

## SIMULATION OF UREA–HYDROXYAPATITE BY USING DENSITY FUNCTIONAL THEORY (DFT)

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**Abstract:** Nitrogen and phosphorus are the main macronutrients needed by crops. Due to environmental factors, these nutrients can be easily washed off before reaching the crops. Slow-release fertilisers have been introduced to solve these problems as it helps release nutrients slowly to the plants. Many experimental studies have been conducted on the effectiveness of urea and hydroxyapatite as a slow-release fertiliser. In a complementary manner, this computational study concentrated on the details of interactions between urea and hydroxyapatite in relative stability, as well as the structural and electronic properties by using density functional theory (DFT) at the level of B3LYP/6-31G(d,p). The calculations were performed using the Gaussian 09 and Multiwfn programmes. The hydroxyapatite cluster was modelled to interact with one urea molecule, which was placed at strategic positions on the cluster's surface. All structures in this investigation are found to form bonding between the N atom in urea and Ca atom in hydroxyapatite. In addition, the interaction energies between urea and hydroxyapatite range from  $-0.09719$  eV to  $-1.2245$  eV. Meanwhile, for the newly-formed bond between N and Ca, the bond lengths range between  $2.64 \text{ \AA} - 2.85 \text{ \AA}$ . Our results confirmed the experimental findings that urea molecules can react favorably with the surfaces of hydroxyapatite.

Keywords: Density functional theory (DFT), hydroxyapatite, urea.

### Introduction

Nitrogen and phosphorus are the two main important macronutrients in the growth and yields of agricultural crops (Giroto *et al.*, 2017; Kottegoda *et al.*, 2011). Nitrogen is provided by urea and commonly used as synthetic fertilizer, while phosphorous can be provided by hydroxyapatite (HA), which has an excellent biocompatibility and high surface area that allows large amount of urea to bind to it (Kottegoda *et al.*, 2017). However, these nutrients are easily washed off due to environmental factors, such as leaching, volatilisation under high temperature and humidity, even before the nutrients reach the crops (Cabezas *et al.*, 1999; Castro-Enríquez *et al.*, 2012; Giroto *et al.*, 2017; Guo *et al.*, 2005; Jarosiewicz *et al.*, 2003; Wu *et al.*, 2008). For this reason, agriculture practitioners will apply more fertilisers on their crops. This in turn can bring many negative impacts to the economy, human health and ecology (Shaviv, 2001). For the economy, applying too much fertiliser may lead

to financial loss for the farmers, meanwhile in terms of human health and ecological problems, high levels of nitrate can be associated to some diseases, like methaemoglobinemia, as well as eutrophication on water surfaces, respectively (Bouchard *et al.*, 1992; Majumdar *et al.*, 2000; Shaviv, 2001).

In order to overcome these problems, slow-release fertilisers have been introduced, which releases nitrogen and phosphorus in a slow manner, in order to improve the consumption of macronutrients in crops (Bouchard *et al.*, 1992; Wu *et al.*, 2008). This is achieved by reducing the dissolution rate (Mohd Ibrahim *et al.*, 2014) and volatilisation in urea while avoiding immobilisation of phosphate in the soil (Giroto *et al.*, 2017).

In addition, slow-release fertilisers have proven its efficiency through previous experimental results. For instance, a previous study on urea coated with HA, which focused

on delivering nutrients to rice via slow release using nanohybrids, showed that a new bond was formed between urea and HA through a N atom in urea as the level of N 1s moved towards higher energy levels (Kottegoda *et al.*, 2017). The binding energy of phosphorus 2p core level of HA has increased, suggesting that the electron density around P has been influenced, which may be due to hydrogen bonding forming between the phosphate group of HA and urea. Besides, the binding energy in calcium ions also increased, possibly due to the change in chemical environment when urea was introduced to HA. The application of the urea coated HA nanohybrids on the rice crops welled to good crop growth, even though only a 50% concentration urea was used (Kottegoda *et al.*, 2017).

