Drug delivery of Mechlorethamine as anticancer drug by Silicon, Carbon and Aluminum Nitride nanocages

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Abstract

The adsorption of Mechlorethamine on silicon, carbon and aluminum nitride ($\text{Si}_{76}$, $\text{C}_{76}$ and $\text{Al}_{38}\text{N}_{38}$) nanocages are investigated. The effects of V adoption on potential of $\text{Si}_{76}$, $\text{C}_{76}$ and $\text{Al}_{38}\text{N}_{38}$ nanocages to delivery the Mechlorethamine are investigated. The adsorption energy, Gibbs free energy, recovery time, orbital gap energy, charge transfer of interactions of $\text{Si}_{76}$, $\text{C}_{76}$, $\text{Al}_{38}\text{N}_{38}$, V-$\text{Si}_{76}$, V-$\text{C}_{76}$ and V-$\text{Al}_{38}\text{N}_{38}$ nanocages with Mechlorethamine are calculated. Results shown that the $\text{Si}_{76}$ and $\text{Al}_{38}\text{N}_{38}$ nanocage has higher potential to Mechlorethamine delivery than $\text{C}_{76}$ nanocage. The V adoption of nanocages can increase the interactions of $\text{Si}_{76}$, $\text{C}_{76}$ and $\text{Al}_{38}\text{N}_{38}$ nanocages with Mechlorethamine and their abilities to drug delivery. Finally, results are demonstrated that the V-$\text{Si}_{76}$ and V-$\text{Al}_{38}\text{N}_{38}$ are acceptable nanocages to delivery of Mechlorethamine with high performance.

1. Introduction

In recent years, the Mechlorethamine has been used as anticancer drug to treat various types of cancers such as prostate, gastric, colorectal and breast cancers [1–3]. The Mechlorethamine is joined to DNA and it is averted the duplication of cancer cells in body [4–6]. In recent years, the potential of nanostructures for delivery of cancer drugs have been examined [8–10].

In recent years, the utilization of nanomaterials including the metal doped nanocages as acceptable materials has been increased because these metal doped nanocages have unique chemical and physical properties [11, 12]. The metal doped nanocages due to structural stability, suitable sensitivity to drugs, unique globular shape are stable candidates to transfer the various types of cancer drugs [13, 14].

Bautista et al. [15] have examined the interactions of acetylsalicylic acid with boron nitride nanostructures by calculation methods and they have demonstrated that the adsorption of acetylsalicylic acid on boron nitride nanostructures complexes is chemical type and it is suitable for drug delivery [15].

Shakerzadeh et al. [16] have examined the adsorption of pristine and metal-encapsulated fullerenes toward the hydroxyurea and nitrosourea anticancer drugs by theoretical methods and they have provided the novel insights for developing the boron nitride nanostructures as drug delivers by calculation methods [16].

Gholami et al. [17] have examined potential of pristine and metal-encapsulated fullerenes in delivery of $\beta$-lapachone anticancer drug by theoretical models ad they have demonstrated that the $\beta$-lapachone anticancer drug can deliver with $\text{B}_{36}\text{N}_{36}$ nanocage [17].

In this study, the adsorption of Mechlorethamine as anticancer drug on metal doped nanocages are investigated. The recovery time for complexes of $\text{Si}_{76}$-Mechlorethamine, $\text{C}_{76}$-Mechlorethamine, $\text{Al}_{38}\text{N}_{38}$-Mechlorethamine, V-$\text{Si}_{76}$-Mechlorethamine, V-$\text{C}_{76}$-Mechlorethamine and V-$\text{Al}_{38}\text{N}_{38}$-Mechlorethamine are examined to predict the properties of interactions of nanocages with Mechlorethamine drug.
2. Computational details

In this work, the structures of Si$_{76}$, C$_{76}$, Al$_{38}$N$_{38}$, V-Si$_{76}$, V-C$_{76}$, V-Al$_{38}$N$_{38}$ and complexes of Si$_{76}$-
Mechlorethamine, C$_{76}$-Mechlorethamine, Al$_{38}$N$_{38}$-Mechlorethamine, V-Si$_{76}$-Mechlorethamine, V-C$_{76}$-
Mechlorethamine and V-Al$_{38}$N$_{38}$-Mechlorethamine are optimized by PW91PW91/6-311 + G (2d, 2p) model
and M06-2X/cc-pVQZ model in GAMESS software [19, 20]. The adsorption parameters, charge transfers,
bond gap energy and recovery time of Si$_{76}$, C$_{76}$, Al$_{38}$N$_{38}$, V-Si$_{76}$, V-C$_{76}$, V-Al$_{38}$N$_{38}$ and Mechlorethamine are
calculated [21–23].

