Studying the effect of different DNA concentrations on the solubility of carbon nanoparticles

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ABSTRACT

Carbon nanoparticles have attracted considerable attention in interdisciplinary nanotechnology research due to their unique physicochemical properties and broad applicability in biotechnology, biosensing, and biomedical systems. However, their limited solubility and strong tendency toward aggregation in aqueous environments remain major challenges for their effective utilization. In the present study, the effect of varying concentrations of single-stranded DNA (ssDNA) on the solubility, dispersion behavior, and colloidal stability of carbon nanoparticles was systematically investigated. Surface modification of the nanoparticles was achieved through noncovalent adsorption of ssDNA, primarily mediated by electrostatic interactions and π–π stacking between nucleobases and carbon surfaces. The resulting DNA–nanoparticle assemblies were characterized using scanning electron microscope (SEM), Zeta Potential, and fluorometric analysis. The results demonstrated that increasing DNA concentration up to an optimal range significantly enhanced nanoparticle dispersion and solubility in aqueous media, while excessively high DNA concentrations led to altered aggregation behavior. Long-term stability assessments further confirmed that DNA-functionalized nanoparticles exhibited superior temporal stability compared to unmodified samples. These findings emphasize the critical role of DNA concentration in regulating the solubility and stability of carbon nanoparticles and provide valuable insights for the rational design of stable carbon-based nanomaterials for interdisciplinary applications in nanobiotechnology and biosensing platforms.

Keywords: *Carbon nanoparticles; DNA concentration; Nanoparticle solubility; Dispersion; Colloidal stability; Biosensing*

1. *INTRODUCTION*

Carbon-based nanomaterials, including carbon nanotubes (CNTs), graphene oxide (GO), and graphene nanoplatelets (GrNPs), possess exceptional physicochemical properties that make them highly attractive for applications in nanobiotechnology, biosensing, and biomedical engineering [1]. Despite these advantages, their practical utilization in aqueous environments is significantly limited by strong aggregation tendencies, primarily driven by π–π stacking and van der Waals interactions, resulting in poor solubility and reduced colloidal stability [2]. Noncovalent functionalization using single-stranded DNA (ssDNA) has emerged as an effective strategy to overcome these limitations while preserving the intrinsic structure of carbon nanomaterials [3,4]. ssDNA adsorbs onto carbon surfaces through π–π interactions of nucleobases with graphitic domains, while the negatively charged phosphate backbone provides electrostatic stabilization. The concentration of DNA is a critical determinant in this process: low concentrations result in incomplete surface coverage and insufficient dispersion, whereas moderate concentrations enhance adsorption uniformity, surface charge, and colloidal stability. At very high DNA concentrations, competitive adsorption and desorption dynamics may reduce overall dispersion efficiency [5,6]. Adsorption studies on GO have shown that DNA binding exhibits concentration-dependent saturation and reversible desorption, directly impacting solubility and dispersion of nanomaterials [7]. Similarly, DNA loading on GO–based sensor platforms has been shown to influence surface interactions and device performance strongly, emphasizing the need for

precise control over DNA concentration [8]. Moreover, recent studies on GrNP-based systems highlight that selective adsorption of ssDNA and overall uptake are strongly dependent on both DNA concentration and available surface area, affecting both DNA capture efficiency and dispersion stability [9]. Collectively, these findings underline the critical role of DNA concentration in controlling adsorption, surface coverage, and colloidal stability of carbon-based nanomaterials. Despite these advances, a systematic understanding of how varying DNA concentrations affect the solubility and dispersion behavior of CNTs, GO, and GrNPs remains incomplete. The present study aims to investigate the effect of different DNA concentrations on the aqueous solubility and dispersion of these carbon nanomaterials, providing insights for the rational design of stable DNA–carbon nanohybrids for biomedical and nanotechnological applications.

2. *Materials and Methods*

Carbon nanoparticles with high purity and stable structures were selected for this study to evaluate the effect of DNA concentration on their dispersion and solubility. These nanoparticles have surface properties suitable for DNA adsorption and applications in aqueous environments and biosensing platforms. Single-stranded DNA (ssDNA, 20-mer, purified, phosphate-buffered solution) was used as a noncovalent stabilizing agent. The negatively charged phosphate backbone and π–π stacking capability of nucleobases make ssDNA ideal for adsorption onto nanoparticle surfaces. Deionized water (18.2 MΩ·cm) and phosphate-buffered saline (PBS, pH 7.4) were used as solvents to provide controlled experimental conditions.

