Investigation On Binding Affinity Of Biomolecules Over Novel Carbon Nanomaterials

A Executive Summary

of THESIS

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Executive Summary

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Chapter 1: Introduction

In a multitude of fields spanning chemistry, biology, materials science, and environmental science, organic materials play an indispensable role in the realm of scientific investigation. Comprising predominantly carbon-based compounds, these materials exhibit a diverse array of advantageous features, rendering them invaluable for various scientific pursuits [1]. Organic materials function as essential foundational elements in the intricate synthesis of both molecules and materials. Leveraging the extensive repertoire of organic compounds available empowers scientists to craft and engineer structures endowed with specific properties. Employing organic synthesis techniques, such as intricate multistep reactions and transformative processes involving functional groups, facilitates the tailored creation of molecules designed for applications ranging from drug discovery and catalysis to polymers and advanced materials [2]. The advancement of knowledge and applications in the realms of biology and medicine significantly benefits from these organic materials. Delving into fields like biochemistry, molecular biology, and medicinal chemistry would be impracticable without their indispensable contributions. Organic molecules play a pivotal role in simplifying the study of biological systems, aiding not only in comprehending their intricacies but also in the development of drugs and molecular probes essential for imaging and sensing applications [3]. Notably, fluorescence microscopy frequently employs organic dyes, utilizing their properties to investigate the root causes of diseases and observe cellular activities. The exceptional qualities and versatility of carbon and its associated materials have garnered substantial attention, reshaping the scientific landscape through their transformative impact. Over the course of history, scientists have been captivated by carbon, the elemental cornerstone of life on Earth, owing to its multifaceted attributes. In the contemporary era, scientific exploration has extended into the realm of nanoscience, where carbon-based

nanomaterials emerge as a potent resource for crafting distinctive structures endowed with extraordinary properties. The abundant presence of carbon on Earth, coupled with its cost-effectiveness and the existence of allotropes boasting unique characteristics, positions the family of carbon nanostructures as a compelling choice for essential electrical sensors [4]. Leveraging their unique structural, electronic, chemical, optical, and sensing attributes, the renowned sp^2 hybridized allotropes within the carbon family, encompassing two-dimensional (2D) graphene and graphene oxide, one-dimensional (1D) carbon nanotubes, and zero-dimensional (0D) fullerene nanocages, have found application across an array of disciplines. These encompass diverse fields such as biology, medicine, and pharmaceuticals, highlighting their versatility and impact [5] [6] [7] [8] [9] [10]. Discovered through experimental synthesis by H. Kroto in 1985, C_{60} fullerene stands as the inaugural carbon nanomaterial to be recognized. Its hydrophobic nature, biocompatibility, expansive surface area owing to its spherical structure, and notably reduced toxicity towards living microorganisms compared to graphene and carbon nanotubes have spurred significant interest in the biomedical domains. Beyond its acclaim, fullerene has proven effective in diverse biomedical applications, serving as a biosensor, facilitating drug sensing, and playing a crucial role in drug delivery methods [11] [12] [13] [14] [15]. In this exploration, DFT and classical MD simulations were harnessed to scrutinize the adsorption capabilities of various pristine fullerenes — namely C_{70}, C_{50}, C_{36}, and C_{24} —when exposed to diverse biomolecules and pharmaceutical substances.

Chapter 2: Methodology

In diverse scientific and technological realms, including biosensing, drug delivery, and nanomedicine, the intricate interplay between biomolecules and carbon nanoparticles plays a pivotal role. Deciphering the molecular interactions governing the binding process is essential

for the development of efficient biomolecular systems. While experimental procedures yield valuable insights, they frequently require considerable time and financial investment. Computational approaches stand out as a potent and cost-effective means to delve into these interactions at the atomic level. Within this chapter, a comprehensive elucidation of the computational methodologies employed in this thesis is provided. The envisioned computational strategy involves the integration of Density Functional Theory (DFT) calculations utilizing Gaussian 09 and Classical Molecular Dynamics (MD) simulations using GROMACS. This synthesis offers a pathway to explore the dynamic properties of the system, facilitating the examination of time-dependent perturbation reactions and delving into the realm of rheological characteristics. These encompass a diverse range of attributes, spanning electronic intricacies, structural dynamics, vibrational traits, and essential transport coefficients. Consequently, this chapter serves as a conduit toward achieving a comprehensive comprehension, detailing the methodologies employed to unravel the molecular intricacies that govern complex interactions within the atomic realm.