In this study we calculated all frequencies of optimized structures including the nanocages (Si$_{76}$, C$_{76}$ and
Al$_{38}$N$_{38}$), metal doped nanocages (V-Si$_{76}$, V-C$_{76}$ and V-Al$_{38}$N$_{38}$), drug (Mechlorethamine), nanocage-drug
complexes and metal doped nanocages-drug complexes by PW91PW91/6-311 + G (2d, 2p) model and
M06-2X/cc-pVQZ model in order to confirm these optimized structures are real structures [19–23].

In this study, all positions for doping the Vanadium atoms on Si$_{76}$, C$_{76}$ and Al$_{38}$N$_{38}$ nanocages are
examined, Results shown that when the Vanadium atoms in Si and C nanocages (Si$_{76}$ and C$_{76}$) are
doped in two front C and Si atoms the most stable nanocages (V-Si$_{76}$ and V-C$_{76}$) from thermodynamic
view point are produced (structures Fig. 1). Results indicated that when the Vanadium atoms in AlN
nanocage (Al$_{38}$N$_{38}$) are doped in two front Al and N atoms the most stable nanocages (V-Al$_{38}$N$_{38}$) from
thermodynamic view point are produced (structures Fig. 1).

In this studym we considered all possible charge ions of Vanadium including the V$^{+2}$ and V$^{+3}$ ions.
Results shown that in the V-Si$_{76}$, V-C$_{76}$, V-Al$_{38}$N$_{38}$ nanocages the Vanadium in V$^{+3}$, V$^{+2}$ and V$^{+3}$ ions have
the most stable nanostructures, respectively. Results indicated that in the V-C$_{76}$-Mechlorethamine and V-
Al$_{38}$N$_{38}$-Mechlorethamine the Vanadium in charge ions of V$^{+2}$, V$^{+3}$ and V$^{+3}$ have the most stable
nanostructures, from thermodynamic viewpoints.

In this study, the COSMO (COnductor-like Screening MOdel) model is used for examination the effects of
water as polar solvent for examination the potential of silicon, carbon and aluminum nitride nanocages
(Si$_{76}$, C$_{76}$, Al$_{38}$N$_{38}$, V-Si$_{76}$, V-C$_{76}$, V-Al$_{38}$N$_{38}$) as drug delivery of Mechlorethamine as anticancer drug [21–
23].

3. Results and discussions

3.1. Structural properties of nanocages

In this section, Si$_{76}$, C$_{76}$, Al$_{38}$N$_{38}$, V-Si$_{76}$, V-C$_{76}$, V-Al$_{38}$N$_{38}$ nanocages and Mechlorethamine are optimized.
The optimized structures of Si$_{76}$, C$_{76}$, Al$_{38}$N$_{38}$, V-Si$_{76}$, V-C$_{76}$, V-Al$_{38}$N$_{38}$ and Mechlorethamine are presented
in Fig. 1.

The adoption energy ($E_{\text{adoption}}$) values of V atoms on C$_{76}$ and Al$_{38}$N$_{38}$ nanocages are examined:
\[ E_{\text{adoption}} = E_{V-C76} - E_{C76} - E_V \text{ and } E_{\text{adoption}} = E_{V-Al38N38} - E_{Al38N38} - E_V \] (1)

Where the \( E_{V-C76} \) and \( E_{V-Al38N38} \) are total energy of complexes of V with C\(_{76}\) and Al\(_{38}N_{38}\) nanocages and the \( E_V \) is isolated energy of V atom and the \( E_{C76} \) and \( E_{Al38N38} \) are total energy of C\(_{76}\) and Al\(_{38}N_{38}\) nanocages.

The \( E_{\text{adoption}} \) of V-Si\(_{76}\), V-C\(_{76}\), V-Al\(_{38}N_{38}\) are negative values and negative values of \( E_{\text{adoption}} \) are shown that V atoms are adopted to Si\(_{76}\), C\(_{76}\) and Al\(_{38}N_{38}\) and therefore V-Si\(_{76}\), V-C\(_{76}\), V-Al\(_{38}N_{38}\) are chemical and physical stable structures. The V atoms are formed the strong bonds with Si, C and AlN atoms of V-Si\(_{76}\), V-C\(_{76}\), V-Al\(_{38}N_{38}\) nanocages.

Here, to investigate the structural stability of Si\(_{76}\), C\(_{76}\) and Al\(_{38}N_{38}\) nanocages the cohesive energy \([24]\) is obtained:

\[ E_{\text{cohesive}} = (E_{C76} - 76*E_C) / 76 \text{ and } E_{\text{cohesive}} = (E_{Al38N38} - 76*E_{AlN}) / 76 \] (2)

Results shown that the \( E_{\text{cohesive}} \) of C\(_{76}\) and Al\(_{38}N_{38}\) are negative values as reported in Table 1.