2.1 Preparation of DNA–Nanoparticle Hybrids

Carbon nanoparticles were dispersed at a fixed concentration (0.1 mg/mL) in aqueous solution. ssDNA was added at varying concentrations (1, 5, 10, and 20 μM) to study the effect of DNA concentration on adsorption, surface coverage, and dispersion behavior. The mixtures were briefly sonicated (5 min, 40% amplitude) to enhance initial dispersion and promote surface interactions between DNA and nanoparticles. Samples were incubated at room temperature for 30 minutes to allow the adsorption equilibrium to be reached. Excess unbound DNA was removed by centrifugation (10,000 rpm, 10 min), and the supernatants were collected for further analysis.

2.2 Microscopic Analysis of graphene

Scanning Electron Microscopy (SEM): Morphology, DNA surface coverage, and aggregation state were examined to study the quality of dispersion and surface interactions.

2.3 Zeta Potential Measurement

The zeta potential of graphene oxide nanoparticles was measured before and after ssDNA immobilization using a [Instrument Name, Model, Manufacturer] at 25°C. Samples were diluted in deionized water, sonicated, and then transferred to disposable folded capillary cells. Zeta potential values were calculated based on the Smoluchowski model and reported as the mean of three replicates.

2.4 Data Analysis

All experiments were performed in triplicate, and results are reported as mean ± standard deviation. The effect of DNA concentration on solubility, particle size, and stability was statistically analyzed using standard methods (ANOVA, $p < 0.05$ considered significant). Data were interpreted using dispersion graphs, particle size histograms, and TEM images to provide both quantitative and qualitative insights into the relationship between DNA concentration and nanoparticle behavior.

3. *Results and Discussion*

3.1. Microscopic Analysis of Carbon Nanotubes

The purchased carbon nanotubes were characterized for morphology and structure using a scanning electron microscope (SEM, MIRA3 TESCAN). SEM analysis confirmed that DNA was bound and hybridized onto the nanotubes [Fig.1].

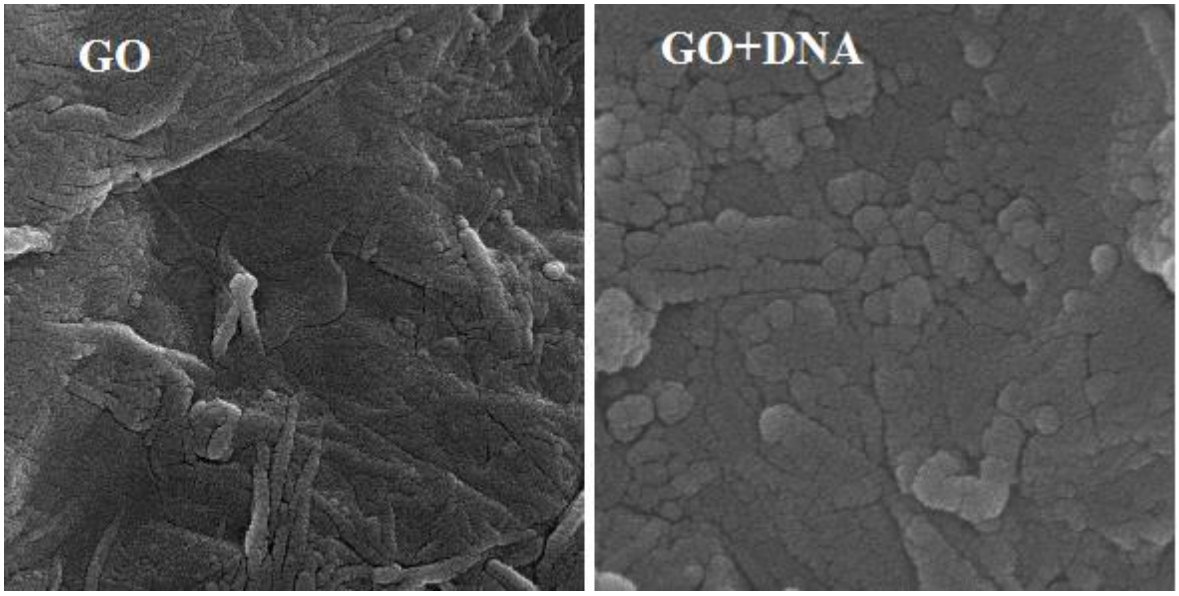

Fig. 1. Scanning Electron Microscopy (SEM) images of graphene (GO) and immobilization of the ssDNA on the graphene (Go+DNA) surface.

