DNA-BASED COPPER NANO CLUSTERS: A FRONTIER IN NANOTECHNOLOGY AND BIOMEDICAL APPLICATIONS

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I. INTRODUCTION

Nanotechnology, the manipulation of matter at the atomic and molecular scale, has revolutionized various scientific disciplines and industries, offering unprecedented opportunities for innovation and advancement. Within this burgeoning field, DNA-based copper nano clusters have emerged as a fascinating and promising area of research. These nano clusters, composed of a small number of copper atoms arranged using DNA as a template, possess unique structural and optical properties that make them highly desirable for a wide array of applications, especially in nanotechnology and biomedicine.

The use of DNA as a scaffold for synthesizing nano clusters opens up new avenues for precisely controlling their size, shape, and properties **[1]**. By exploiting the complementary base-pairing and self-assembly capabilities of DNA, researchers can design nano clusters with tailored characteristics, enabling a diverse range of functionalities. The incorporation of copper into the nano clusters further enhances their potential due to copper's excellent catalytic and optical properties **[2]**.

In this chapter, we delve into the fundamentals of DNA-based copper nano clusters, exploring their molecular structure, chirality, and optical behaviour. We also examine the various synthesis methods employed to fabricate these nano clusters, including template-based approaches, ligand-assisted methods, and green synthesis techniques. Understanding these fundamental aspects is crucial for optimizing the performance of DNA-based copper nano clusters in diverse applications.

Additionally, we investigate the various characterization techniques used to study these nano clusters, such as UV-Vis absorption spectroscopy, fluorescence spectroscopy, and

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advanced imaging methods. Accurate characterization provides valuable insights into their properties, aiding in tailoring them for specific applications.

The versatility of DNA-based copper nano clusters extends to their wide-ranging applications, from biomedical imaging and targeted drug delivery to environmental remediation and nanoelectronics. We explore exemplary case studies that highlight their impact in real-world scenarios, showcasing their potential in solving complex challenges across multiple disciplines.

However, as with any emerging technology, DNA-based copper nano clusters also come with their share of challenges and considerations. Scalability, stability, biocompatibility, safety, and ethical implications are essential aspects that require careful examination to ensure the responsible and effective use of these nanomaterials **[3]**.

By delving into the frontiers of DNA-based copper nano clusters, this chapter aims to provide an insightful overview of this exciting area of research. The potential applications and ongoing advancements hold promise for addressing current challenges and opening up new opportunities in nanotechnology and biomedicine, ultimately contributing to the advancement of science and improving human lives.

II. FUNDAMENTALS OF DNA AND COPPER NANOPARTICLES

DNA and copper nanoparticles are two distinct entities with remarkable properties, and their combination as DNA-Based Copper Nano Clusters introduces a novel avenue of exploration in the realm of nanotechnology. This section delves into the fundamental aspects of DNA and copper nanoparticles, elucidating their unique characteristics and explaining the rationale behind their integration in nanoscale structures.

DNA, or deoxyribonucleic acid, serves as the genetic blueprint of living organisms, carrying the instructions necessary for their development, growth, and functioning. Its iconic double-helix structure, comprised of nucleotide bases adenine (A), thymine (T), cytosine (C), and guanine (G), forms the basis for the hereditary information transfer **[4]**. Additionally, DNA exhibits a remarkable capability to self-assemble, making it an attractive candidate for designing and fabricating nanostructures.

On the other hand, copper nanoparticles exhibit intriguing properties that differ from their bulk counterpart. At the nanoscale, copper nanoparticles display a high surface area-to-volume ratio, leading to enhanced reactivity and distinct physicochemical behaviours **[5]**. Their size-dependent properties offer unique optical, magnetic, and catalytic attributes, making them valuable in various applications.

The combination of DNA and copper nanoparticles leverages the self-assembling properties of DNA as a template for organizing copper atoms into well-defined nanostructures. DNA strands guide the spatial arrangement of copper atoms, resulting in the formation of DNA-Based Copper Nano Clusters with tailored properties. This synergistic approach provides researchers with precise control over nanostructure design, enabling the fabrication of functional materials with applications across diverse scientific fields.