**Table 1.** The \( E_{\text{adoption}} \), \( E_{\text{HLG}} \) and \( E_{\text{cohesive}} \) of Si\(_{76}\), C\(_{76}\), Al\(_{38}N_{38}\), V-Si\(_{76}\), V-C\(_{76}\), V-Al\(_{38}N_{38}\) nanocages in eV and the \( E_{\text{adsorption}} \), \( \Delta H_{\text{adsorption}} \), \( \Delta G_{\text{adsorption}} \), \( E_{\text{HLG}} \), \( q\) (e) and \( \tau \) (sec) of Si\(_{76}\)-Mechlorethamine, C\(_{76}\)-Mechlorethamine, Al\(_{38}N_{38}\)-Mechlorethamine, V-Si\(_{76}\)-Mechlorethamine, V-C\(_{76}\)-Mechlorethamine, V-Al\(_{38}N_{38}\)-Mechlorethamine nanocages complexes in eV.
<table>
<thead>
<tr>
<th>Nanocages</th>
<th>$E_{\text{adoption}}$</th>
<th>$E_{\text{HLG}}$</th>
<th>$E_{\text{cohesive}}$</th>
<th>$E_{\text{adoption}}$</th>
<th>$E_{\text{HLG}}$</th>
<th>$E_{\text{cohesive}}$</th>
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</thead>
<tbody>
<tr>
<td>$C_{76}$</td>
<td>2.60</td>
<td>-7.94</td>
<td>-2.63</td>
<td>-7.87</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Al_{38}N_{38}$</td>
<td>2.26</td>
<td>-8.26</td>
<td>2.29</td>
<td>-8.19</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Si_{76}$</td>
<td>2.08</td>
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<td>2.11</td>
<td>-8.43</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$V-C_{76}$</td>
<td>-4.26</td>
<td>-8.12</td>
<td>-4.20</td>
<td>2.40</td>
<td>-8.02</td>
<td></td>
</tr>
<tr>
<td>$V-Al_{38}N_{38}$</td>
<td>-4.38</td>
<td>-8.32</td>
<td>-4.33</td>
<td>2.10</td>
<td>-8.25</td>
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<td>$V-Si_{76}$</td>
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<td>-8.61</td>
<td>-4.46</td>
<td>1.94</td>
<td>-8.49</td>
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**PW91PW91/6-311+G (2d, 2p) in gas phase**