In another report, urea modified with HA and encapsulated with wood was studied using Fourier Transform Infrared Spectroscopy (FTIR) (Kottegoda *et al.*, 2011). N-H stretching in FTIR showed a peak shift towards the lower wavelength in the urea-HA spectrum, which showed existence of hydrogen bonding forming between N-H groups in urea with O-H group in HA. Furthermore, N-H bonding in urea-HA had shifted towards the lower frequency, indicating the presence of free N-H bonds following absorption. In carbonyl stretching frequency, it had changed to a lower frequency from pure urea to urea-HA, which indicates the electron density of C=O being affected by the hydrogen bonding of N-H in HA (Kottegoda *et al.*, 2011).

Technological advancements have been an integral part of improving yield in the agricultural sector (Heng, 2020; Hermassi *et al.*, 2020; Natarajan *et al.*, 2019; R. Tabal, 2020; W, 2020). In this paper, the simulation of the interaction between urea and hydroxyapatite using DFT is discussed in depth. The discussion is also focused on their relative stability, structural and electronic properties as it is yet to be explored. The new findings are compared with the experimental results from previous studies and discussed in the next section. Finally, the conclusion for the entire study is explained and summarised.

## Methodology

The Gaussian 09 suite of programmes (Frisch *et al.*, 2013) was used in implementing the scheme of Density Functional Theory (DFT) throughout this study at the B3LYP/6-31G(d,p) level. B3LYP is a hybrid functional method that is commonly used in recent years (Sousa *et al.*, 2007). This hybrid functional has become the standard method in studying different types of molecules, including organic chemistry in a gas phase and aqueous solution (Barone *et al.*, 1995; Fernandez-Ramos *et al.*, 2000; Hohenberg *et al.*, 1964; Riley *et al.*, 2005; Riley *et al.*, 2007; Tirado-Rives *et al.*, 2008).

This combination method of DFT and the basis set level at 6-31G(d,p) have been used in many previous studies in adding polarisation to improve the results. For instance, B3LYP/6-31G(d,p) was used to identify the intermolecular interactions and the most stable systems between harmene and selected functional monomers (Kowalska *et al.*, 2009). In another study, B3LYP/6-31G(d,p) was used in calculating the dipole moment and energy gap of HA. It indicated that this combination provided a better result than PM6 and HF/3-21G\*\*, which has high dipole moments with a lower band gap for reactivity of HA (Youness *et al.*, 2017). Besides, B3LYP/6-31G(d,p) was also used to confirm the hypothesis that weak intermolecular bonds can form between HA and collagen fragments based on experimental investigation (Aminova *et al.*, 2013).

The crystal structure of monoclinic HA as shown in Figure 1 was obtained from a report by Elliot *et al.* (1973). A cluster model was crafted out of the crystal structure, where the outermost layer consists of oxygen atoms. In this study, we focused on the hydrogen-terminated system as there is no clear evidence from previous experiments that the oxygen will remain bared before the absorption of the urea molecule. One molecule of urea was used in this study.

The single urea molecule has been positioned in different places on HA, either in vertical or horizontal positions, based on the electrostatic potential (ESP) of HA as shown

in Figure 2. The blue regions represent positive charge for nucleophile activity while red regions represent negative charge for electrophilic activity.