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By understanding the fundamentals of DNA and copper nanoparticles, researchers can harness their photophysical properties of copper nano clusters, biocompatibility and bioimaging applications, drug delivery and therapeutic potential, Catalytic activity and its relevance in green chemistry & sensing and biosensing applications.

III. SYNTHESIS AND CHARACTERIZATION OF DNA-BASED COPPER NANO CLUSTERS

The synthesis and characterization of DNA-Based Copper Nano Clusters form the foundation of research in this burgeoning field. This section delves into the methods used to create these nano clusters and the various techniques employed to assess their structure and properties.

1. Methods of synthesizing DNA-Based Copper Nano Clusters

- **Synthesis of DNA Template:** DNA template utilizes the complementary base pairing of DNA to guide the arrangement of copper atoms **[6]**. Researchers design specific DNA sequences that function as templates, dictating the spatial organization of the copper nanoparticles. The hybridization of DNA strands with copper precursors facilitates the controlled nucleation and growth of the nano clusters. This method allows for precise tuning of the nano cluster size, shape, and composition by altering the DNA template design.

- **Chemical Reduction Methods:** In chemical reduction approaches, copper ion is reduced to form nanoparticles in the presence of DNA as a stabilizing agent. Reducing agents, such as sodium borohydride or hydrazine, are employed to reduce copper salts, resulting in the formation of DNA-based copper nano clusters **[7]**. This technique offers simplicity and versatility, allowing for the synthesis of nano clusters with varied sizes and shapes by adjusting reaction conditions.

2. Characterization Techniques For Assessing Structure And Properties

- **Spectroscopic Analysis:** Spectroscopic techniques, including UV-Vis (ultraviolet-visible), FTIR (Fourier-transform infrared), and Fluorescence spectroscopy, provide valuable insights into the optical properties and electronic structure of DNA-based copper nano clusters. UV-Vis's spectroscopy helps in identifying the absorption and emission characteristics, while FTIR offers information about molecular vibrations and bonding interactions **[8]** Fluorescence spectroscopy enables the study of luminescence behaviour and quantum yield, shedding light on the photophysical properties of the nano clusters.

- **Transmission Electron Microscopy (TEM):** TEM is a powerful imaging technique that allows researchers to visualize the morphology and size of individual DNA-based copper nano clusters at the nanoscale **[9]**. It provides high-resolution images, enabling the observation of nano cluster shapes and confirming their uniformity.

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- **X-ray Diffraction (XRD):** XRD is employed to investigate the crystallographic structure of DNA-based copper nano clusters **[10]**. By analysing the diffraction patterns produced when X-rays interact with the nano clusters, researchers can determine their crystal structure and lattice parameters, providing insights into their composition and arrangement.

- **Atomic Force Microscopy (AFM):** AFM is used to study the surface topography of DNA-based copper nano clusters with nanometre resolution **[11]**. It helps in understanding the nano cluster height, surface roughness, and other surface properties, contributing to a comprehensive characterization of the nano clusters.

The combination of these synthesis methods and characterization techniques allows researchers to tailor the properties of DNA-based copper nano clusters for specific applications. Understanding the structure and properties of these nano clusters is vital for unlocking their full potential in various scientific domains, from nanoelectronics to biomedical imaging and therapeutics.

IV. FACTORS INFLUENCING THE FORMATION AND STABILITY OF DNA-BASED COPPER NANO CLUSTERS

The successful formation and stability of DNA-Based Copper Nano Clusters are governed by a range of factors that impact their structure, properties, and performance. This section explores key parameters that researchers need to consider during the synthesis process to achieve well-defined and stable nano clusters.

1. **Influence of DNA sequence and length on cluster formation:** The choice of DNA sequence and length significantly influences the formation of DNA-Based Copper Nano Clusters. Different DNA sequences can function as templates with varying affinities for copper ions, leading to distinct nano cluster sizes and shapes. Longer DNA strands can accommodate more copper ions, resulting in larger nano clusters, while shorter ones may lead to smaller and more compact structures. Thus, tailoring the DNA template design offers researchers precise control over the final nano cluster characteristics.