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<tr>
<th>Complexes</th>
<th>$E_{\text{adsorption}}$</th>
<th>$\Delta H_{\text{adsorption}}$</th>
<th>$\Delta G_{\text{adsorption}}$</th>
<th>$E_{\text{HLG}}$</th>
<th>$q$ (e)</th>
<th>$\tau$ (sec)</th>
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<tbody>
<tr>
<td>$C_{76}$-Mechlorethamine (a)</td>
<td>-2.50</td>
<td>-2.89</td>
<td>-2.85</td>
<td>3.64</td>
<td>0.372</td>
<td>45.38</td>
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<td>$Al_{38}N_{38}$-Mechlorethamine (c)</td>
<td>-2.64</td>
<td>-3.01</td>
<td>-2.97</td>
<td>3.34</td>
<td>0.390</td>
<td>48.14</td>
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<tr>
<td>$Si_{76}$-Mechlorethamine (i)</td>
<td>-2.70</td>
<td>-3.10</td>
<td>-3.06</td>
<td>3.26</td>
<td>0.400</td>
<td>49.10</td>
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<tr>
<td>$V-C_{76}$-Mechlorethamine (e)</td>
<td>-3.16</td>
<td>-3.56</td>
<td>-3.53</td>
<td>3.43</td>
<td>0.450</td>
<td>51.07</td>
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<td>$V-Al_{38}N_{38}$-Mechlorethamine (g)</td>
<td>-3.27</td>
<td>-3.67</td>
<td>-3.61</td>
<td>3.14</td>
<td>0.471</td>
<td>55.19</td>
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<tr>
<td>$V-Si_{76}$-Mechlorethamine (k)</td>
<td>-3.38</td>
<td>-3.80</td>
<td>-3.75</td>
<td>3.07</td>
<td>0.484</td>
<td>55.79</td>
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<tr>
<td>$C_{76}$-Mechlorethamine (b)</td>
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<td>-2.83</td>
<td>-2.79</td>
<td>3.68</td>
<td>0.366</td>
<td>44.47</td>
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<td>$Al_{38}N_{38}$-Mechlorethamine (d)</td>
<td>-2.59</td>
<td>-2.95</td>
<td>-2.91</td>
<td>3.38</td>
<td>0.385</td>
<td>47.18</td>
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<td>$Si_{76}$-Mechlorethamine (l)</td>
<td>-2.65</td>
<td>-3.03</td>
<td>-2.99</td>
<td>3.30</td>
<td>0.394</td>
<td>48.12</td>
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<td>$V-C_{76}$-Mechlorethamine (f)</td>
<td>-3.09</td>
<td>-3.49</td>
<td>-3.46</td>
<td>3.48</td>
<td>0.445</td>
<td>50.04</td>
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<td>$V-Al_{38}N_{38}$-Mechlorethamine (h)</td>
<td>-3.21</td>
<td>-3.60</td>
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<td>3.19</td>
<td>0.467</td>
<td>54.08</td>
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<tr>
<td>$V-Si_{76}$-Mechlorethamine (l)</td>
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<td>-3.72</td>
<td>-3.68</td>
<td>3.12</td>
<td>0.479</td>
<td>54.66</td>
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**M06-2X/cc-pVQZ in gas phase**
<table>
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<tr>
<th>Complexes</th>
<th>$E_{\text{adsorption}}$</th>
<th>$\Delta H_{\text{adsorption}}$</th>
<th>$\Delta G_{\text{adsorption}}$</th>
<th>$E_{\text{HLG}}$</th>
<th>$q \ (e)$</th>
<th>$\tau \ (\text{sec})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>C$_{76}$-Mechlorethamine ($a$)</td>
<td>-2.43</td>
<td>-2.80</td>
<td>-2.76</td>
<td>3.76</td>
<td>0.353</td>
<td>43.12</td>
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<tr>
<td>Al$<em>{38}$N$</em>{38}$-Mechlorethamine ($c$)</td>
<td>-2.56</td>
<td>-2.92</td>
<td>-2.88</td>
<td>3.45</td>
<td>0.371</td>
<td>45.73</td>
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<td>Si$_{76}$-Mechlorethamine ($i$)</td>
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<td>-3.00</td>
<td>-2.96</td>
<td>3.37</td>
<td>0.380</td>
<td>46.65</td>
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<tr>
<td>V-C$_{76}$-Mechlorethamine ($e$)</td>
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<td>-3.46</td>
<td>-3.43</td>
<td>3.53</td>
<td>0.427</td>
<td>48.51</td>
</tr>
<tr>
<td>V-Al$<em>{38}$N$</em>{38}$-Mechlorethamine ($g$)</td>
<td>-3.18</td>
<td>-3.56</td>
<td>-3.51</td>
<td>3.23</td>
<td>0.447</td>
<td>52.42</td>
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<td>3.16</td>
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<td>C$_{76}$-Mechlorethamine ($b$)</td>
<td>-2.38</td>
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<td>0.422</td>
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<td>V-Al$<em>{38}$N$</em>{38}$-Mechlorethamine ($h$)</td>
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<td>3.27</td>
<td>0.443</td>
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<tr>
<td>V-Si$_{76}$-Mechlorethamine ($l$)</td>
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<td>-3.56</td>
<td>3.19</td>
<td>0.454</td>
<td>51.93</td>
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</table>

**COSMO in water**

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<th>Complexes</th>
<th>$E_{\text{adsorption}}$</th>
<th>$\Delta H_{\text{adsorption}}$</th>
<th>$\Delta G_{\text{adsorption}}$</th>
<th>$E_{\text{HLG}}$</th>
<th>$q \ (e)$</th>
<th>$\tau \ (\text{sec})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>C$_{76}$-Mechlorethamine ($a$)</td>
<td>-2.58</td>
<td>-2.97</td>
<td>-2.93</td>
<td>3.530</td>
<td>0.39</td>
<td>47.65</td>
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<tr>
<td>Al$<em>{38}$N$</em>{38}$-Mechlorethamine ($c$)</td>
<td>-2.72</td>
<td>-3.11</td>
<td>-3.06</td>
<td>3.240</td>
<td>0.41</td>
<td>50.55</td>
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<td>Si$_{76}$-Mechlorethamine ($i$)</td>
<td>-2.78</td>
<td>-3.19</td>
<td>-3.14</td>
<td>3.165</td>
<td>0.42</td>
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<tr>
<td>V-C$_{76}$-Mechlorethamine ($e$)</td>
<td>-3.25</td>
<td>-3.66</td>
<td>-3.62</td>
<td>3.320</td>
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<td>53.62</td>
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<tr>
<td>V-Al$<em>{38}$N$</em>{38}$-Mechlorethamine ($g$)</td>
<td>-3.36</td>
<td>-3.79</td>
<td>-3.71</td>
<td>3.040</td>
<td>0.50</td>
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<td>-2.87</td>
<td>3.570</td>
<td>0.39</td>
<td>46.70</td>
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</table>
In this study, to examine of electronic properties of Si$_{76}$, C$_{76}$, Al$_{38}$N$_{38}$, V-Si$_{76}$, V-C$_{76}$, V-Al$_{38}$N$_{38}$ nanocages and Mechlorethamine the gap energy ($E_{HLG}$) are calculated through the difference of energy of HOMO and LUMO orbitals [25] by theoretical methods:

$$E_{HLG} = E_{\text{LUMO}} - E_{\text{HOMO}}$$ \hspace{1cm} (3)