The initial placement of the urea molecule is based on chemical intuition of possible interaction of the urea molecule with the surface of HA. Each combination of urea and HA have

been labeled as structures A, B, C and D as shown in Figure 3. For each structure, the urea was placed differently at the slightly negative charge (yellow region). However, for structures B and C, they were distinguished by the vertical and horizontal positions of urea. These positions and the locations of urea on the HA surface act as the manipulated variables in determining

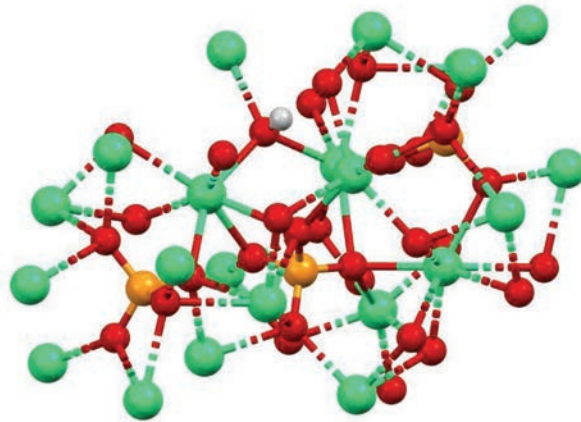


Figure 1: The structure of monoclinic HA generated using the Mercury software. The red balls represent oxygen atoms, the green balls calcium atoms, while the orange and white balls are phosphorus and hydrogen atoms, respectively

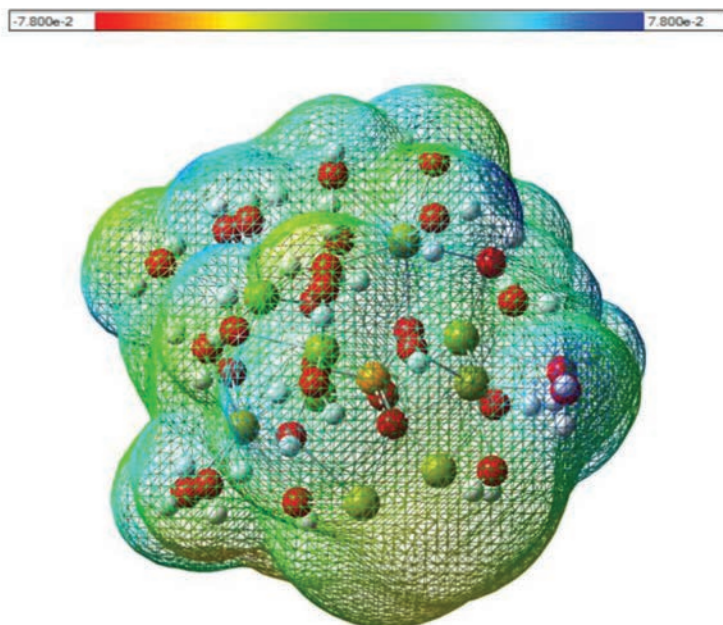


Figure 2: The mesh representation of the Potential Energy Surface (PES) of the first structure of HA viewed using Gauss View. The scale indicated the energy values of HA in eV

which location and positions would be the most stable combination with the lowest interaction energy.

In Equation (1), the interaction energy,  $E_{int}$ , is used to determine the relative stability of urea and HA by calculating the strength of interaction between urea and hydroxyapatite. This equation has been used in many previous studies when calculating the interaction energy, for instance calculating the interaction energies between HA with collagen, citric acid, polyacrylic acid and glycosaminoglycan saccharides (Almora-

Barrios *et al.*, 2009; Bhowmik *et al.*, 2007; De Leeuw, 2010; Filgueiras *et al.*, 2006; Streeter *et al.*, 2011):

$$E_{int} = E_{HA+Urea} - (E_{HA} + E_{Urea}) \quad (1)$$

$E_{int}$  is the interaction energy between urea and HA;  $E_{HA} + E_{Urea}$  is the energy after the composite structure is minimised;  $E_{HA}$  is the energy of the same composite structure after the urea molecule is removed; and, lastly,  $E_{Urea}$  is the energy of the composite structure after the HA surface is removed. Using this formula, a