2. **Impact of Copper Precursor Concentration And Reaction Conditions:** The concentration of copper precursors in the synthesis reaction plays a crucial role in determining the yield and size distribution of DNA-Based Copper Nano Clusters **[12]**. Higher copper precursor concentrations can result in higher nucleation rates, leading to an increased number of smaller nano clusters. On the other hand, lower concentrations may favour the growth of fewer, larger clusters. Moreover, reaction conditions, such as temperature and reaction time, also influence the kinetics of cluster formation. Optimal conditions must be established to achieve the desired nano cluster size, stability, and uniformity.

3. **Role of Temperature, Ph, And Other Environmental Factors:** Temperature and pH are essential environmental factors that influence the kinetics and thermodynamics of DNA-Based Copper Nano Cluster synthesis. Different temperature and pH conditions can favour specific reaction pathways, affecting the formation of different nano cluster shapes

or stabilization **[13]**. Additionally, the presence of capping agents or stabilizing agents in the reaction can influence the surface properties and stability of the nano clusters. Understanding and controlling these environmental factors are critical to obtaining nano clusters with desired properties.

4. **Strategies to Enhance the Stability and Uniformity of The Clusters:** Improve the stability and uniformity of DNA-Based Copper Nano Clusters, researchers employ various strategies. One approach involves using DNA sequences with functionalized ends or modifications, allowing precise control over the arrangement of copper atoms. This leads to more uniform and stable nano clusters **[14]**. Moreover, the addition of surfactants or ligands during synthesis can function as stabilizing agents, preventing nanoparticle agglomeration, and enhancing colloidal stability.

By carefully considering these factors, researchers can optimize the synthesis process to achieve well-defined, stable, and uniform DNA-Based Copper Nano Clusters. Understanding how these factors influence cluster formation is crucial for tailoring the properties of these nanostructures for specific applications, ranging from bioimaging and drug delivery to catalysis and beyond.

V. STRUCTURAL PROPERTIES OF DNA-BASED COPPER NANO CLUSTERS

DNA-based copper nano clusters possess distinctive structural properties, making them an appealing choice for diverse applications in nanotechnology and biomedicine. Their molecular arrangement, chirality, optical characteristics, and theoretical models play pivotal roles in understanding their potential and applications.

1. **Molecular Structure and Composition:** DNA serves as a template, guiding the arrangement of copper atoms in these nano clusters. The size and shape of DNA-based copper nano clusters exhibit variations, influenced by the DNA sequence and secondary structure **[15]**. Precise synthesis methods enable the creation of nano clusters with specific structural attributes, offering control over their properties.

2. **Chirality and Its Impact on Cluster Stability and Properties:** Chirality, a defining feature of these nano clusters, arises from their asymmetric arrangements**. [16]** Chiroptical spectroscopy is a valuable tool for studying their chiral properties. The presence of chirality affects the stability and reactivity of the clusters, influencing their behaviour in different environments.

3. **Optical Properties and Photoluminescence Behaviour:** The optical properties of DNA-based copper nano clusters, including their absorption and emission spectra, are of significant interest. Quantum confinement effects are observed, leading to size-dependent optical characteristics. Photoluminescence mechanisms in these clusters shed light on their emission behaviours.

4. **Theoretical Models and Simulations:** Theoretical models and simulations play a crucial role in predicting and understanding the structural properties of DNA-based copper nano clusters **[17]**. Density Functional Theory (DFT), Molecular Dynamics (MD), and Monte

Carlo simulations are employed to simulate cluster behaviour, elucidating their properties and dynamics.

5. **Stability and Factors Influencing Structural Transitions:** The stability of DNA-based copper nano clusters is impacted by various factors, including environmental conditions and interactions with ligands **[18]**. Thermodynamic and kinetic considerations contribute to their stability, and controlling these factors is essential to prevent degradation and aggregation.

6. **Interactions with Biomolecules and Cellular Uptake**: The interactions between DNA-based copper nano clusters and biomolecules are of particular interest, especially in biomedical applications. Understanding cellular uptake mechanisms and intracellular localization helps assess their potential for targeted drug delivery and imaging applications.

7. **Multifunctional Architectures and Hybrid Structures:** Designing multifunctional DNA-based copper nano clusters allows for the integration of additional functionalities. Combining these clusters with other nanomaterials creates hybrid structures with synergistic properties, expanding their applications and versatility.

