


 Cite this: *RSC Adv.*, 2021, 11, 34402

Reversible CO₂ storage and efficient separation using Ca decorated porphyrin-like porous C₂₄N₂₄ fullerene: a DFT study†

 Mehdi D. Eshrafi^a and Sharieh Hosseini^b

The search for novel materials for effective storage and separation of CO₂ molecules is a critical issue for eliminating or lowering this harmful greenhouse gas. In this paper, we investigate the potential application of a porphyrin-like porous fullerene (C₂₄N₂₄) as a promising material for CO₂ storage and separation using thorough density functional theory calculations. The results show that CO₂ is physisorbed on bare C₂₄N₂₄, implying that this material cannot be used for efficient CO₂ storage. Coating C₂₄N₂₄ with Ca atoms, on the other hand, can greatly improve the adsorption strength of CO₂ molecules due to polarization and charge-transfer effects. Furthermore, the average adsorption energy for each of the maximum 24 adsorbed CO₂ molecules on the fully decorated Ca₆C₂₄N₂₄ fullerene is −0.40 eV, which fulfills the requirement needed for efficient CO₂ storage (−0.40 to −0.80 eV). The Ca coated C₂₄N₂₄ fullerene also have a strong potential for CO₂ separation from CO₂/H₂, CO₂/CH₄, and CO₂/N₂ mixtures.

 Received 3rd August 2021
 Accepted 13th October 2021

DOI: 10.1039/d1ra05888f

rsc.li/rsc-advances

1. Introduction

The discovery of fullerene C₆₀ in 1985 (ref. 1) and subsequently of related materials like carbon nanotubes (CNTs)^{2,3} and graphene^{4,5} marked the beginning of a new era in carbon chemistry. Numerous potential applications of these nanosized carbon structures have been proposed, including hydrogen storage,^{6–8} microelectronics,^{9,10} and smart and novel composites.^{11,12} These structures are also well suited for use as a support in heterogeneous catalysis due to their huge specific area.^{13–15} The ability to tune the electronic and surface properties of carbon-based nanomaterials by introducing defects or heteroatoms has shed light on their potential use in sensors and energy technologies.^{16–19} Theoretical calculations^{20–22} and experimental investigations,^{23,24} for example, have demonstrated that N atoms may be effectively incorporated in different carbon materials, tailoring their chemical and electronic characteristics. Although the loading of metal atoms on pure carbon nanomaterials usually results in aggregation due to weak metal–surface interactions, previous studies have demonstrated that the doping of N atoms can substantially enhance metal atom dispersion on these systems due to polarized C–N

bonds.^{22,25,26} Furthermore, a variety of porous N-rich carbon nanomaterials including graphitic carbon nitride (g-C₃N₄)^{27,28} and porphyrin like graphene^{29–31} or CNTs^{32,33} have been prepared using different experimental methods. There is also evidence that N-rich porous carbon fullerenes can provide as active sites for metal atoms by forming strong metal–N covalent bonds.^{34,35} C₂₄N₂₄, a truncated N-doped C₆₀ fullerene, is the best example of such systems. This fullerene comprises six porphyrin-like N₄ cavities, each of which is made up of eight s-triazine rings linked together by C–C bonds.³⁶ Metal atoms may be efficiently trapped by these N₄ cavities, and the clustering problem of metal atoms is therefore avoided due to the strong metal–N interactions. In fact, the potential of such single atom catalysts (SACs) based on porous C₂₄N₂₄ has been found in a variety of chemical processes, including N₂O³⁷ or O₂ reduction,³⁸ and CO oxidation.³⁹

Growing energy demands, along with the ongoing use of fossil fuels in vehicles and power plants, has resulted in serious environmental issues such as emission of greenhouse gases and air pollution. CO₂ is the most dangerous and prevalent greenhouse gas that has the potential to contribute to global warming and climate change.⁴⁰ Given these facts, several strategies have been explored in order to lower the level of CO₂ in the atmosphere. The most essential and straightforward method is to switch from fossil fuels to cleaner ones, such as natural gas.⁴¹ Natural gas emits less CO₂ than other fossil fuels and is inexpensive and widely available. Landfills are a source of natural gas, but they can also contain significant amounts of CO₂. As a result, separating CO₂ from methane is a critical issue.⁴² Hydrogen is a clean fuel that emits no CO₂ when burned,

^aDepartment of Chemistry, Faculty of Basic Sciences, University of Maragheh, P.O. Box 55136-553, Maragheh, Iran. E-mail: esrafi@maragheh.ac.ir; Fax: +98 4212276060; Tel: +98 4212237955

^bDepartment of Chemistry, Faculty of Pharmaceutical Chemistry, Tehran Medical Sciences, Islamic Azad University, Tehran, Iran

† Electronic supplementary information (ESI) available. See DOI: 10.1039/d1ra05888f



therefore the separation of CO₂ from H₂ is also important for practical purposes.⁴³ Another alternative is to look into potential CO₂ storage, capture, or transformation technologies.^{44–47} Recently, there has been a lot of interest in the capture and storage of CO₂ on porous materials with high selectivity and capacity, such as zeolites^{48,49} and covalent organic frameworks.^{50,51} However, for efficient CO₂ storage, these materials generally require either low temperature or high pressure. As a result, it is critical to investigate novel materials capable of capturing CO₂ under normal conditions.

CO₂ mostly acts as a Lewis acid in supramolecular chemistry by accepting electrons from the host material, but there is evidence that it may also serve as a Lewis base due to the existence of O lone-pair electrons.⁵² Because N-doped carbon nanostructures such as graphene, fullerenes, and CNTs are electron-rich materials, they may initially be assumed to be effective CO₂ adsorbents. However, previous DFT calculations^{53,54} have shown that CO₂ is generally weakly physisorbed on these surfaces due to lack of a permanent dipole moment. Some effective ways for solving the problem have been proposed, such as coating these substrates with atoms such as Ca,^{55,56} using an external electric field^{57,58} and charge regulation of the substrate.⁵⁹ For instance, prior studies have shown that coating carbon fullerenes or their analogues^{60,61} with Ca atoms can significantly increase the CO₂ storage capacity of these systems. The current work aims to investigate CO₂ adsorption and storage on bare and Ca coated C₂₄N₂₄ fullerenes using density functional theory (DFT) calculations. It appears that the existence of N₄ cavities in C₂₄N₂₄ not only provides active sites for Ca atoms to be located, but also induces a significant positive charge on the Ca, which improves adsorption abilities towards CO₂ molecules. Surprisingly, the addition of Ca atoms causes C₂₄N₂₄ to behave as a Lewis acid when it interacts with CO₂. Furthermore, the capability of Ca coated C₂₄N₂₄ fullerenes to separate CO₂ from various gas mixtures (CO₂/N₂, CO₂/CH₄, CO₂/H₂) is investigated.

