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RESVERATROL ADSORPTION ON CARBON NANOTUBES: A FIRST PRINCIPLES STUDY[1]

ADSORÇÃO DE RESVERATROL EM NANOTUBOS DE CARBONO: UM ESTUDO DE PRIMEIROS PRINCÍPIOS

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ABSTRACT

In this paper, the structural and electronic properties of carbon nanotubes in pristine and carboxylated form, interacting with resveratrol molecules, are studied through first principles calculations based on the Density Functional Theory. The results demonstrate that resveratrol molecules interact with carbon nanotubes with binding energies lower than 0.5 eV. There were no significant differences observed in the structural or in the electronic properties of the final systems. The interaction occurs via physical adsorption, which is a valuable property for carbon nanotube and for the purpose of its use as drug delivery systems.

Keywords: *ab initio* calculations, biological molecules, carbon nanostructures, drug.

RESUMO

Neste estudo apresenta-se as propriedades estruturais e eletrônicas de nanotubos de carbono, na forma pura ou carboxilada, que interagem com moléculas de resveratrol. O estudo foi realizado por meio de cálculos de primeiros princípios baseados na teoria do funcional de densidade via código computacional SIESTA. Os resultados demonstram que a molécula de resveratrol interage com as nanoestruturas de carbono com energia de ligação inferior a 0,5 eV. Além disso, não ocorreram alterações significativas nas propriedades estruturais e eletrônicas dos sistemas. Portanto, as interações ocorrem por meio de adsorção física, propriedade muito importante para a aplicação de nanoestruturas de carbono em sistemas de entrega de fármacos.

Palavras-chave: *cálculos ab initio, moléculas biológicas, nanoestruturas de carbono, fármacos.*

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INTRODUCTION

Carbon nanotubes (CNTs) have attracted attention of the scientific community due to their original and intriguing structure, interesting electronic characteristics and diverse properties (PASTORIN et al., 2005). Based on the geometric characteristics of CNTs, such as diameter and tube chirality, this material can present different electronic properties, which could be semiconducting, metallic or superconducting (lower temperatures) (BANDARU, 2007; SOUZA; FAGAN, 2007).

In 1991 Iijima identified, for the first time, carbon nanotubes (IIJIMA, 1991) that is a nanomaterial with promising applications, being used to create new materials for electronic, medicine, aesthetics and other areas (CAI et al., 2012; DA SILVA, 2007; VUTTIPITTAYAMONGKOL et al., 2015; XU et al., 2012).

Much more fascinating applications of CNTs can arise from the possibility of functionalizing them with other molecules, which place specific molecules in their surface area, These functionalizations could present some well-defined biological, chemical or physical functions (FAGAN et al., 2003). These molecules chemically connected to the CNTs can be used to facilitate the interaction with organic molecules or other chemical groups (FU, 2002). Another interesting application is the use of CNTs for carrying drugs (BIANCO et al., 2005; KAM et al., 2004; MENEZES; ZANELLA; FAGAN, 2015; MENEZES et al., 2012; PRATO et al., 2008).

In parallel, resveratrol consists of a polyphenol found in nature, in the root of *Polygonum cuspidatum.* It has strong antioxidant, anti-inflammatory, anticarcinogenic, cardioprotective properties, which empowers the immune system. It is also known by its anti-aging effects (BARGER et al., 2008).

Studies have shown the benefits of resveratrol in the prevention of degenerative diseases and cancer. In addition, it can block the enzymes that are responsible for activating carcinogenesis, increasing the organism antioxidant capacity, delaying cellular proliferation, inducing damaged cells into apoptosis, inhibiting angiogenesis in tumoral tissues and suppressing the metastasis (BORRIELLO et al., 2010; KUNDU; SURH, 2008; LI et al., 2012).

However, resveratrol has low chemical stability. Thus, the interaction of this molecule with carbon nanostructures, which are highly stable systems, could increase the chemical stability and facilitate its bioavailability.

In this paper, the interaction of pristine and carboxylated CNT with the resveratrol molecule was analyzed through computational *ab initio* simulation. This study is important to comprehend to evaluate the resulting structural and electronic properties. It was observed weak interactions, with few alterations in the CNTs electronic and structural properties, which empower their future biological applications with the resveratrol.