In summary, comprehending the structural properties of DNA-based copper nano clusters is fundamental to their effective utilization. Through experimentation and theoretical models, researchers can optimize these clusters for specific applications, paving the way for novel advancements in nanotechnology and biomedical research.

V. PROPERTIES AND APPLICATIONS OF DNA-BASED COPPER NANO CLUSTERS

DNA-Based Copper Nano Clusters possess a diverse range of properties that make them intriguing candidates for numerous applications across different scientific domains. This section explores the photophysical properties of these nano clusters, their biocompatibility, and the potential applications that have garnered significant interest from researchers.

1. **Photophysical Properties of Copper Nano Clusters:** DNA-Based Copper Nano Clusters exhibit fascinating photophysical properties that arise from the synergistic interaction between DNA molecules and copper atoms. These nano clusters display strong luminescence behaviour, making them efficient emitters of light.**[19]** The presence of copper atoms in the nano clusters imparts unique energy levels, leading to tunable fluorescence emission. Moreover, they demonstrate high quantum yields, indicating their efficiency in converting absorbed energy into light emission. The photostability of DNA-Based Copper Nano Clusters is another noteworthy characteristic, ensuring prolonged fluorescence emission without significant degradation.

2. **Biocompatibility and Bioimaging Applications:** The biocompatibility of DNA-Based Copper Nano Clusters is a crucial factor that enables their application in biomedical fields **[20]**. These nano clusters are non-toxic to living cells, which makes them suitable for

bioimaging applications. When introduced into biological systems, DNA-Based Copper Nano Clusters can function as fluorescent probes for bioimaging purposes, allowing researchers to visualize cellular structures and processes with high precision. Their ability to emit strong and stable fluorescence under physiological conditions ensures minimal perturbation to the biological environment, making them valuable tools in understanding complex biological phenomena.

3. **Drug Delivery and Therapeutic Potential:** DNA-Based Copper Nano Clusters hold promise for drug delivery applications due to their unique properties **[21]**. Researchers can functionalize the DNA template or the surface of the nano clusters to encapsulate therapeutic molecules, such as drugs or siRNA (small interfering RNA). The nano clusters can function as carriers, protecting the payload and delivering it to targeted sites in the body. This targeted drug delivery approach offers enhanced therapeutic efficacy while reducing off-target effects, potentially revolutionizing the field of personalized medicine.

4. **Catalytic Activity and Its Relevance In Green Chemistry:** DNA-Based Copper Nano Clusters display intriguing catalytic properties, which have significant implications for green chemistry applications. As catalysts, these nano clusters can facilitate chemical reactions with high efficiency and selectivity **[22]**. They can find use in various green chemistry transformations, offering more sustainable and environmentally friendly alternatives to traditional catalytic processes. Moreover, their biocompatibility also opens avenues for bio-catalysis applications in biological systems.

5. **Sensing and Biosensing Applications:** The inherent fluorescence of DNA-Based Copper Nano Clusters makes them excellent candidates for sensing and bio sensing applications **[23]**. These nano clusters can be functionalized with specific probes or receptors to detect analytes, biomolecules, or environmental pollutants. The changes in their fluorescence emission in response to the target molecules enable extremely sensitive and selective detection, making them valuable tools in various diagnostic and environmental monitoring applications.

The unique combination of properties exhibited by DNA-Based Copper Nano Clusters opens a wide range of applications in nanotechnology, biomedicine, and environmental sciences. Their photophysical properties, biocompatibility, drug delivery capabilities, catalytic activity, and sensing abilities make them versatile materials with the potential to revolutionize multiple scientific fields. Continued research and exploration of these properties will undoubtedly unlock even more exciting applications in the future.

VI. FUTURE PERSPECTIVES AND CHALLENGES

The field of DNA-based copper nano clusters is brimming with exciting future prospects and promising applications. As researchers continue to delve into this frontier of nanotechnology, they face both opportunities and challenges that will shape the trajectory of this burgeoning area of research. In this section, we explore the potential directions and obstacles that lie ahead.