2. Computational details

The Perdew–Burke–Ernzerhof (PBE)⁶² formalism within the DMol³ (ref. 63 and 64) was used to execute spin polarized DFT computations. To get reliable results, an all-electron double-numeric atomic orbital basis set (DNP) was used, which was augmented by d-polarization functions. Fully optimized structures were obtained without the application of symmetry constraints. In this study, the Hirshfeld analysis was used to provide atomic charges and charge-transfer values. The Grimme's PBE + D2 (ref. 65) method was used to account for weak van der Waals interactions. A convergence tolerance of 1 × 10^{−5} Ha, 0.001 Ha Å^{−1}, and 0.005 Å was used for energy change, maximum force, and maximum displacement, respectively. The porous C₂₄N₂₄ was produced as follows. First, two carbon atoms of C₆₀ fullerene linking the two five-membered rings were deleted, and then four carbon atoms in the closest nearby places were replaced with N atoms. For the computations, a periodic cubic box with dimensions $a = b = c = 30$ Å was used, the Brillouin zone sampling by the Γ point.

The following equation was used to calculate the adsorption energy per adsorbed CO₂ molecule $E_{\text{ads}}(\text{CO}_2)$, on Ca coated C₂₄N₂₄ clusters:

$$E_{\text{ads}}(\text{CO}_2) = 1/n[E_{\text{complex}} - E_{\text{cluster}} - nE_{\text{CO}_2}] \quad (1)$$

where n is the number of adsorbed CO₂ molecules, E_{complex} represents the energy of CO₂ adsorbed on the Ca coated C₂₄N₂₄ structure, E_{cluster} represents the energy of Ca coated C₂₄N₂₄, and E_{CO_2} is the energy of a free CO₂ molecule.

The adsorption of CO₂ is supposed to cause a mutual redistribution of electron density on C₂₄N₂₄ as well as on CO₂. To demonstrate this, we used the following equation to obtain electron density difference (EDD) maps:

$$\text{EDD} = \rho(\text{CO}_2@C_{24}N_{24}) - \rho(\text{CO}_2) - \rho(C_{24}N_{24}) \quad (2)$$

in which $\rho(\text{CO}_2@C_{24}N_{24})$, $\rho(\text{CO}_2)$ and $\rho(C_{24}N_{24})$ are the electron densities of CO₂ adsorbed on C₂₄N₂₄, free CO₂ and C₂₄N₂₄, respectively.

The Bader's atoms in molecules (AIM)⁶⁶ theory was utilized to investigate the nature of the interaction between CO₂ molecules and Ca coated C₂₄N₂₄ fullerenes. In summary, the AIM theory is based on the topology of the electron density. In the AIM theory, the nature of the interaction between two interacting atoms is characterized by analyzing electron density (ρ_{BCP}) and its Laplacian ($\nabla^2\rho_{\text{BCP}}$) at a specific point called the bond critical point (BCP), where the gradient of the electron density is zero.⁶⁶ For a closed-shell or noncovalent interaction, such as most weak and moderate hydrogen bonds, the electron density at the BCPs is low and the Laplacian is positive. For a chemical bonding, on the other hand, the ρ_{BCP} is big and its $\nabla^2\rho_{\text{BCP}}$ is negative at the corresponding BCP. In the AIM, another useful indicator for analyzing the nature of the interaction is the total electron energy density (H_{BCP}), whose sign, together with the sign of $\nabla^2\rho_{\text{BCP}}$, may indicate whether the interaction is electrostatic or covalent. That is, $\nabla^2\rho_{\text{BCP}} < 0$ and $H_{\text{BCP}} < 0$ for strong covalent bonds; $\nabla^2\rho_{\text{BCP}} > 0$ and $H_{\text{BCP}} > 0$ for electrostatic interactions; and $\nabla^2\rho_{\text{BCP}} > 0$ and $H_{\text{BCP}} < 0$ for partially covalent interactions.⁶⁷ To perform the AIM analysis, wavefunctions were first generated at the PBE/PBE/6-31G* level using the PBE/DNP optimized geometries by means of Gaussian 09 suite of program.⁶⁸ The AIM2000 (ref. 69) was then used for topology analysis of the electron densities.

3. Results and discussion

3.1. Bare C₂₄N₂₄

Fig. 1a depicts the optimized structure of bare C₂₄N₂₄ cluster. It was prepared *via* truncated N-doping of C₆₀ fullerene in accordance with ref. 37. As can be seen, C₂₄N₂₄ is made up of six porphyrine-like N₄ cavities, each of which is composed of eight *s*-triazine rings connected by C–C bonds. The optimized C–N and C–C bond lengths in C₂₄N₂₄ are 1.34 and 1.55 Å, respectively, which are consistent with other DFT studies.^{36,38,70} The Hirshfeld charges on the N and C atoms are determined to be −0.12 and +0.12| e |, respectively, suggesting that C₂₄N₂₄ has

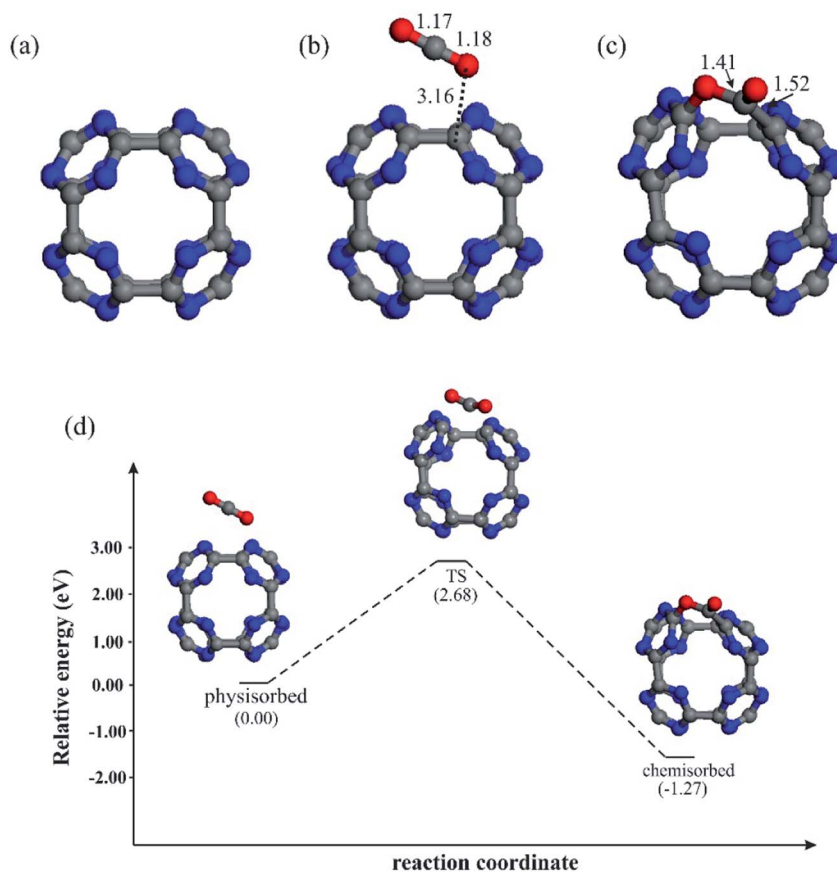


Fig. 1 (a) The optimized structure of $C_{24}N_{24}$, (b) physisorbed structure of CO_2 on $C_{24}N_{24}$, (c) chemisorbed structure of CO_2 on $C_{24}N_{24}$ and (d) the energy map for the physisorbed-to-chemisorbed transformation of CO_2 on of $C_{24}N_{24}$. The color code of the atoms: O (red); C (gray); N (blue). The values on the optimized structures are bond distances (in Å).