Where the $E_{\text{HOMO}}$ and $E_{\text{LUMO}}$ are energies of HOMO and LUMO orbitals of Si$_{76}$, C$_{76}$, Al$_{38}$N$_{38}$, V-Si$_{76}$, V-C$_{76}$, V-Al$_{38}$N$_{38}$ nanocages and Mechlorethamine.

The $E_{HLG}$ of Si$_{76}$, C$_{76}$, Al$_{38}$N$_{38}$, V-Si$_{76}$, V-C$_{76}$, V-Al$_{38}$N$_{38}$ nanocages and Mechlorethamine are stated in Table 1. When Si, C and AlN atoms of Si$_{76}$, C$_{76}$, Al$_{38}$N$_{38}$ nanocages are replaced with V atoms the $E_{HLG}$ are reduced. Therefore, the V-Si$_{76}$, V-C$_{76}$, V-Al$_{38}$N$_{38}$ nanocages with lower $E_{HLG}$ than C$_{76}$ and Al$_{38}$N$_{38}$ nanocages have higher potential and abilities to transfer electrons and interactions with Mechlorethamine. In V-Si$_{76}$, V-C$_{76}$, V-Al$_{38}$N$_{38}$ nanocages the V atoms are the important sites and suitable positions for transferring the electrons and charges to Mechlorethamine.

### 3.2. Adsorption of Mechlorethamine on nanocages

In this study, to examine the abilities of Si$_{76}$, C$_{76}$, Al$_{38}$N$_{38}$, V-Si$_{76}$, V-C$_{76}$, V-Al$_{38}$N$_{38}$ nanocages for carrier of Mechlorethamine, the electronic properties and adsorption parameters of Si$_{76}$-Mechlorethamine, C$_{76}$-Mechlorethamine, Al$_{38}$N$_{38}$-Mechlorethamine, V-Si$_{76}$-Mechlorethamine, V-C$_{76}$-Mechlorethamine and V-Al$_{38}$N$_{38}$-Mechlorethamine complexes are calculated. The possible positions for adsorption of Mechlorethamine on Si$_{76}$, C$_{76}$, Al$_{38}$N$_{38}$, V-Si$_{76}$, V-C$_{76}$, V-Al$_{38}$N$_{38}$ nanocages are investigated and structures of Si$_{76}$-Mechlorethamine, C$_{76}$-Mechloethamine, Al$_{38}$N$_{38}$-Mechlorethamine, V-Si$_{76}$-Mechlorethamine, V-C$_{76}$-Mechlorethamine, V-C$_{76}$-Mechloethamine and V-Al$_{38}$N$_{38}$-Mechlorethamine complexes are presented in Fig. 1.

Here, adsorption energy ($E_{\text{adsorption}}$) values for Si$_{76}$-Mechlorethamine, C$_{76}$-Mechlorethamine, Al$_{38}$N$_{38}$-Mechlorethamine, V-Si$_{76}$-Mechlorethamine, V-C$_{76}$-Mechlorethamine and V-Al$_{38}$N$_{38}$-Mechlorethamine complexes are calculated in Table 1:

$$E_{\text{adsorption}} = E_{\text{Mechlorethamine-nanocage}} - (E_{\text{nanocage}} + E_{\text{Mechlorethamine}})$$ \hspace{1cm} (4)
Where, $E_{\text{nancg}e}$, $E_{\text{Mechlorethamine-nanocage}}$ and $E_{\text{Mechlorethamine}}$ are total energy of nanocages ($C_{76}, Al_{38}N_{38}$, $V-C_{76}, V-Al_{38}N_{38}$), Mechlorethamine and nanoacge-Mechlorethamine complexes ($C_{76}$-Mechlorethamine, $Al_{38}N_{38}$-Mechlorethamine, $V-C_{76}$-Mechlorethamine and $V-Al_{38}N_{38}$-Mechlorethamine) [26–28].