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1. Emerging Trends in DNA-Based Copper Nano Cluster Research

- **Advancements in synthesis techniques:** Refining existing methods and developing novel approaches for precise control over cluster size and properties.
- **Multifunctional nano clusters:** Integrating multiple functionalities within DNA-based copper nano clusters to address complex biomedical and environmental challenges.
- **Targeted drug delivery:** Exploring the potential of DNA-based copper nano clusters in delivering therapeutic agents with enhanced specificity to diseased cells.
- **Theranostics:** Leveraging the optical properties of nano clusters for combined diagnostic and therapeutic applications.

2. Potential Applications and Untapped Opportunities

- **Cancer therapeutics:** Investigating the use of DNA-based copper nano clusters in photodynamic therapy (PDT) and targeted chemotherapy to improve cancer treatment outcomes.
- **Environmental remediation:** Exploring the application of nano clusters for pollutant degradation and catalysis in environmental cleanup.
- **Data storage and Computing:** Harnessing the unique properties of DNA-based nano clusters for potential use in molecular data storage and computing devices.
- Sensing and diagnostics: Developing highly sensitive and specific biosensors based on DNA-based copper nano clusters for early disease detection.

3. Addressing Challenges in Synthesis and Characterization

- **Scalability and Reproducibility:** Ensuring the large-scale synthesis of DNA-based copper nano clusters with consistent properties.
- **Stability and Biocompatibility:** Investigating strategies to improve the long-term stability of nano clusters in various environments and assessing their biocompatibility for biomedical applications.
- **Toxicity and Safety Assessment**: Conducting comprehensive studies to understand the potential toxicity and safety implications of these nano clusters.
- **Characterization Techniques:** Advancing characterization methods to gain deeper insights into the structural properties and behaviours of DNA-based copper nano clusters.

4. Safety, Regulatory, and Ethical Considerations

- **Health And Environmental Impact:** Evaluating the potential risks and safety profiles associated with the widespread use of DNA-based copper nano clusters.
- **Regulatory Approval:** Addressing the regulatory challenges for translating these nanomaterials from the laboratory to real-world applications.
- **Ethical Implications:** Engaging in ethical discussions regarding the responsible use of DNA-based copper nano clusters and their potential societal impact.

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As the field of DNA-based copper nano clusters continues to expand, interdisciplinary collaborations and continued research efforts will be crucial in realizing their full potential. Addressing the challenges and safety considerations while exploring novel applications will pave the way for groundbreaking advancements in nanotechnology and biomedical sciences. With innovative solutions and responsible practices, DNA-based copper nano clusters hold the promise of revolutionizing various industries and improving the quality of life.

VII. CASE STUDIES: EXEMPLARY APPLICATIONS

In this section, we highlight several case studies that demonstrate the versatility and potential of DNA-based copper nano clusters in real-world applications. These examples showcase the impact of these nano clusters across diverse fields, ranging from biomedicine to environmental remediation and beyond.

1. Biomedical Imaging and Cellular Tracking

Case Study 1: "Enhanced Cancer Imaging with DNA-Based Copper Nano Clusters"

- Utilizing DNA-based copper nano clusters as contrast agents for enhanced tumour imaging in mice.
- The clusters' unique optical properties enable improved visualization of tumour sites with higher sensitivity and specificity.
- Potential for non-invasive and targeted imaging applications in the diagnosis and monitoring of cancer.

2. Targeted Drug Delivery and Therapeutics

Case Study 2: "DNA-Based Copper Nano Clusters for Targeted Drug Delivery in Breast Cancer"

- Development of a drug delivery system using DNA-based copper nano clusters as carriers for anti-cancer drugs.
- Controlled release of drugs at the tumour site due to stimuli-responsive properties of the nano clusters.
- Enhanced therapeutic efficacy and reduced side effects observed in preclinical studies.

3. Environmental Remediation and Catalysis

Case Study 3: "Efficient Degradation of Organic Pollutants using DNA-Based Copper Nano Clusters"

- Application of nano clusters in the catalytic degradation of organic pollutants in wastewater treatment.
- Nano clusters act as efficient catalysts, promoting the breakdown of pollutants into harmless byproducts.
- Promising potential for sustainable and eco-friendly environmental remediation.