a partially polarized C–N bonds. The formation energy (E_{form}) of $C_{24}N_{24}$ is determined to be about -6.0 eV, which is defined as $E_{\text{form}} = 1/48[E_{C_{24}N_{24}} - 24E_C - 24E_N]$, where $E_{C_{24}N_{24}}$ is the energy of $C_{24}N_{24}$ and E_C and E_N are the energies of a single C and N atom, respectively. This negative number, which agrees satisfactory with that reported by Srinivasu and Ghosh,³⁶ suggests that the formation of $C_{24}N_{24}$ is a thermodynamically favorable process.

To assess the CO_2 storage capability of bare $C_{24}N_{24}$, we first study the adsorption properties of a single CO_2 molecule on this system. Fig. 1b and c depict the most stable geometries of a CO_2 molecule adsorbed on $C_{24}N_{24}$. Consistent with other DFT studies,^{74,72} two stable configurations were located for CO_2 , namely the physisorbed and chemisorbed. In the physisorbed configuration, CO_2 is nearly parallel to the C–C bond of fullerene, and the minimum binding distance between CO_2 and $C_{24}N_{24}$ is 3.16 Å. The adsorption energy (E_{ads}) is -0.14 eV, which is much smaller than the minimum target for an efficient storage of CO_2 molecule (-0.40 eV).⁷³ Meanwhile, this low adsorption energy and negligible charge transfer ($0.02|e|$) owing to CO_2 adsorption suggest that bare $C_{24}N_{24}$ cannot efficiently adsorb CO_2 . Our DFT results, on the other hand, show that CO_2 may be strongly chemisorbed on the $C_{24}N_{24}$, with an adsorption energy of -1.42 eV. This E_{ads} value is much larger than that of on the B_{80} (ref. 71) and B_{40} (ref. 72) clusters, suggesting that CO_2

is strongly bound to the $C_{24}N_{24}$. However, unlike the physisorbed structure, the formation of the chemisorbed structure on $C_{24}N_{24}$ requires the passing of an activation barrier. To investigate the mechanism of CO_2 chemisorption, the potential energy profile for the physisorption-to-chemisorption conversion of CO_2 molecule is investigated (Fig. 1d). Our results demonstrate that, while the conversion of physisorbed-to-chemisorbed configuration on $C_{24}N_{24}$ is exothermic, a significant activation barrier must be overcome for this process to occur. As a result, $C_{24}N_{24}$ cannot be used as an efficient CO_2 storage material at room temperature.

3.2. Ca coated $C_{24}N_{24}$

The interaction of a Ca atom with $C_{24}N_{24}$ is then considered. The most stable atomic configuration for a Ca atom adsorbed on the $C_{24}N_{24}$ is shown in Fig. 2a. The Ca atom, like transition metals,^{38,74–76} prefers to reside in the N_4 cavity, with an E_{ads} value of -6.85 eV. The distance between the Ca atom and the adjacent N atoms is 2.33 Å. Furthermore, the presence of the Ca atom alters slightly the geometry of $C_{24}N_{24}$, as evidenced by the elongation of adjacent C–N bond lengths from 1.34 Å in bare $C_{24}N_{24}$ to 1.38 Å in $CaC_{24}N_{24}$. The decorated Ca atom is positively charged by $0.74|e|$, whereas the nitrogen atoms around it are negatively charged by $0.17|e|$, according to the Hirshfeld