Chapter 3: Biosensing Activity of C_{24} Fullerene towards DNA Nucleobases

In this chapter, the focus is on examining how different nucleobases (Adenine (A), Thymine (T), Guanine (G), Cytosine (C), and Uracil (U)) interact with the C24 fullerene, characterized by D6d symmetry. The aim is to determine the binding sequence of these nucleobases using dispersion (D3) corrected Density Functional Theory (DFT). The evaluation of nucleobase-C24 fullerene interaction encompasses the calculation of adsorption energy, NBO analysis, Mulliken charge analysis, density of state, as well as sensing response and recovery time. The observed adsorption sequence of nucleobases reveals a pattern: A > C > G > T > U. The interaction between nucleobases and the C_{24} fullerene induces charge

redistribution, leading to the generation of dipole moments. Adenine exhibits distinct behavior, isolating itself from other DNA nucleobases, whereas cytosine and guanine can be detected with a recovery time of 10^{-14} seconds in the gas phase. The increased interaction energy for adenine and cytosine in the presence of a solvent further validates their potential as carriers [16].

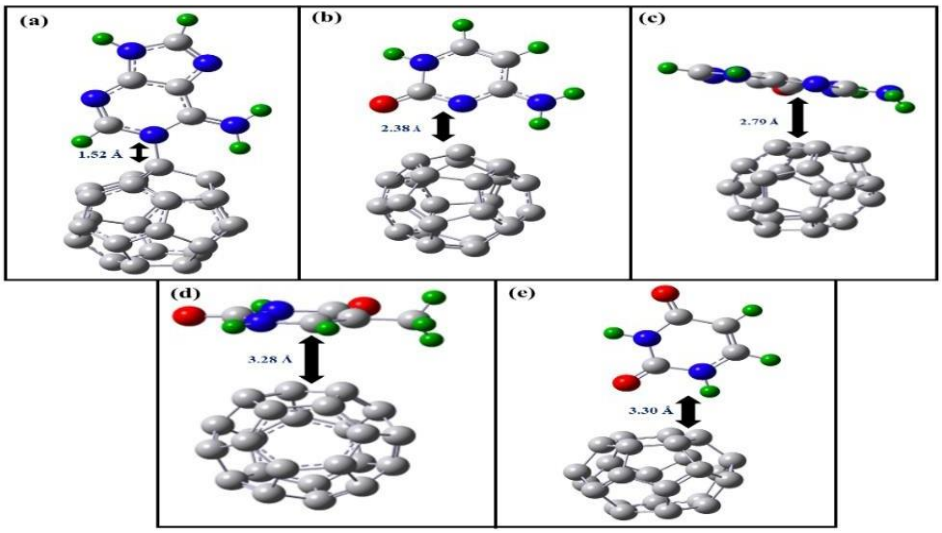

Figure 1: Minimum energetic geometry of Adenine (a), Cytosine (b), Guanine (c), Thymine (d) and Uracil (e) adsorbed over C_{24} fullerene, respectively.

Chapter 4: Exploring C_{24} Fullerene as an illicit Drug sensor

This chapter elucidates the application of both density functional theory (DFT) and classical molecular dynamics simulations for comprehending the interaction mechanisms between three illicit drug molecules—Amphetamine (AMP), Ketamine (KET), and Mercaptopurine (MER)—and the pristine C_{24} fullerene. It is observed that, in the gas phase, the adsorption sequence of the drug molecules follows the order AMP > KET > MER. Yet, with the introduction of a solvent effect, the adsorption energy experiences an augmentation for the

AMP and KET drug molecules onto C24, signifying a chemisorption phenomenon. This implies that C24 could be considered as a promising candidate for efficiently removing AMP and KET drugs from the environment. Conversely, in the case of the MER drug molecule, the interaction involves physisorption, characterized by an appropriate interatomic distance, making it apt for detection purposes. Through a comprehensive classical MD simulation study, the stability, both structurally and dynamically, of the sensing material C24 at room temperature has been substantiated. The MD calculations encompass assessments like the time-dependent evaluation of Root Mean Square Deviation (RMSD), Radial Distribution Function (RDF), energy profiles, and temperature, providing validation for the findings obtained through Density Functional Theory (DFT) [17].