3.2. Effect of ssDNA Concentration on Dispersion and Colloidal Stability

At low DNA concentrations (1 µM), partial coverage of nanoparticle surfaces provided limited stabilization, resulting in moderate aggregation and reduced solubility. Increasing the DNA concentration to 5–10 µM provided sufficient surface coverage, significantly reducing aggregation and improving colloidal stability. However, at 20 µM, a slight decrease in dispersion efficiency was noted, likely due to competitive adsorption and saturation effects, as also discussed in [8]. Comparing the overall behavior, carbon nanoparticles demonstrated a concentration-dependent adsorption pattern similar to that reported for graphene oxide and graphene nanoplatelets. SEM analysis revealed a more uniform DNA coating at intermediate DNA concentrations, while overloading DNA caused partial desorption or loose binding on the surface, affecting long-term stability. The results suggest that controlling DNA concentration is crucial for optimizing nanoparticle solubility and colloidal stability. These findings provide valuable insights for the design of DNA-functionalized carbon nanomaterials for biosensing and biomedical applications, aligning well with mechanisms proposed in earlier studies [7] to [9].

3.3. Zeta potential analysis to investigate the stability of nanoparticle solutions and dispersions

Zeta potential is a critical analysis for investigating the stability of nanoparticle solutions and their dispersion. Also, using this analysis, it is possible to examine the changes in the surface charge of nanoparticles after DNA adsorption. DNA is negatively charged under physiological conditions of the cell. After immobilization of ssDNA on the surface of GO nanoparticles, a large change in the zeta potential of GO suspensions was observed compared to that before ssDNA adsorption. The GO nanoparticle suspension was very unstable before DNA immobilization and precipitated quickly, but after ssDNA adsorption, the suspension stabilized. Before ssDNA adsorption on GO, the zeta potential was -1.54 mV, and after adsorption, it reached -16.38 mV.

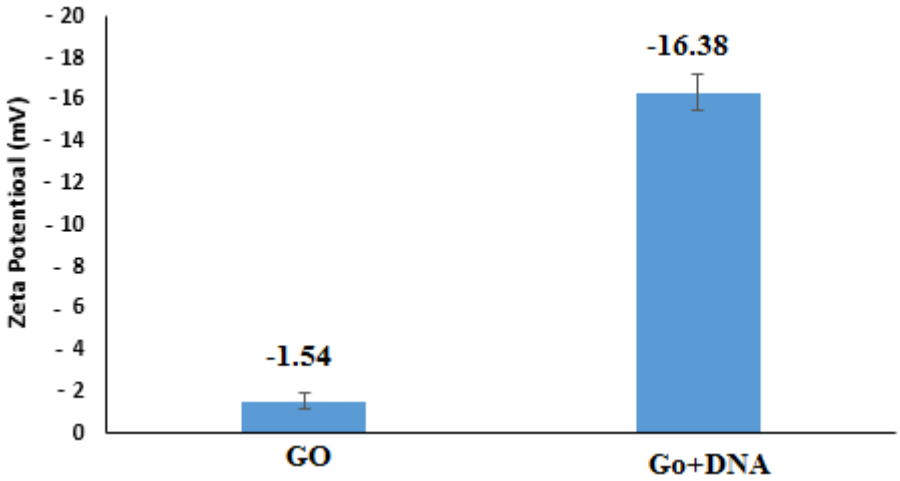

Fig. 2. Zeta potential changes before and after adsorption of ssDNA onto GO

4. Conclusion

In this study, the effect of ssDNA concentration on the dispersion, solubility, and colloidal stability of carbon nanoparticles was systematically investigated. Our results demonstrate that DNA concentration plays a critical role in modulating nanoparticle behavior in aqueous environments. Intermediate concentrations (5–10 μM) provided optimal surface coverage, leading to enhanced dispersion, reduced aggregation, and improved long-term stability. In contrast, low DNA concentrations resulted in insufficient surface coverage and partial aggregation, while excessive DNA loading (20 μM) slightly decreased dispersion efficiency due to competitive adsorption and surface saturation effects. These findings highlight the importance of precise control of DNA concentration in designing functionalized carbon nanomaterials for biosensing, biomedical applications, and other nanotechnology-related fields. The observed concentration-dependent adsorption patterns and stability profiles are consistent with previously reported mechanisms on DNA–nanomaterial interactions [7] to [9], emphasizing the general applicability of these principles across different carbon-based nanomaterials. Overall, this work provides practical guidance for optimizing DNA–nanoparticle hybrid systems, establishing a foundation for the development of highly stable and dispersible nanomaterials tailored for specific applications in bio-nanotechnology.

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