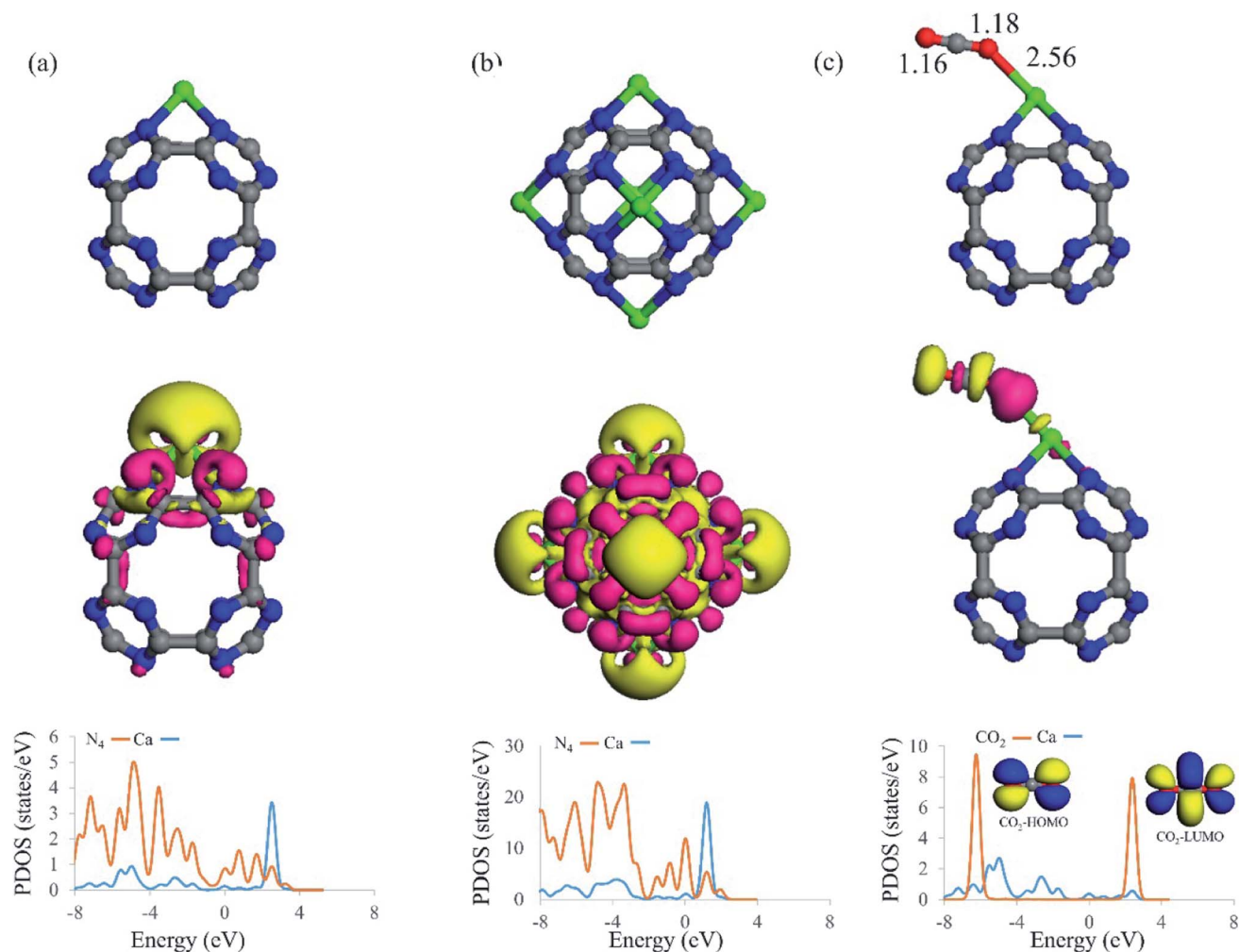


Fig. 2 The optimized structure (above), corresponding EDD (middle, isovalue = 0.002 au) and the PDOS plots of (a) CaC₂₄N₂₄, (b) Ca₆C₂₄N₂₄ and (c) CO₂@CaC₂₄N₂₄. In the EDD plots, the electron gain and loss regions are denoted by pink and yellow colors, respectively. The Fermi level in the PDOS plots is set to zero. The color code of the atoms: Ca (green); O (red); C (gray); N (blue).

analysis. Due to Coulomb interactions, such a large charge transfer might be helpful to the stability of Ca atoms coated on C₂₄N₂₄. Furthermore, the significant localization of positive charge on the Ca atom may generate an electric field that polarizes the adsorbed CO₂ molecules, fascinating their adsorption. Fig. 2a also shows the associated EDD map, which is used to evaluate the degree of electron density redistribution induced by Ca adsorption. A significant electron density loss region emerges on the Ca atom as a result of the formation of the CaC₂₄N₂₄ complex, demonstrating the ability of this site to interact with the electron donating species. Meanwhile, electron density gain regions exist between the Ca and N atoms, confirming the formation of Ca–N covalent bonds in CaC₂₄N₂₄. The PDOS analysis in Fig. 2a, on the other hand, clearly shows that the electronic states of the Ca and its surrounding N atoms are substantially mixed above and below the Fermi level ($E = 0$). As a consequence, it is reasonable to conclude that charge-transfer effects, in addition to electrostatic and polarization interactions between Ca and N atoms, are driving forces in the formation of Ca–N bonds.

Fig. 1b shows the optimized structure of Ca₆C₂₄N₂₄ cluster, in which one Ca atom is placed on each N₄ cavity of C₂₄N₂₄. According to the calculations, the E_{ads} value per Ca atom in this system is -6.31 eV, which is less negative than that of CaC₂₄N₂₄, partly due to repulsion between the decorated Ca atoms. To clarify this, we removed C₂₄N₂₄ from Ca₆C₂₄N₂₄ and calculated the single-point energy of the remaining 6 Ca atoms. The average energy of the leftover 6 Ca atoms was determined to be 0.17 eV higher than the energy of a single Ca atom. On the other hand, as the number of the incorporated Ca atoms increases, it is natural to expect that the tendency of the cluster to accept electrons from the Ca atoms decreases. Hence, we believe that the lower average E_{ads} value of Ca atom compared to the E_{ads} value of CaC₂₄N₂₄ can be attributed to the latter two effects. This is supported by the Hirshfeld analysis, which shows that the average positive charge (0.64|e|) on the Ca atoms in Ca₆C₂₄N₂₄ is likewise less than the positive charge on the Ca atom in CaC₂₄N₂₄ (0.74|e|). Furthermore, the significant electron density shifts caused by Ca atoms adsorption on C₂₄N₂₄, as well as the strong coupling between the electronic states in Fig. 2b,

demonstrate that the Ca atoms are firmly bonded to the N atoms. As previously stated, the aggregation of coated Ca atoms may have a detrimental influence on CO₂ storage. To address this issue, we compared the average E_{ads} value of Ca atoms in Ca₆C₂₄N₂₄ to the cohesive energy of bulk Ca (−1.82 eV per Ca atom). It is revealed that, due to higher average E_{ads} , Ca atoms are firmly adsorbed on the N₄ cavities of C₂₄N₂₄, avoiding the formation of Ca clusters on this cluster. This is also seen in Fig. 3, where the formation of a Ca₆ cluster on C₂₄N₂₄ from Ca₆C₂₄N₂₄ is highly endothermic by 23.01 eV. Such a result can be validated further by *ab initio* molecular dynamic (MD) simulations. The final structure of Ca₆C₂₄N₂₄ following MD simulation at 500 K and for 2ps is depicted in Fig. S1 of the ESI.† The Ca atoms are clearly shown to be still located on the hollow sites of C₂₄N₂₄, and therefore the Ca₆C₂₄N₂₄ stays stable after the MD simulations. As a result, Ca₆C₂₄N₂₄ is stable enough to be employed as a CO₂ storage material at ambient or even high temperatures.

We investigated the adsorption of CO₂ molecules on Ca coated clusters to examine if the Ca coating improves CO₂ adsorption energy and storage on C₂₄N₂₄. First, consider CO₂ molecule adsorption on the single Ca atom coated C₂₄N₂₄. Fig. 2c depicts the most stable geometry for CO₂ adsorption on CaC₂₄N₂₄. Table 1 shows the associated adsorption energy (E_{ads}), net charge transfer (Q_{CT}) and Hirshfeld charge on the Ca atom (Q_{Ca}). The CO₂ molecule is end-on on CaC₂₄N₂₄, with one of its O facing the Ca atom. The binding distance between the O atom of CO₂ and Ca is 2.56 Å, and the associated adsorption energy is −0.48 eV. This low adsorption energy implies that the formed CO₂@CaC₂₄N₂₄ complex is stable and that CO₂ adsorption on CaC₂₄N₂₄ would be reversible. The adsorbed CO₂ molecule, according to the Hirshfeld analysis, serves as a Lewis base since it supplies 0.17|e| to the nanocage. This is followed by a reduction in the atomic charge of the Ca from 0.74|e| in the bare CaC₂₄N₂₄ to 0.61|e| in the CO₂@CaC₂₄N₂₄. This means that the transferred charge from CO₂ is primarily concentrated on the Ca atom. Despite this, the EDD map in Fig. 2c indicates that the positively charged Ca atom polarizes the electron density on

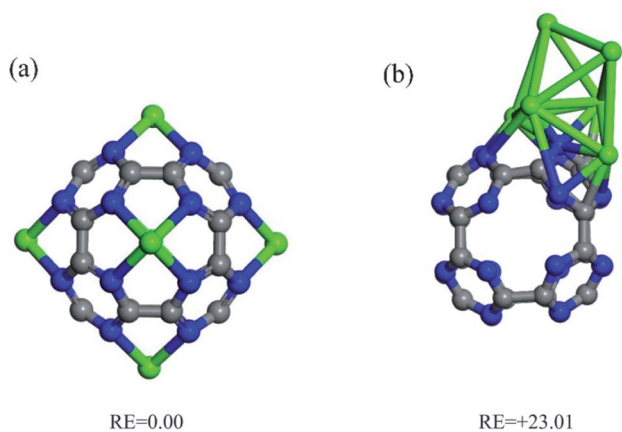


Fig. 3 Two stable isomers and correspond relative energy (RE, in eV) of Ca₆C₂₄N₂₄: (a) Ca atoms are disperse on N₄ cavities of C₂₄N₂₄ and (b) Ca atoms form a Ca₆ cluster on C₂₄N₂₄.