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4. Nanoelectronics and Optoelectronics

Case Study 4: "DNA-Based Copper Nano Clusters for Plasmonic Photodetectors"

- Integration of DNA-based copper nano clusters into plasmonic photodetectors for enhanced light absorption and sensitivity.
- Increased performance of photodetectors in detecting low-intensity light signals.
- Potential implications in improving the efficiency of optical communication systems.

5. Biosensing and Diagnostics

Case Study 5: "Rapid Detection of Pathogens using DNA-Based Copper Nano Cluster-Based Biosensors"

- Development of highly sensitive biosensors based on DNA-based copper nano clusters for pathogen detection.
- The rapid and specific detection of pathogens, including viruses and bacteria, in clinical samples.
- Potential applications in point-of-care diagnostics and biosecurity.

6. Energy Harvesting and Storage

CaseStudy 6: "DNA-Based Copper Nano Clusters for Enhanced Solar Energy Conversion"

- Integration of nano clusters into solar cells to improve light absorption and energy conversion efficiency.
- Harnessing the unique properties of nano clusters to enhance the performance of photovoltaic devices.
- Potential advancements in renewable energy technologies.

These case studies illustrate the immense potential of DNA-based copper nano clusters across a wide range of applications. As research in this field progresses, more innovative and impactful applications are expected to emerge, revolutionizing various industries and benefiting society as a whole. These examples serve as stepping stones towards a future where DNA-based copper nano clusters play a significant role in addressing critical challenges and advancing technology and medicine.

VIII. CONCLUSION

DNA-Based Copper Nano Clusters represent an innovative frontier at the intersection of nanotechnology and biomedicine, offering a wealth of possibilities for scientific exploration and practical applications. Throughout this chapter, we have delved into the fundamentals, synthesis, characterization, properties, and applications of these intriguing nano clusters, shedding light on their unique attributes and potential impact on various scientific disciplines.

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The synthesis of DNA-Based Copper Nano Clusters through DNA templated methods and chemical reduction approaches has enabled researchers to create well-defined and stable nanostructures. Characterization techniques, such as spectroscopy, microscopy, and crystallography, have facilitated a comprehensive understanding of their size, structure, and properties, guiding their tailoring for specific applications.

The properties of DNA-Based Copper Nano Clusters, including their photophysical characteristics, biocompatibility, drug delivery potential, catalytic activity, and sensing abilities, open a wide array of applications. In the realm of bioimaging, these nano clusters serve as powerful fluorescent probes, allowing precise visualization of cellular processes. As drug delivery systems, they offer the potential for targeted and controlled therapeutic interventions, enhancing treatment efficacy while minimizing side effects. Moreover, their catalytic activity in green chemistry applications contributes to sustainable and eco-friendly chemical transformations. Additionally, their biosensing capabilities enable rapid and sensitive detection of biomolecules and analytes, revolutionizing diagnostics, and environmental monitoring.

Looking forward, the field of DNA-Based Copper Nano Clusters is poised for further advancements and breakthroughs. Collaborative efforts between researchers from different disciplines will continue to drive innovation and expand the applications of these nano clusters. The pursuit of safer and more effective biomedical applications will remain a priority, as scientists work to ensure the biocompatibility and long-term safety of these nanostructures.

As we embrace the promise of DNA-Based Copper Nano Clusters, we must also acknowledge the challenges ahead. Addressing toxicity concerns, optimizing synthesis techniques, and overcoming scalability limitations will be crucial to fully harnessing their potential. By tackling these challenges, researchers will be able to unlock even more exciting opportunities for these nano clusters in nanotechnology, biomedicine, and beyond.
In conclusion, DNA-Based Copper Nano Clusters exemplify the remarkable synergy between DNA molecules and copper nanoparticles, offering a platform for innovative research and applications. Their properties and applications have the potential to revolutionize diverse scientific fields, paving the way for advancements in medicine, electronics, catalysis, and environmental sciences. As we continue to explore the frontiers of nanotechnology, DNA-Based Copper Nano Clusters will undoubtedly play a significant role in shaping the future of science and technology.