MATERIALS AND METHODS

In this work, the single-walled CNT (8,0) in pristine and carboxylated forms interacting with resveratrol molecules was analyzed. The calculations were performed by using the density functional theory (DFT) (KOHN; SHAM, 1965) with local density approximation (LDA) (PERDEW et al., 1992) for the exchange and correlation potential, implemented in the SIESTA code (SOLER et al., 2002). The interactions between ionic cores and valence electrons were described by using norm-conserving pseudopotentials. In all calculations were used double zeta basis set plus polarization functions (DZP) to describe the pseudoatomic orbitals. The charge density was described through a cutoff of 200 Ry for the grid integration, which is used to project the charge density in the real space and to calculate the self-consistent Hamiltonian matrix elements. The size of the cell was 17.08 x 40.00 x 40.00 $Å^3$ and the number of k-points 3x1x1. All the studied systems geometries were optimized until the forces were less than 0.05 eV/Å.

SIESTA code uses a localized atomic basis set, which that has the advantage of not interacting with its periodic image system. However, these basis set are not entirely complete, which results in an intrinsic error in binding energy calculation. Therefore, it is necessary to use the basis of superposition error correction (BSSE - Basis Set Superposition Error) (BOYS; BERNARDI, 1970). This correction is performed with counting method using "ghost" atoms. The binding energies (E_b) were calculated according to the following equation:

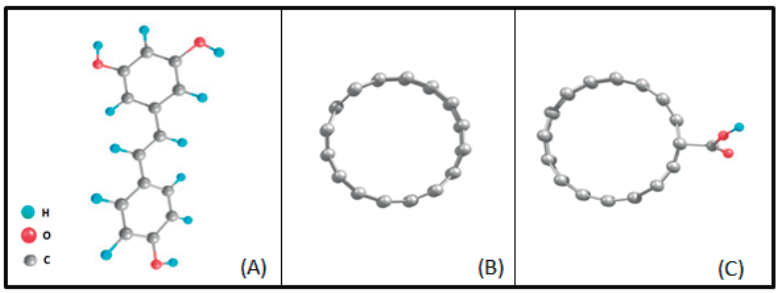
$$E_b = - \{ E_T (CNT + A) - E_T (CNT_{ghost} + A) - E_T (CNT + A_{ghost}) \} \quad (1)$$

where E_T is the total energy of the CNT and the resveratrol molecule (A). CNT_{ghost} or A_{ghost} corresponds to the additional basis of the central orbital on the CNT or on the adsorbed compound, without any atomic potential or addition of electrons from the "ghost" atoms.

RESULTS AND DISCUSSION

In order to analyze the resveratrol adsorption on CNTs, these two systems were relaxed separately. The optimized structures of resveratrol molecule and pristine and carboxylated forms of (8,0) single-walled CNTs are shown in figure 1(A), (B) and (C), respectively.

Figure 1 - Structures of the (A) resveratrol molecule (B) (8,0) single-walled pristine CNT, and (C) (8,0) single-walled carboxylated CNT.

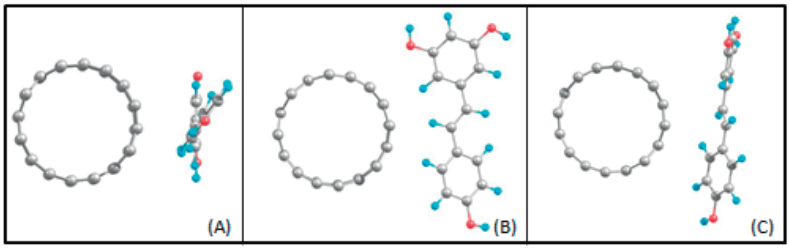


Initially, the results concerning pristine CNTs interacting with the resveratrol molecule are presented and discussed. In the second part of the section, carboxylated CNTs interacting with the resveratrol molecule is analyzed.

I - Pristine (8,0) single-walled CNTs interacting with resveratrol

The resveratrol molecule was approximated to CNT by three different configurations as they can be seen on figure 2. Figure 2 (A) shows the most stable structures studied, where the resveratrol molecule was approximated in parallel to the CNT axis [CNT+Resveratrol I]. The other two configurations are represented in figures 2 (B) and 2 (C), with the resveratrol molecule perpendicular to the tube axis [CNT+Resveratrol II] and with a 90 degree rotation from position B [CNT+Resveratrol III], respectively.