Table 1 Calculated average adsorption energy (E_{ads} , eV), binding distance ($R_{\text{Ca-O}}$, Å), net charge-transfer (Q_{CT} , electrons), Hirshfeld atomic charge on the Ca atom (Q_{Ca} , |e|) of CO₂ adsorbed configurations and the electron density (ρ_{BCP} , a.u.), its Laplacian ($\nabla^2\rho_{\text{BCP}}$, a.u.) and total electronic energy density (H_{BCP} , a.u.) at the Ca⋯OCO BCPs

Complex	E_{ads}	$R_{\text{Ca-O}}$	Q_{CT}^a	Q_{Ca}	ρ_{BCP}	$\nabla^2\rho_{\text{BCP}}$	H_{BCP}
1CO ₂ @CaC ₂₄ N ₂₄	−0.48	2.56	0.17	0.61	0.020	0.095	0.003
2CO ₂ @CaC ₂₄ N ₂₄	−0.47	2.58	0.15	0.51	0.019	0.093	0.003
3CO ₂ @CaC ₂₄ N ₂₄	−0.45	2.59	0.13	0.40	0.018	0.088	0.003
4CO ₂ @CaC ₂₄ N ₂₄	−0.42	2.65	0.12	0.37	0.015	0.072	0.003
5CO ₂ @CaC ₂₄ N ₂₄	−0.40	2.76	0.10	0.36	0.013	0.060	0.002
24CO ₂ @Ca ₆ C ₂₄ N ₂₄	−0.40	2.73	0.02	0.39	0.014	0.063	0.002

^a The $Q_{\text{CT}} > 0$ values show charge transfer from the CO₂ to nanocage.

the interacting O atom of CO₂, as indicated by a significant electron density gain region (pink color). According to the PDOS analysis, the highest occupied molecular orbital (HOMO) of CO₂ is substantially coupled with the electronic states of Ca atom below the Fermi level, confirming our claim that CO₂ acts as a Lewis base on CaC₂₄N₂₄.

To determine the maximum adsorption capacity of CaC₂₄N₂₄, more CO₂ molecules are introduced to this cluster until saturation is reached. The relaxed structures of two, three, four and five CO₂ molecules attached on the Ca atom of CaC₂₄N₂₄ are shown in Fig. 4. It is seen that all the newly added CO₂ molecules adopt an end-on configuration on the Ca atom, but the corresponding average binding distance between the CO₂ molecules and Ca atom becomes larger and larger as the number of the CO₂ molecules increases (Table 1). Accordingly, the adsorption energy per CO₂ molecule in 2CO₂@CaC₂₄N₂₄, 3CO₂@CaC₂₄N₂₄, 4CO₂@CaC₂₄N₂₄ and 5CO₂@CaC₂₄N₂₄ complexes is −0.47, −0.45, −0.42 and −0.40 eV, respectively. It is worth noting that the amount of change in adsorption energies caused by successive addition of CO₂ molecules on CaC₂₄N₂₄ is less than that seen on CaC₆₀.⁶⁰ The reasons for the latter observation will be addressed later. The average charge-transfer value and atomic charge on the Ca atoms also become smaller as the number of the CO₂ molecules increases on the CaC₂₄N₂₄ cluster. Since CO₂ molecules are positively charged as a result of donating electrons to the cluster, they repel each other, resulting in decreasing E_{ads} and Q_{CT} values as the number of CO₂ molecules increases. Furthermore, the average Hirshfeld charge on the Ca atom decreases progressively due to CO₂ molecules addition. When the sixth CO₂ molecule is added, we found that the average E_{ads} value of CO₂ molecule decreased to −0.33 eV, indicating that the maximum capacity for the adsorption of CO₂ molecule on CaC₂₄N₂₄ is five.

Based on these findings, we allowed five CO₂ molecules to adsorb on each Ca atom of Ca₆C₂₄N₂₄. Following the geometry optimizations, we found that each Ca atom of Ca₆C₂₄N₂₄ can adsorb up to four CO₂ molecules. According to Table 1, the E_{ads} value per CO₂ molecule in the resulting 24@Ca₆C₂₄N₂₄ complexes is −0.40 eV, which is 17% less than the E_{ads} value of a CO₂ value on Ca@C₂₄N₂₄. The average charge-transfer value from Ca₆C₂₄N₂₄ to CO₂ molecules is 0.08|e|, indicating that CO₂