In this study, to investigate the stability of $Si_{76}$-Mechlorethamine, $C_{76}$-Mechlorethamine, $Al_{38}N_{38}$-Mechlorethamine, $V-Si_{76}$-Mechlorethamine, $V-C_{76}$-Mechlorethamine and $V-Al_{38}N_{38}$-Mechlorethamine complexes from thermodynamic view point, the thermodynamic indexes including the enthalpy change ($\Delta H$) and Gibbs free energy ($\Delta G$) are calculated. Here, $\Delta H$ and $\Delta G$ values for nanocage-Mechlorethamine complexes are calculated in Table 1:

$$\Delta G_{\text{adsorption}} = G_{\text{Mechlorethamine-nanocage}} - (G_{\text{nancg}e} + G_{\text{Mechlorethamine}}) \quad (5)$$

$$\Delta H_{\text{adsorption}} = H_{\text{Mechlorethamine-nanocage}} - (H_{\text{nancg}e} + H_{\text{Mechlorethamine}}) \quad (6)$$

The $G_{\text{nancg}e}$, $G_{\text{Mechlorethamine-nanocage}}$ and $G_{\text{Mechlorethamine}}$ are Gibbs free energy of nanocages ($C_{76}$, $Al_{38}N_{38}$, $V-C_{76}$, $V-Al_{38}N_{38}$), Mechlorethamine and nanoacge-Mechlorethamine complexes ($C_{76}$-Mechlorethamine, $Al_{38}N_{38}$-Mechlorethamine, $V-C_{76}$-Mechlorethamine and $V-Al_{38}N_{38}$-Mechlorethamine). Also, in this study the $H_{\text{nancg}e}$, $H_{\text{Mechlorethamine-nanocage}}$ and $H_{\text{Mechlorethamine}}$ are enthalpy of nanocages, Mechlorethamine and nanoacge-Mechlorethamine complexes [29].

The Fig. 1a to 1k are presented the structures of possible nanoacge-Mechlorethamine complexes ($Si_{76}$-Mechlorethamine, $C_{76}$-Mechlorethamine, $Al_{38}N_{38}$-Mechlorethamine, $V-Si_{76}$-Mechlorethamine, $V-C_{76}$-Mechlorethamine and $V-Al_{38}N_{38}$-Mechlorethamine). The geometries of metal doped nanocages ($V-C_{76}$ and $V-Al_{38}N_{38}$) after adsorption of Mechlorethamine are changed and there are strong interactions between atoms of Mechlorethamine with $V$ atoms of $V-C_{76}$ and $V-Al_{38}N_{38}$. The Mechlorethamine are adsorbed on surfaces of $V$ sites of metal doped nanocages and about $V-Si_{76}$-Mechlorethamine, $C_{76}$-Mechlorethamine, $Al_{38}N_{38}$-Mechlorethamine the Mechlorethamine has week interaction with C and AlN atoms of $C_{76}$ and $Al_{38}N_{38}$.

The calculated the suitable distances between the Mechlorethamine and $Si_{76}, C_{76}, Al_{38}N_{38}, V-Si_{76}, V-C_{76}, V-Al_{38}N_{38}$ nanocages as drug delivers to achieve the best adsorption energy of drug-nanocage complexes ($Si_{76}$-Mechlorethamine, $C_{76}$-Mechlorethamine, $Al_{38}N_{38}$-Mechlorethamine, $V-Si_{76}$-Mechlorethamine, $V-C_{76}$-Mechlorethamine and $V-Al_{38}N_{38}$-Mechlorethamine) are reported in Fig. 1. Results shown that for each drug-nanocage complexes ($Si_{76}$-Mechlorethamine, $C_{76}$-Mechlorethamine, $Al_{38}N_{38}$-Mechlorethamine, $V-Si_{76}$-Mechlorethamine, $V-C_{76}$-Mechlorethamine, $V-Al_{38}N_{38}$-Mechlorethamine) the one reported distance between the Mechlorethamine and $Si_{76}, C_{76}, Al_{38}N_{38}, V-Si_{76}, V-C_{76}, V-Al_{38}N_{38}$ nanocages can achieve the best adsorption energy of drug-nanocage complexes.

The calculated $E_{\text{adsorption}}$, $\Delta G_{\text{adsorption}}$ and $\Delta H_{\text{adsorption}}$ of nanoacge-Mechlorethamine complexes including the structures $a$ to $k$ are reported in Table 1. The all of $E_{\text{adsorption}}$, $\Delta G_{\text{adsorption}}$ and $\Delta H_{\text{adsorption}}$
values are negative and so, adsorption of Mechlorethamine on surfaces of Si\textsubscript{76}, C\textsubscript{76}, Al\textsubscript{38}N\textsubscript{38}, V-Si\textsubscript{76}, V-C\textsubscript{76}, V-Al\textsubscript{38}N\textsubscript{38} are spontaneous interactions and exothermic reactions.