Figure 2 - Different configurations of resveratrol molecule adsorbed on pristine (8,0) single-walled CNT. (A) CNT + Resveratrol I; (B) CNT+Resveratrol II and (C) CNT +Resveratrol III.

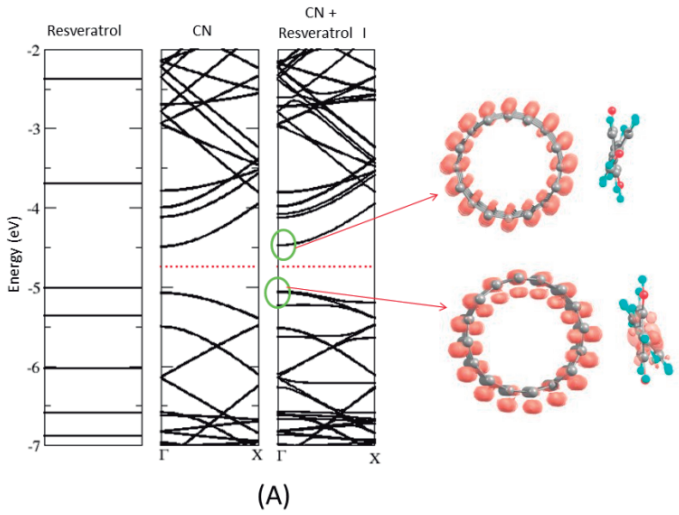


The resveratrol molecule was adsorbed on the CNT surface with binding energies lower than 0.5 eV, table 1. The interaction occurred by physical adsorption regime (weak interaction), which can be corroborated by its electronic properties. It is not observed significant changes in the electronic structure of the resulting system, compared to the pristine CNT. This behavior can be seen in figure 3, which shows the electronic band structure for the most stable configuration (CNT+Resveratrol I). No changes was noticed in electronic levels around Fermi level. The resulting system maintains the semiconductor characteristic with a gap of 0.59 eV; the same was observed in relation to pristine CNT.

Table 1 - Binding energy values (E_b) of CNT interacting with resveratrol, distances (Å) between the molecule and carbon nanotube and charge transfer (Δ q) for the different configurations studied (positive Δq indicates that there is charge transfer from CNT to resveratrol).

Configurations	E_b (eV)	Distance (Å)	Charge transfer (Δ q)
CNT+Resveratrol I	0.49	2.40	+0.02
CNT+Resveratrol II	0.45	2.48	+0.09
CNT+Resveratrol II	0.47	2.59	+0.03

Figure 3 - Electronic energy levels of the resveratrol molecule and electronic band structures for the pristine CNT and CNT interacting with the resveratrol molecule and the respective localized charge plots of the indicated levels. The isosurface is 0.00286 $e^-/Å^3$.



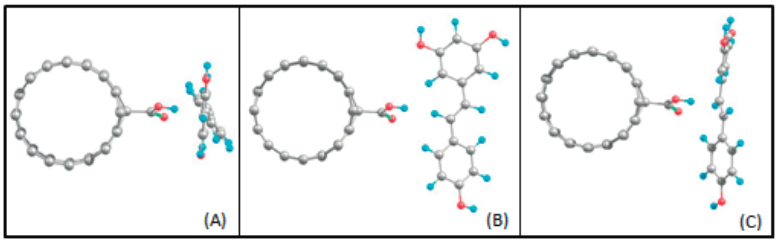
(A)

The localized electronic density plot around the valence band shows that the charge contribution is present in the center of the resveratrol molecule and on the nanotube surface. For the electronic conduction band, the charge is homogeneously localized on the CNT structure. In addition, as shown in table 1, for all configurations, the electronic charge is transferred from the CNT to the resveratrol molecule.

II - Carboxylated (8,0) single-walled CNTs interacting with resveratrol

The applicability of carbon nanostructures in biological systems requires making them water soluble (CASALS et al., 2008; LIU et al., 2007). This water solubility can be achieved by the functionalization with carboxylic groups (BAHR; TOUR, 2002). Thus, the interaction between the carboxylated CNT (COOH-CN) and the resveratrol molecule is evaluated, as shown in figure 4, in the same configurations studied for pristine tubes.

Figure 4 - Different configurations of resveratrol molecule adsorbed on (8,0) single-walled COOH-CNTs. (A) CN+Resveratrol I +COOH, (B) CNT+Resveratrol II +COOH, and (C) CNT+Resveratrol III+ COOH.



