating complex nanostructures tailored for specific applications in nanoelectronics, nanophotonics, and catalysis. By utilizing DNA as a template for metallization, researchers can achieve a high degree of customization in nanomaterials, paving the way for innovative solutions in electronic technology [20]. The scalability and efficiency of microwave reactor technology, along with refining simulation techniques to incorporate complex kinetics, are critical for advancing the industrial application of DNA nanostructures in electronic systems. Producing high-quality nanosheets with tailored properties through chemical vapor deposition and other scalable synthesis methods will further enhance the performance and functionality of electronic components.

The potential impact of DNA nanostructures extends to catalysis, where advanced synthesis techniques and conjugation with molecular recognition elements can significantly enhance the selectivity and efficiency of metal nanoparticles [24]. This could lead to more effective catalytic processes in chemical manufacturing and energy production, contributing to sustainability and efficiency in industrial operations.

Despite these advancements, challenges remain in the integration and practical applicability of electrochemical biosensors [25]. Continued research and innovation are necessary to address these challenges and realize the potential of DNA nanostructures in transforming various industries. By leveraging the unique properties of DNA and advancing synthesis and integration techniques, DNA nanotechnology is set to profoundly impact healthcare, electronics, environmental monitoring, and beyond.

8 Conclusion

The exploration of two-dimensional DNA nanostructures underscores their pivotal role in advancing biosensor technology and nanomaterial synthesis. These nanostructures serve as versatile frameworks for constructing intricate nanoscale systems, culminating in the creation of highly sensitive biosensors with exceptional selectivity. The enhancement of electronic properties through metallization techniques enables these structures to facilitate the real-time detection of multiple biomarkers, which is crucial for both diagnostic and environmental applications.

The synthesis of metallic nanosheets using DNA templates, combined with innovative approaches such as chemical vapor deposition and plasma-liquid interactions, demonstrates significant potential for producing high-quality nanomaterials with customizable properties. Plasma-liquid interactions, in particular, offer a versatile synthesis method, providing precise control over nanomaterial dimensions and morphology through the modulation of plasma parameters and reaction conditions. These advancements are critical for applications in nanoelectronics and nanophotonics, where achieving high-resolution metallic patterns with near-perfect yield is essential.

As the demand for advanced nanomaterials continues to grow, it becomes increasingly important to understand their toxicological impacts and to establish comprehensive guidelines for their safe use. Future research should focus on overcoming challenges related to the scalability of synthesis processes, the long-term stability of DNA nanostructures, and the integration of advanced computational techniques to optimize biosensor designs. By leveraging the distinctive properties of DNA and advancing synthesis and integration methodologies, DNA nanotechnology holds the promise to transform industries such as healthcare, electronics, and environmental monitoring, fostering innovative solutions and enhancing technological capabilities.

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