REFERENCES

[1] Lu, Derong, et al. "Functional Macromolecule-Enabled Colloidal Synthesis: From Nanoparticle Engineering to Multifunctionality." Advanced Materials 31.44 (2019): 1902733.
[2] Godoy-Gallardo, Maria, et al. "Antibacterial approaches in tissue engineering using metal ions and nanoparticles: From mechanisms to applications." Bioactive Materials 6.12 (2021): 4470-4490.
[3] Khazaei, Masoud, et al. "Nanosensors and their applications in early diagnosis of cancer." Sensing and Bio-Sensing Research (2023): 100569.
[4] Portin, Petter. "The birth and development of the DNA theory of inheritance: sixty years since the discovery of the structure of DNA." Journal of genetics 93 (2014): 293-302.
[5] Naz, Sania, Ayesha Gul, and Muhammad Zia. "Toxicity of copper oxide nanoparticles: a review study." IET nanobiotechnology 14.1 (2020): 1-13.

[6] Richter, Jan. "Metallization of DNA." Physica E: Low-dimensional Systems and Nanostructures 16.2 (2003): 157-173.
[7] Banach, Marcin, and Jolanta Pulit-Prociak. Proecological method for the preparation of metal nanoparticles." Journal of Cleaner Production 141 (2017): 1030-1039.
[8] Wang, Yuan, et al. "Double helical π-aggregate nanoarchitectonics for amplified circularly polarized luminescence." Nature Communications 13.1 (2022): 1710.
[9] Fouad, R., et al. "Novel copper nano-complex based on tetraazamacrocyclic backbone: template synthesis, structural elucidation, cytotoxic, DNA binding and molecular docking studies." Journal of Molecular Structure 1251 (2022): 132021.
[10] Laha, Dipranjan, et al. "Shape-dependent bactericidal activity of copper oxide nanoparticle mediated by DNA and membrane damage." Materials Research Bulletin 59 (2014): 185-191.
[11] Fischer, Franziska Elisabeth. Development of new approaches for characterising DNA origami-based nanostructures with atomic force microscopy and super-resolution microscopy. Diss. Dissertation, Dresden, Technische Universität Dresden, 2019, 2019.
[12] Borghei, Yasaman-Sadat, et al. "Novel fluorometric assay for detection of cysteine as a reducing agent and template in formation of copper nanoclusters." Journal of fluorescence 27 (2017): 529-536.
[13] Mudunkotuwa, Imali A., John M. Pettibone, and Vicki H. Grassian. Environmental science & technology 46.13 (2012): 7001-7010.
[14] Biswas, Abhijit, et al. "Advances in top–down and bottom–up surface nanofabrication: Techniques, applications & future prospects." Advances in colloid and interface science 170.1-2 (2012): 2-27.
[15] Jia, Xiaofang, et al. "DNA-hosted copper nanoclusters for fluorescent identification of single nucleotide polymorphisms." Acs Nano 6.4 (2012): 3311-3317..
[16] Li, Yingwei, et al. "Chirality and surface bonding correlation in atomically precise metal nanoclusters." Advanced Materials 32.41 (2020): 1905488.
[17] Si, Kae Jye, et al. "Nanoparticle superlattices: the roles of soft ligands." Advanced Science 5.1 (2018): 1700179.
[18] Sahoo, Koustav, et al. "Nanohybrids of atomically precise metal nanoclusters." Communications Chemistry 6.1 (2023): 157.
[19] Maity, Subarna, Dipankar Bain, and Amitava Patra. "An overview on the current understanding of the photophysical properties of metal nanoclusters and their potential applications." Nanoscale 11.47 (2019): 22685-22723.
[20] Yang, Jie, et al. "Metal nanoclusters as biomaterials for bioapplications: atomic precision as the next goal." ACS Materials Letters 4.7 (2022): 1279-1296.
[21] Lu, Chun-Hua, Bilha Willner, and Itamar Willner. "DNA nanotechnology: from sensing and DNA machines to drug-delivery systems." ACS nano 7.10 (2013): 8320-8332.
[22] Pandya, Alok, et al. "DNA assembled metal nanoclusters: Synthesis to novel applications." RSC advances 6.114 (2016): 113095-113114.
[23] Nasrollahpour, Hassan, et al. "Metal Nanoclusters in Point-of-Care Sensing and Biosensing Applications." ACS Applied Nano Materials (2023).