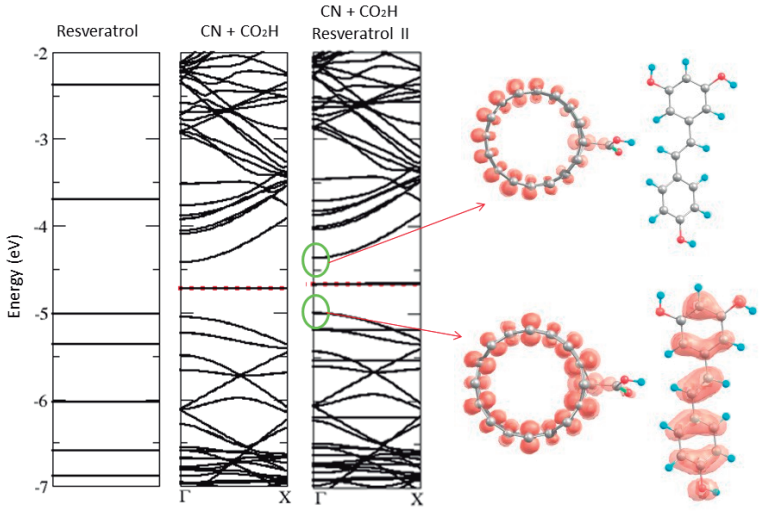
The results indicate that the system interacts with binding energy of 0.42eV for the most stable configuration (Table 2). The values found for the COOH-CNT system are smaller than the ones found for pristine systems.

Table 2 - Binding Energy (E_b) values for carboxylated (8,0) single-walled COOH-CNTs interacting with resveratrol, distances (Å) between the molecule and carbon nanotube and charge transfer (Δq) for the different configurations studied (positive [negative] Δq indicates that there is charge transfer from COOH-CNT [resveratrol] to resveratrol [COOH-CNT]).

Configurations	E_b (eV)	Distance (Å)	Charge Transfer (Δq)
CNT+Resveratrol + COOH I	0.32	2.05	-0.13
CNT+Resveratrol + COOH II	0.42	2.02	+0.006
CNT+Resveratrol + COOH III	0.06	1.89	-0.15

The electronic structure of the COOH-CNT presents a half-filled level on the Fermi energy due to the COOH-functionalization (Figure 5). This behavior occurs due to sp^3 hybridization of the carbon atom of CNT that presents covalent bond with the COOH group (SOUZA; FAGAN, 2007).

Figure 5 - Electronic energy levels of the resveratrol molecule and electronic band structures for the carboxylated CNT (COOH-CNT) and COOH-CNT interacting with the resveratrol molecule and the respective localized charge plots of the indicated levels. The isosurface is 0.00286 $e^-/Å^3$.



(B)

From the localized plots of the electronic charge densities below and above, the Fermi energy is observed, compared with the pristine CNT, that the functionalization modifies the charge distribution around the COOH group (Figure 5). In addition, the level below the Fermi energy presents charge distribution on COOH-CNT and on the resveratrol molecule.

The electronic charge transfer for configurations CNT+Resveratrol+COOH I and CNT+Resveratrol+COOH III have opposite behavior from the systems with resveratrol adsorbed on the pristine CNT. In these configurations the functionalization induces the charge transfer from the resveratrol molecule to COOH-CNT, but the same does not occur with the CNT+Resveratrol+COOH II configuration. This behavior occurs due to the presence of COOH group and the resulting charge polarization of the nanotube.

CONCLUSIONS

In summary, the interactions of the resveratrol molecule with pristine and carboxylated (8,0) single-walled CNT were evaluated through *ab initio* calculations. It was observed that the interactions occur through a physic adsorption regime with binding energies varying from 0.06 to 0.49 eV. No significant changes in the structural or in the electronic properties of the final systems were observed compared with the pristine ones.

For all configurations of the pristine CNT interacting with resveratrol, it was observed charge transfer to the resveratrol molecule. The COOH-CNT acts as a charge acceptor for most configurations due to charge redistribution and polarization around the functionalization.

In addition, it is concluded that depending on the studied configuration or functionalization, different values for charge transfer, charge density behavior and binding energy can be obtained. However, all studied systems, pristine or functionalized CNT with resveratrol, presented low binding energy values, which is characteristic of physical adsorption regime. These results are interesting due to the possible applications of CNT in pristine or carboxylate form in drug delivery systems.

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