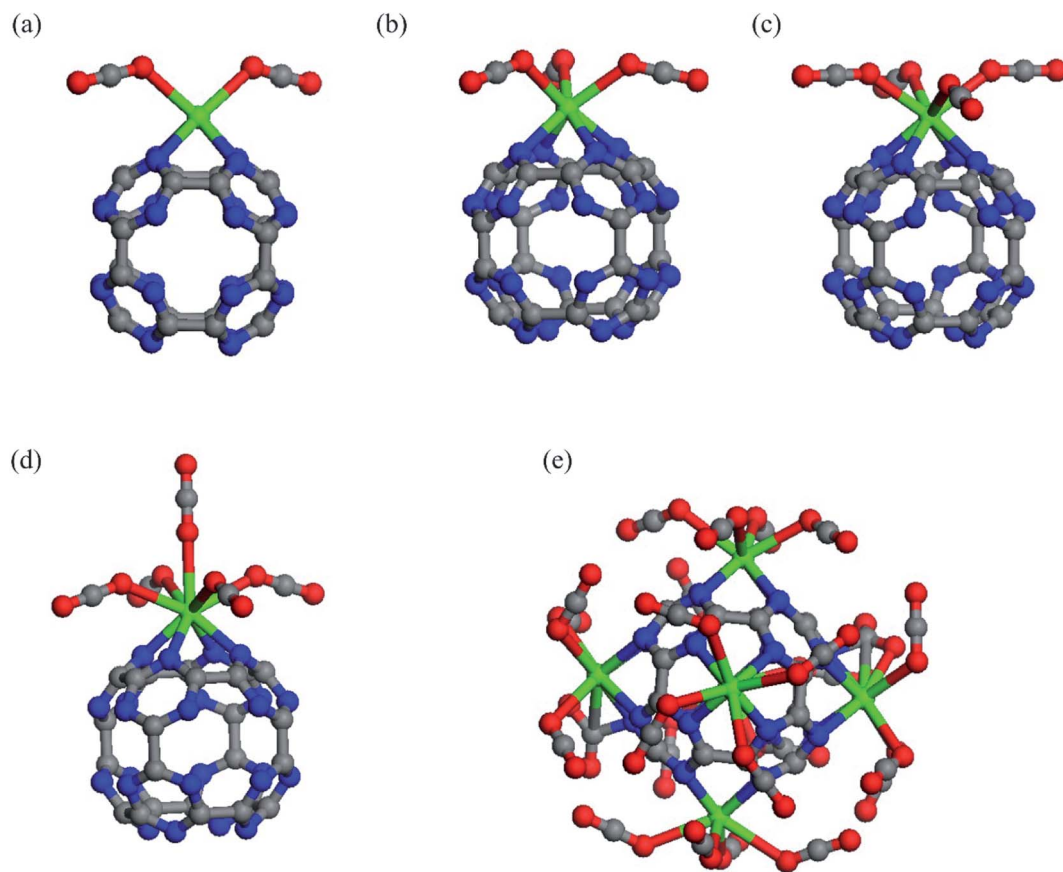


Fig. 4 The optimized structure of the most stable configuration of (a) $2\text{CO}_2@CaC_{24}N_{24}$, (b) $3\text{CO}_2@CaC_{24}N_{24}$, (c) $4\text{CO}_2@CaC_{24}N_{24}$, (d) $5\text{CO}_2@CaC_{24}N_{24}$ and (e) $24\text{CO}_2@Ca_6C_{24}N_{24}$ complexes. The color code of the atoms: Ca (green); O (red); C (gray); N (blue).

molecules are activated on this cluster. Furthermore, the average E_{ads} value of a CO_2 molecule in the obtained $24@Ca_6C_{24}N_{24}$ (-0.40 eV) is within the range suggested for an ideal CO_2 adsorbent (from -0.40 to -0.80 eV).⁷³

3.3. Nature of $\text{Ca}\cdots\text{CO}_2$ interactions

Further information on the nature of the $\text{Ca}\cdots\text{CO}_2$ interactions may be gained by topological analysis of the electron density. The calculated ρ_{BCP} , $\nabla^2\rho_{\text{BCP}}$ and H_{BCP} values at the $\text{Ca}\cdots\text{CO}_2$ BCPs of different CO_2 adsorbed complexes are listed in Table 1. Fig. S2† depicts the corresponding molecular graphs. The ρ_{BCP} values for all examined systems are small, indicating that the $\text{Ca}\cdots\text{CO}_2$ interactions in these systems are moderate. For the $CaC_{24}N_{24}$ fullerene, the tendency of electrons to localize at the $\text{Ca}\cdots\text{CO}_2$ BCPs decreases as the number of CO_2 molecules on the Ca atom increases. For example, the average ρ_{BCP} value at the $\text{Ca}\cdots\text{CO}_2$ BCPs of $5\text{CO}_2@CaC_{24}N_{24}$ is 0.013 a.u., which is about 30% less than the value at $1\text{CO}_2@CaC_{24}N_{24}$. Given the linear relationship between bond strengths and ρ_{BCP} values at respective BCP,⁷⁷ the $\text{Ca}\cdots\text{CO}_2$ interactions weaken as the number of CO_2 molecules on the Ca atom increases. Remarkably, the molecular graphs of the complexes $4\text{CO}_2@CaC_{24}N_{24}$ and $5\text{CO}_2@CaC_{24}N_{24}$ exhibit BCPs between the C atoms of CO_2 molecules and the C atoms of the fullerene, implying the

formation of side interactions in these systems (Fig. S2†). This explains why the average adsorption energy of these systems decreases slowly as the number of CO_2 molecules increases.

The $\nabla^2\rho_{\text{BCP}}$ and H_{BCP} values at the $\text{Ca}\cdots\text{CO}_2$ BCPs are positive in all complexes studied, indicating that CO_2 adsorption is mainly mediated by electrostatic effects. This finding is explained by the coulombic interaction of positively charged Ca atoms and negative O atom in CO_2 . However, when the number of CO_2 molecules increases over the Ca atom, the $\nabla^2\rho_{\text{BCP}}$ and H_{BCP} values decrease, suggesting that the contribution of electrostatic interactions in these systems are decreasing.

3.4. Selectivity

In addition to high capacity, a CO_2 storage material should have high selectivity in order to separate CO_2 molecules from other gases such as CH_4 , H_2 and N_2 present in natural gas or flue gas mixtures. So, in order to assess the selectivity of the Ca coated $C_{24}N_{24}$ cluster, we investigated the adsorption properties of CH_4 , H_2 , and N_2 molecules. Fig. 5 depicts the most stable geometries of these molecules on $CaC_{24}N_{24}$, as well as their associated binding distances. Table 2 also summarizes the E_{ads} and Q_{CT} values of these molecules. According to the results, all of the CH_4 , H_2 , and N_2 molecules are weakly bound to the $CaC_{24}N_{24}$, as shown by their low E_{ads} and Q_{CT} values. This

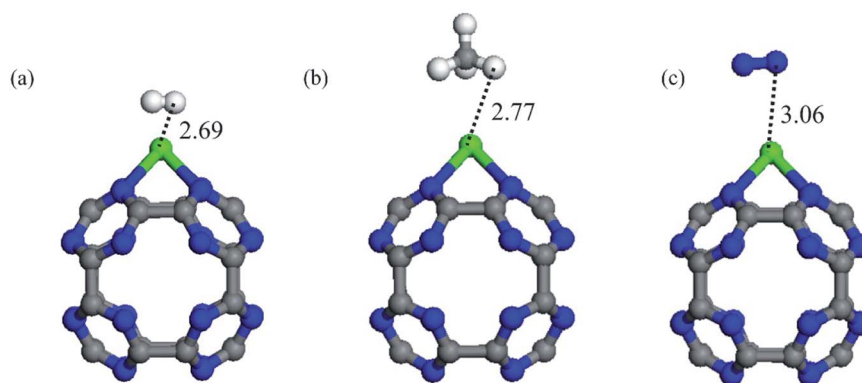


Fig. 5 The optimized structure and relevant bond distances (in Å) of the most stable configuration of (a) H₂, (b) CH₄ and (c) N₂ adsorbed on CaC₂₄N₂₄.