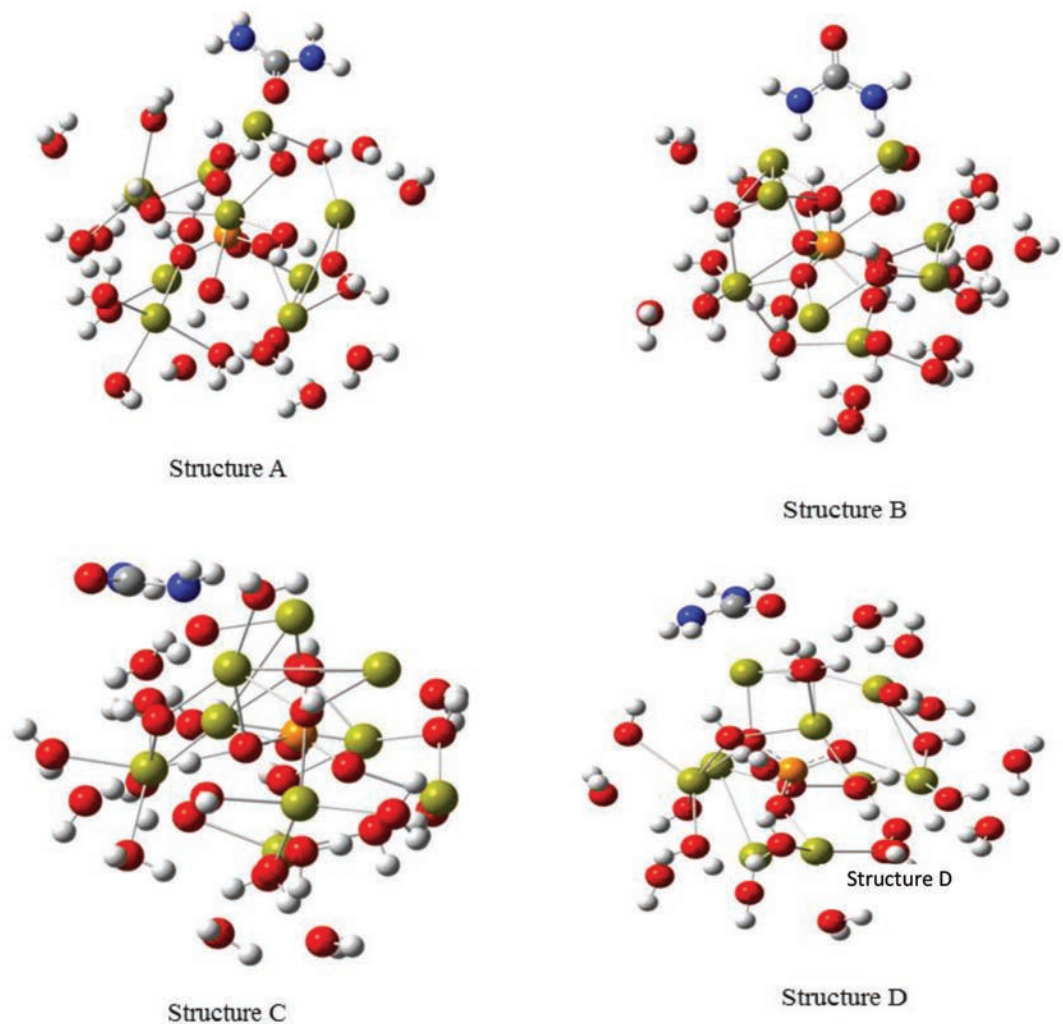


Figure 3: The initial structures of A, B, C and D, in which urea was placed in different regions on HA. The structures were illustrated using the ball-and-stick model. The white balls represent hydrogen atoms, the green balls calcium atoms, the red balls oxygen atoms, and the orange ball and blue balls phosphorus and nitrogen atoms, respectively



more negative value of interaction energy,  $E_{int}$ , indicates stronger interaction energy between urea and HA. The Multiwfn programme was used to identify the topology analysis between urea and HA (Lu *et al.*, 2012a, 2012b).