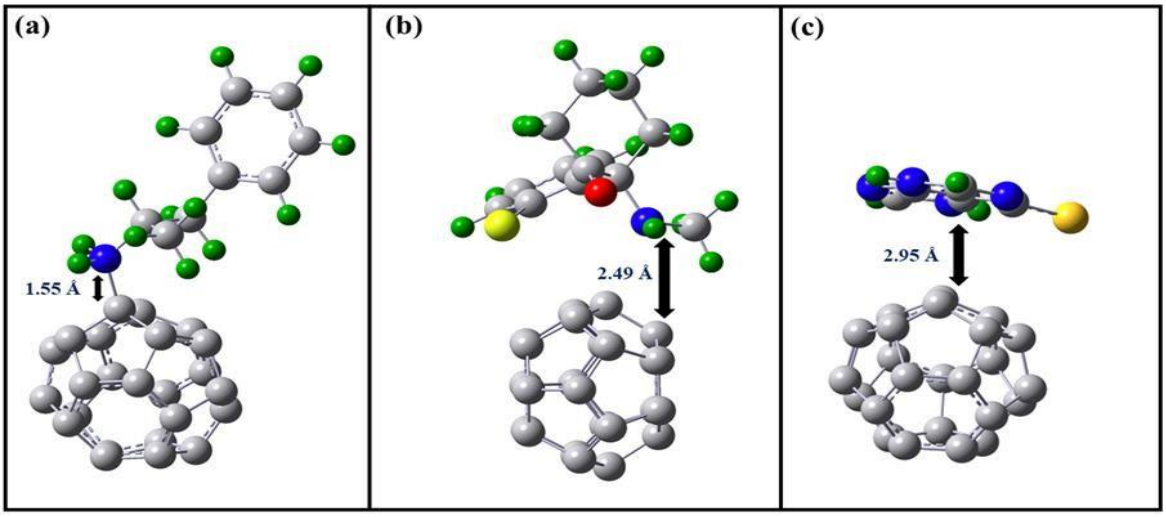

Figure 2: Minimum energetic geometry of AMP(a), KET (b) and MER (c) adsorbed over C_{24} fullerene, respectively.

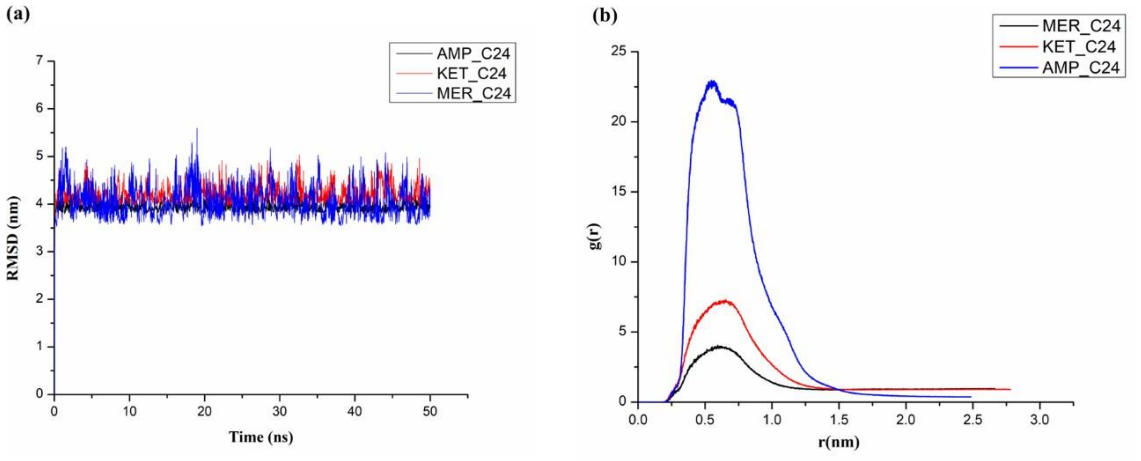

Figure 3: (a)RMSD curves for the interacted drug molecules and C_{24} fullerene as a function of time and (b)comparison of radial distribution (g(r)) of drug molecules around the C_{24} fullerene surfaces versus distance.

Chapter 5: Size dependent Activity of Carbon-based Fullerenes with L-leucine

The interaction inclinations of size-variable fullerenes (C_{24}, C_{36}, C_{50}, and C_{70}) towards L-Leucine (LEU), one of the important amino acids, are assessed and comprehended using dispersion corrected density functional theory (DFT-D3) and classical molecular dynamics (MD) simulations. In the gas phase, the affinity of the LEU biomolecule increased in the following order: C_{24} > C_{70} >C_{36} >C_{50}. When the solvent effect is applied to the LEU biomolecule, it shows chemisorption behaviour with enhanced adsorption energy across C_{24} and C36. This increases the possibility of using C_{24} and C_{36} as feasible options for LEU separation from biological systems. The interaction between LEU and fullerenes was validated further by the NBO analysis, Mulliken charge analysis, DOS calculation, RDG analysis, sensing response, and recovery time, all of which were consistent with the adsorption study. Classical MD simulation analysis was used to confirm the structure and dynamical stability of the biosensing materials C_{24} and C_{36} fullerene at room temperature. We concluded from a

combination of DFT and MD simulation results that C_{24} and C_{36} fullerenes might be an excellent alternative for developing new-generation high performance biomolecule functionalization and sensors in a water environment at room temperature (310K).

Chapter 6: Summary and Future Prospects

The last chapter of the thesis summarizes the entire work. It consists of a summary of results, conclusion, application, and future scope of work.

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