The calculated $E_{\text{HLG}}$ of nanoacge-Mechlorethamine complexes including the structures a to h by are reported in Table 1. The $E_{\text{HLG}}$ of Si\textsubscript{76}, C\textsubscript{76}, Al\textsubscript{38}N\textsubscript{38}, V-Si\textsubscript{76}, V-C\textsubscript{76}, V-Al\textsubscript{38}N\textsubscript{38} after Mechlorethamine adsorption are changed, significantly. The Mechlorethamine has suitable effects on $E_{\text{HLG}}$ of C\textsubscript{76}, Al\textsubscript{38}N\textsubscript{38}, V-C\textsubscript{76} and V-Al\textsubscript{38}N\textsubscript{38} which is indicated the strong interactions between the Mechlorethamine and nanocages. The $E_{\text{HLG}}$ of V-Al\textsubscript{38}N\textsubscript{38}-Mechlorethamine are lower than V-C\textsubscript{76}-Mechlorethamine and also the Al\textsubscript{38}N\textsubscript{38}-Mechlorethamine has lower the $E_{\text{HLG}}$ than C\textsubscript{76}-Mechlorethamine.

In this study, the recovery or desorption time ($\tau$) as important index for Mechlorethamine delivery is calculated to predict the needed time to desorb the Mechlorethamine from Si\textsubscript{76}, C\textsubscript{76}, Al\textsubscript{38}N\textsubscript{38}, V-Si\textsubscript{76}, V-C\textsubscript{76}, V-Al\textsubscript{38}N\textsubscript{38} nanocages [30]. The $\tau$ index is exponentially associated to $E_{\text{adsorption}}$ and the high adsorption interactions of Si\textsubscript{76}, C\textsubscript{76}, Al\textsubscript{38}N\textsubscript{38}, V-Si\textsubscript{76}, V-C\textsubscript{76}, V-Al\textsubscript{38}N\textsubscript{38} with Mechlorethamine are needed to high desorption time. The $\tau$ index is calculated in Table 1:

$$\tau = \left( \frac{1}{\delta} \right) \times \exp \left( -\frac{E_{\text{adsorption}}}{KT} \right) (7)$$

Where, K is Boltzmann’s constant, T is temperature in Kelvin and $\delta$ is attempt frequency of nanoacge-Mechlorethamine complexes (C\textsubscript{76}-Mechlorethamine, Al\textsubscript{38}N\textsubscript{38}-Mechlorethamine, V-C\textsubscript{76}-Mechlorethamine and V-Al\textsubscript{38}N\textsubscript{38}-Mechlorethamine). Results indicated that, the $\tau$ index of V-C\textsubscript{76}-Mechlorethamine and V-Al\textsubscript{38}N\textsubscript{38}-Mechlorethamine due to strong interactions between metal doped nanocages and Mechlorethamine are higher than C\textsubscript{76}-Mechlorethamine and Al\textsubscript{38}N\textsubscript{38}-Mechlorethamine. The $\tau$ index of V-Si\textsubscript{76}-Mechlorethamine and V-Al\textsubscript{38}N\textsubscript{38}-Mechlorethamine are higher than V-C\textsubscript{76}-Mechlorethamine and also the Al\textsubscript{38}N\textsubscript{38}-Mechlorethamine has higher the $\tau$ index than C\textsubscript{76}-Mechlorethamine.

In this study, results indicated that V-C\textsubscript{76}-Mechlorethamine and V-Al\textsubscript{38}N\textsubscript{38}-Mechlorethamine have lower $E_{\text{HLG}}$ values, higher $E_{\text{adsorption}}$ and $\Delta G_{\text{adsorption}}$ values and also have higher the recovery or desorption time than Al\textsubscript{38}N\textsubscript{38}-Mechlorethamine and C\textsubscript{76}-Mechlorethamine. Finally, through examined parameters including the $E_{\text{adsorption}}$, $\Delta G_{\text{adsorption}}$ and $\tau$ index it can be concluded the V-Al\textsubscript{38}N\textsubscript{38} and V-C\textsubscript{76} have high potential to Mechlorethamine adsorption and V-Al\textsubscript{38}N\textsubscript{38} and V-C\textsubscript{76} are acceptable nanocages to Mechlorethamine carry and delivery of Mechlorethamine.