Table 2 Calculated adsorption energy (E_{ads} , eV), net charge-transfer (Q_{CT} , electrons) and Hirshfeld atomic charge on the Ca atom (Q_{Ca} , |e|) of H₂, CH₄ and N₂ molecules adsorbed on CaC₂₄N₂₄

Complex	E_{ads}	Q_{CT}^a	Q_{Ca}
H ₂ @CaC ₂₄ N ₂₄	-0.14	0.08	0.67
CH ₄ @CaC ₂₄ N ₂₄	-0.34	0.17	0.60
N ₂ @CaC ₂₄ N ₂₄	-0.07	0.09	0.62

^a The $Q_{\text{CT}} > 0$ values show charge transfer from the CO₂ to nanocage.

means that when the Ca coated C₂₄N₂₄ is exposed to CO₂/H₂, CO₂/CH₄ and CO₂/N₂ mixtures, the CO₂ molecules are preferentially adsorbed on the Ca atoms. As a result, Ca coated C₂₄N₂₄ can be considered as a selective adsorbent for CO₂ separation from the aforementioned gas mixtures.

4. Conclusions

To summarize, the effect of Ca coating on the CO₂ adsorption behaviors of porphyrin-like porous fullerene (C₂₄N₂₄) was thoroughly studied using the DFT calculations. A CO₂ molecule may be reversibly adsorbed on Ca coated C₂₄N₂₄ with an adsorption energy of -0.48 eV, as opposed to bare C₂₄N₂₄. The Ca atoms are located on the center of the N₄ cavity of C₂₄N₂₄ due to strong electrostatic interactions as well as charge transfer from the Ca atoms to the fullerene. Ca atoms do not aggregate and cluster on C₂₄N₂₄ because to the strong Ca-N interactions. Each Ca atom in the fully coated Ca₆C₂₄N₂₄ fullerene may adsorb up to four CO₂ molecules with an E_{ads} value of -0.40 eV per CO₂. This is within the recommended range for an ideal CO₂ storage material. Furthermore, Ca coated C₂₄N₂₄ has a high potential for separating CO₂ gas from flue gas or natural gas mixtures. These findings might inspire intensive experimental attempts to develop high-efficiency CO₂ storage media.

Conflicts of interest

There are no conflicts to declare.

References

- H. W. Kroto, J. R. Heath, S. C. O'Brien, R. F. Curl and R. E. Smalley, *Nature*, 1985, **318**, 162–163.
- S. Iijima and T. Ichihashi, *Nature*, 1993, **363**, 603–605.
- S. Iijima, *Phys. B*, 2002, **323**, 1–5.
- K. S. Novoselov, A. K. Geim, S. V. Morozov, D.-e. Jiang, Y. Zhang, S. V. Dubonos, I. V. Grigorieva and A. A. Firsov, *Science*, 2004, **306**, 666–669.
- C. Berger, Z. Song, T. Li, X. Li, A. Y. Ogbazghi, R. Feng, Z. Dai, A. N. Marchenkov, E. H. Conrad and P. N. First, *J. Phys. Chem. B*, 2004, **108**, 19912–19916.
- A. E. Mahdy, *Mol. Phys.*, 2015, **113**, 3531–3544.
- C. Ramos-Castillo, J. Reveles, R. Zope and R. De Coss, *J. Phys. Chem. C*, 2015, **119**, 8402–8409.
- C. Ramos-Castillo, J. Reveles, M. Cifuentes-Quintal, R. Zope and R. de Coss, *J. Phys. Chem. C*, 2016, **120**, 5001–5009.
- F. Bottacchi, L. Petti, F. Späth, I. Namal, G. Tröster, T. Hertel and T. D. Anthopoulos, *Appl. Phys. Lett.*, 2015, **106**, 51–52.
- X. Wang, G. Li, G. Hong, Q. Guo and X. Zhang, *ACS Appl. Mater. Interfaces*, 2017, **9**, 41323–41331.
- T. Ye, Y. Sun, X. Zhao, B. Lin, H. Yang, X. Zhang and L. Guo, *J. Mater. Chem. A*, 2018, **6**, 18994–19003.
- L. Bai, Y. Lei, H. Huang and Y. Xiang, *ACS Appl. Mater. Interfaces*, 2020, **12**, 33139–33151.
- P. Su, K. Iwase, S. Nakanishi, K. Hashimoto and K. Kamiya, *Small*, 2016, **12**, 6083–6089.
- I. H. Lin, Y. H. Lu and H. T. Chen, *J. Comput. Chem.*, 2017, **38**, 2041–2046.
- M. D. Esrafil, *Chem. Phys. Lett.*, 2018, **705**, 44–49.
- Y. Zhang, D. Zhang and C. Liu, *J. Phys. Chem. B*, 2006, **110**, 4671–4674.
- Y. Chen, B. Gao, J.-X. Zhao, Q.-H. Cai and H.-G. Fu, *J. Mol. Model.*, 2012, **18**, 2043–2054.
- J. N. Gavani, A. Hasani, M. Nouri, M. Mahyari and A. Salehi, *Sens. Actuators, B*, 2016, **229**, 239–248.
- L.-F. Velázquez-López, S.-M. Pacheco-Ortín, R. Mejía-Olvera and E. Agacino-Valdés, *J. Mol. Model.*, 2019, **25**, 1–11.
- L. Ferrighi, M. I. Trioni and C. Di Valentin, *J. Phys. Chem. C*, 2015, **119**, 6056–6064.