**Results and Discussion**

B3LYP/6-31G(d,p) was used as the level of theoretical study in investigating the interaction between urea and HA. Table 1 shows the number of electrons and basis functions of urea and system of urea + HA. Due to the large number of basis functions, only partial geometry optimisations were performed on the atoms near to the urea molecule. The geometry of the urea molecule was also optimised.

As an indicator of the strength of the interaction between urea and HA, the interaction energy for the different placements of urea onto HA were calculated. The results are shown in Table 2. The more negative a value is, the stronger the interaction. As all the interaction energies were negative, this implied that for the four positions, urea being absorbed onto HA can possibly happen. This result agrees with past experimental observations (Kottegoda *et al.*, 2011; Kottegoda *et al.*, 2017). However, comparing the interaction energy value for the different absorption region is not enough to give an indication on the effectiveness of slow-release fertilisers in releasing nutrients to crops. Further calculations are needed for the absorption of different compounds onto HA. Table 2 shows

the calculated interaction energy between urea and HA in structures A, B, C and D at the level B3LYP/6-31G(d,p).

From Table 2, it can be seen that structure C is the most stable structure while structure A is the least stable structure among the four calculated structures as mentioned in the previous section. However, the stability of these combinations does not differ significantly as the energy changes around 0.1 eV between a combination of the next lower combination.

As for the chemical bonding between atoms of urea and HA, a topology path analysis was performed, and the results are given in Figures 4, 5, 6 and 7. All structures (A, B, C and D) showed a new formed bond between calcium atom in HA and nitrogen atom in the urea molecule. This agrees with a previous experimental study by Kottegoda *et al.* (2017), in which the level energy of N 1s at the core level moved towards a higher level energy, which may be due to the new bonding formed between nitrogen atom in urea with HA.

The relevant bonds for all structures are tabulated in Table 3. The data shows that structure B has the shortest bond length among all structures, which means that calcium and nitrogen atoms have very strong interactions. Hence, our results show that it is possible for urea to combine with HA, with the bond lengths between nitrogen atom and the nearest calcium atom of HA ranging between 2.64 Å and 2.85 Å.

Table 1: Number of electrons and the basis functions of HA and urea + hA system

System	Number of Electrons	Basis Functions
HA	467	861
Urea and HA	499	941

Table 2: Interaction energies for structure A, B, C and D

Structures	Interaction Energy (eV)
A	-0.9719
B	-1.2245
C	-1.3395
D	-1.1242

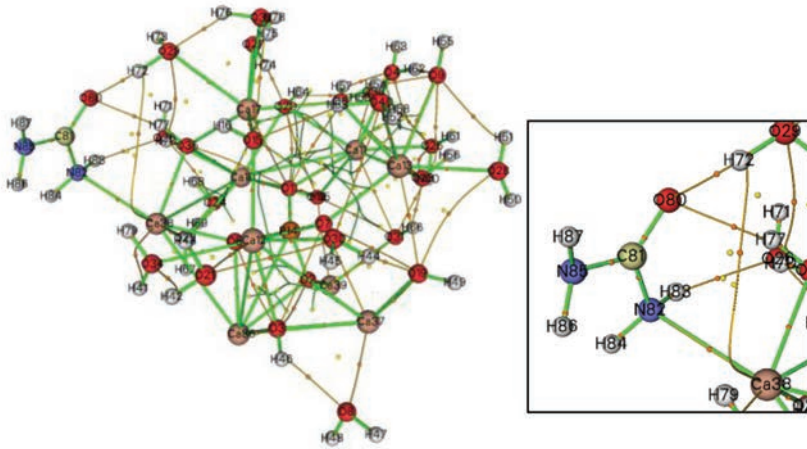


Figure 4: The structure of A, showing the newly formed bond paths between urea and HA, which is highlighted with a dotted rectangular box. An enlarged view of the dotted box is given in the solid-line box