### 3.3. Solvent effects on Mechlorethamine adsorption on nanocages

In this study, effects solvent is examined on Mechlorethamine adsorption on Si\textsubscript{76}, C\textsubscript{76}, Al\textsubscript{38}N\textsubscript{38}, V-Si\textsubscript{76}, V-C\textsubscript{76}, V-Al\textsubscript{38}N\textsubscript{38} nanocages. Here, the $E_{\text{adsorption}}$, $\Delta G_{\text{adsorption}}$ and $\Delta H_{\text{adsorption}}$ values of nanoacge-Mechlorethamine complexes (C\textsubscript{76}-Mechlorethamine, Al\textsubscript{38}N\textsubscript{38}-Mechlorethamine, V-C\textsubscript{76}-Mechlorethamine and V-Al\textsubscript{38}N\textsubscript{38}-Mechlorethamine) are calculated. The calculated $E_{\text{HLG}}$, $q$ and $\tau$ index of interactions of
Si$_{76}$, C$_{76}$, Al$_{38}$N$_{38}$, V-Si$_{76}$, V-C$_{76}$, V-Al$_{38}$N$_{38}$ with Mechloretamine including the structures a to k by are calculated in water and results are reported in Table 1.

In water, all calculated $E_{\text{adsorption}}$, $\Delta G_{\text{adsorption}}$ and $\Delta H_{\text{adsorption}}$ values are negative similar to gas phase which is shown interactions of Mechloretamine with Si$_{76}$, C$_{76}$, Al$_{38}$N$_{38}$, V-Si$_{76}$, V-C$_{76}$, V-Al$_{38}$N$_{38}$ nanocages are exothermic reactions. The $E_{\text{adsorption}}$, $\Delta G_{\text{adsorption}}$ and $\Delta H_{\text{adsorption}}$ values of V-C$_{76}$-Mechloretamine and V-Al$_{38}$N$_{38}$-Mechloretamine are more negative than C$_{76}$-Mechloretamine and Al$_{38}$N$_{38}$-Mechloretamine in water. Also the Al$_{38}$N$_{38}$ has more negative $E_{\text{adsorption}}$, $\Delta G_{\text{adsorption}}$ and $\Delta H_{\text{adsorption}}$ values than C$_{76}$ to Mechloretamine adsorption in water. The water as polar solvent is increased and improved the interactions of Mechloretamine with nanocages.

4. Conclusions

The Mechloretamine adsorption on Si$_{76}$, C$_{76}$, Al$_{38}$N$_{38}$, V-Si$_{76}$, V-C$_{76}$, V-Al$_{38}$N$_{38}$ nanocages are calculated. The V-Si$_{76}$, V-C$_{76}$, V-Al$_{38}$N$_{38}$ nanocages with lower $E_{\text{HLG}}$ than Si$_{76}$, C$_{76}$ and Al$_{38}$N$_{38}$ nanocages have higher potential to transfer electrons to Mechloretamine. In V-Si$_{76}$, V-C$_{76}$, V-Al$_{38}$N$_{38}$ nanocages the V atoms are the important sites for transferring the electrons and charges to Mechloretamine. The calculated $E_{\text{adsorption}}$, $\Delta G_{\text{adsorption}}$ and $\Delta H_{\text{adsorption}}$ values for nanocages-Mechloretamine complexes are negative and Mechloretamine adsorption on nanocages are spontaneous interactions and exothermic reactions. The $E_{\text{adsorption}}$, $\Delta G_{\text{adsorption}}$ and $\Delta H_{\text{adsorption}}$ values of V doped nanocages are more negative than nanocages. Results indicated that, the $\tau$ index of V-Si$_{76}$-Mechloretamine, V-C$_{76}$-Mechloretamine and V-Al$_{38}$N$_{38}$-Mechloretamine are higher than C$_{76}$-Mechloretamine and Al$_{38}$N$_{38}$-Mechloretamine. The nanocages-Mechloretamine in water have lower $E_{\text{HLG}}$ than gas phase. In water the $\tau$ index of V-Si$_{76}$-Mechloretamine and V-Al$_{38}$N$_{38}$-Mechloretamine are higher than V-C$_{76}$-Mechloretamine. Finally, the results demonstrated that the V-Si$_{76}$ and V-Al$_{38}$N$_{38}$ is acceptable nanocage to Mechloretamine carry with high performance.

Declarations

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**Consent to participate:** I confirmed

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**References**


Figures

Figures 1

Structures of $\text{Si}_{76}$, $\text{C}_{76}$, $\text{Al}_{38}\text{N}_{38}$, $\text{V-Si}_{76}$, $\text{V-C}_{76}$, $\text{V-Al}_{38}\text{N}_{38}$ nanocages and Mechlorethamine and structures of $\text{Si}_{76}$-Mechlorethamine, $\text{C}_{76}$-Mechlorethamine, $\text{Al}_{38}\text{N}_{38}$-Mechlorethamine, $\text{V-C}_{76}$-Mechlorethamine, $\text{V-C}_{76}$-Mechlorethamine, $\text{V-Al}_{38}\text{N}_{38}$-Mechlorethamine nanocages complexes.