- 21 H. Miao, S. Li, Z. Wang, S. Sun, M. Kuang, Z. Liu and J. Yuan, *Int. J. Hydrogen Energy*, 2017, **42**, 28298–28308.
- 22 M. D. Esrafil and S. Asadollahi, *Appl. Surf. Sci.*, 2018, **463**, 526–534.
- 23 P. Sun, H. Liu, M. Feng, Z. Zhai, Y. Fang, X. Zhang and V. K. Sharma, *Appl. Catal., B*, 2020, **272**, 119005.
- 24 J. Guo, S. Zhang, M. Zheng, J. Tang, L. Liu, J. Chen and X. Wang, *Int. J. Hydrogen Energy*, 2020, **45**, 32402–32412.
- 25 X. Zhang, Z. Lu and Z. Yang, *J. Mol. Catal. A: Chem.*, 2016, **417**, 28–35.
- 26 M. Wang and Z. Wang, *RSC Adv.*, 2017, **7**, 48819–48824.
- 27 X. Zhang, X. Xie, H. Wang, J. Zhang, B. Pan and Y. Xie, *J. Am. Chem. Soc.*, 2013, **135**, 18–21.
- 28 Z. Jin and L. Zhang, *J. Mater. Sci. Technol.*, 2020, **49**, 144–156.
- 29 V. Tripkovic, M. Vanin, M. Karamad, M. r. E. Björketun, K. W. Jacobsen, K. S. Thygesen and J. Rossmeisl, *J. Phys. Chem. C*, 2013, **117**, 9187–9195.
- 30 Z. Wang, J. Zhao and Q. Cai, *Phys. Chem. Chem. Phys.*, 2017, **19**, 23113–23121.
- 31 E. Ashori, F. Nazari and F. Illas, *Phys. Chem. Chem. Phys.*, 2017, **19**, 3201–3213.
- 32 D. H. Lee, W. J. Lee, W. J. Lee, S. O. Kim and Y.-H. Kim, *Phys. Rev. Lett.*, 2011, **106**, 175502.
- 33 J. Zeng and K.-Q. Chen, *Appl. Phys. Lett.*, 2014, **104**, 033104.
- 34 H. Hamadi, E. Shakerzadeh and M. D. Esrafil, *Chem. Phys. Lett.*, 2019, **724**, 80–85.
- 35 E. Shakerzadeh, H. Hamadi and M. D. Esrafil, *Inorg. Chem. Commun.*, 2019, **106**, 190–196.
- 36 K. Srinivasu and S. K. Ghosh, *J. Phys. Chem. C*, 2012, **116**, 25184–25189.
- 37 M. D. Esrafil and B. Nejadbrahimi, *Chem. Phys. Lett.*, 2019, **716**, 11–16.
- 38 B. Modak, K. Srinivasu and S. K. Ghosh, *Int. J. Hydrogen Energy*, 2017, **42**, 2278–2287.
- 39 M. D. Esrafil and H. Hamadi, *Mol. Phys.*, 2020, **118**, e1797919.
- 40 A. Tatar, A. Barati-Harooni, A. Najafi-Marghmaleki, A. Mohebbi, M. M. Ghiasi, A. H. Mohammadi and A. Hajinezhad, *Int. J. Greenhouse Gas Control*, 2016, **53**, 85–972016.
- 41 I. G. Wilson and I. Staffell, *Nat. Energy*, 2018, **3**, 365–372.
- 42 T. Montanari, E. Finocchio, E. Salvatore, G. Garuti, A. Giordano, C. Pistarino and G. Busca, *Energy*, 2011, **36**, 314–319.
- 43 J. O. Abe, A. Popoola, E. Ajenifuja and O. Popoola, *Int. J. Hydrogen Energy*, 2019, **44**, 15072–15086.
- 44 J. Bradshaw, S. Bachu, D. Bonijoly, R. Burruss, S. Holloway, N. P. Christensen and O. M. Mathiassen, *Int. J. Greenhouse Gas Control*, 2007, **1**, 62–68.
- 45 F. D. Meylan, V. Moreau and S. Erkman, *J. CO₂ Util.*, 2015, **12**, 101–108.
- 46 M. S. Duyar, S. Wang, M. A. Arellano-Trevino and R. J. Farrauto, *J. CO₂ Util.*, 2016, **15**, 65–71.
- 47 P. Kelemen, S. M. Benson, H. Pilorgé, P. Psarras and J. Wilcox, *Front. Clim.*, 2019, **1**, 9.
- 48 F. Su, C. Lu, S.-C. Kuo and W. Zeng, *Energy Fuels*, 2010, **24**, 1441–1448.
- 49 S. Kumar, R. Srivastava and J. Koh, *J. CO₂ Util.*, 2020, **41**, 101251.
- 50 R. Babarao and J. Jiang, *Energy Environ. Sci.*, 2008, **1**, 139–143.
- 51 Y. Zeng, R. Zou and Y. Zhao, *Adv. Mater.*, 2016, **28**, 2855–2873.
- 52 W. Leitner, *Coord. Chem. Rev.*, 1996, **153**, 257–284.
- 53 G. Qin, Q. Cui, W. Wang, P. Li, A. Du and Q. Sun, *ChemPhysChem*, 2018, **19**, 2788–2795.
- 54 N. Sathishkumar, S.-Y. Wu and H.-T. Chen, *Chem. Eng. J.*, 2020, **391**, 123577.
- 55 A. Liu, J. Long, S. Yuan, W. Cen and J. Li, *Phys. Chem. Chem. Phys.*, 2019, **21**, 5133–5141.
- 56 C. Chen, K. Xu, X. Ji, L. Miao and J. Jiang, *Phys. Chem. Chem. Phys.*, 2014, **16**, 11031–11036.
- 57 M. D. Esrafil, *J. Mol. Graphics Modell.*, 2019, **90**, 192–198.
- 58 N. Sathishkumar, S.-Y. Wu and H.-T. Chen, *Chem. Eng. J.*, 2021, **407**, 127194.
- 59 C. He, R. Wang, D. Xiang, X. Li, L. Fu, Z. Jian, J. Huo and S. Li, *Appl. Surf. Sci.*, 2020, **509**, 145392.
- 60 B. Gao, J.-x. Zhao, Q.-h. Cai, X.-g. Wang and X.-z. Wang, *J. Phys. Chem. A*, 2011, **115**, 9969–9976.
- 61 G. Gao, F. Ma, Y. Jiao, Q. Sun, Y. Jiao, E. Waclawik and A. Du, *Comput. Mater. Sci.*, 2015, **108**, 38–41.
- 62 J. P. Perdew, K. Burke and M. Ernzerhof, *Phys. Rev. Lett.*, 1996, **77**, 3865–3868.
- 63 B. Delley, *J. Chem. Phys.*, 1990, **92**, 508–517.
- 64 B. Delley, *J. Chem. Phys.*, 2000, **113**, 7756–7764.
- 65 S. Grimme, *J. Comput. Chem.*, 2006, **27**, 1787–1799.
- 66 R. Bader, *Atoms in Molecules: A Quantum Theory*, Clarendon Press, Oxford, 1990.
- 67 I. Rozas, I. Alkorta and J. Elguero, *J. Am. Chem. Soc.*, 2000, **122**, 11154–11161.
- 68 M. Frisch, G. Trucks, H. Schlegel, G. Scuseria, M. Robb, J. Cheeseman, G. Scalmani, V. Barone, B. Mennucci and G. Petersson, Gaussian Inc., Wallingford CT, 2009.
- 69 F. Biegler-König and J. Schönbohm, *J. Comput. Chem.*, 2002, **23**, 1489–1494.
- 70 E. Shakerzadeh, Z. Mashak Shabavi and E. C. Anota, *Appl. Organomet. Chem.*, 2020, **34**, e5694.
- 71 Q. Sun, M. Wang, Z. Li, A. Du and D. J. Searles, *J. Phys. Chem. C*, 2014, **118**, 2170–2177.
- 72 H. Dong, B. Lin, K. Gilmore, T. Hou, S.-T. Lee and Y. Li, *Curr. Appl. Phys.*, 2015, **15**, 1084–1089.
- 73 S. Chu and A. Majumdar, *Nature*, 2012, **488**, 294.
- 74 D. C. Camacho-Mojica, E. Muñoz-Sandoval and F. López-Urías, *Carbon*, 2017, **116**, 381–390.
- 75 E. Shakerzadeh, H. Hamadi and M. D. Esrafil, *Inorg. Chem. Commun.*, 2019, **106**, 190–196.
- 76 P. Mousavian and M. D. Esrafil, *Inorg. Chem. Commun.*, 2020, **122**, 108317.
- 77 M. A. Spackman, *Cryst. Growth Des.*, 2015, **15**, 5624–5628.