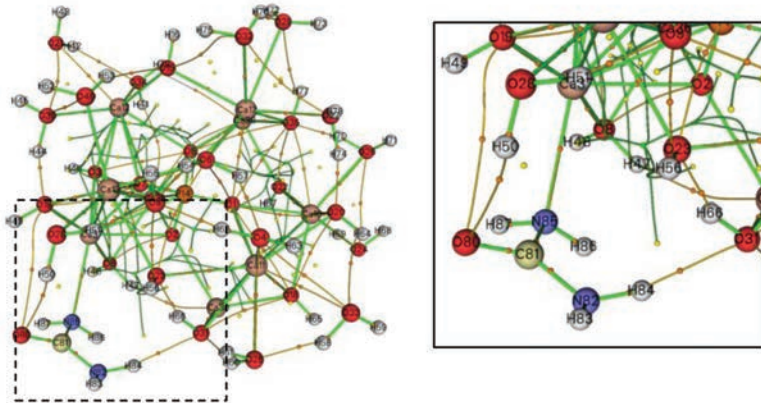


Figure 5: The structure of B, showing the newly formed bond paths between urea and HA, which is highlighted with a dotted rectangular box. An enlarged view of the dotted box is given in the solid-line box

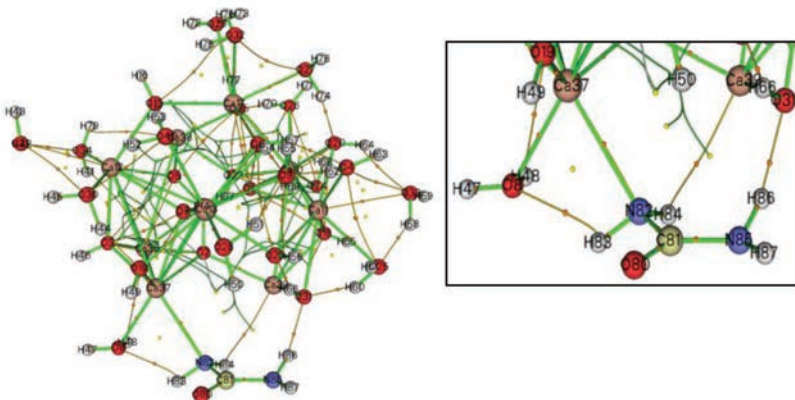


Figure 6: The structure of C, showing the newly formed bond paths between urea and HA, which is highlighted with a dotted rectangular box. An enlarged view of the dotted box is given in the solid-line box

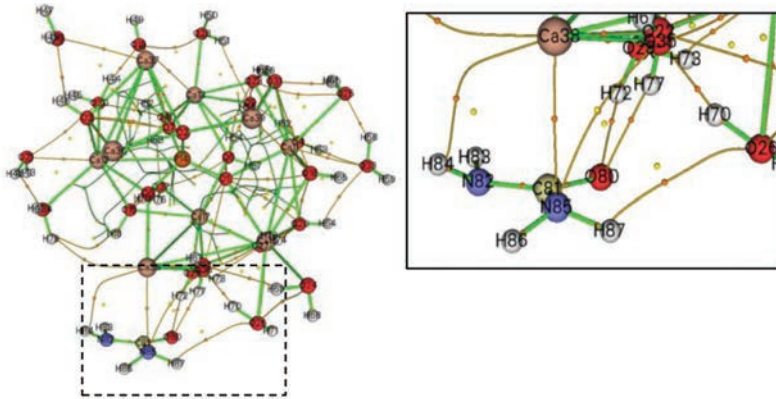


Figure 7: The structure of D, showing the newly formed bond paths between urea and HA, which is highlighted with a dotted rectangular box. An enlarged view of the dotted box is given in the solid-line box

Table 3: The bond lengths of the nitrogen atom of urea with the nearest calcium atom of HA for structures A-D

Structures and Labels	Bond Length (Å)
A (N82-Ca38)	2.8291
B (N85-Ca37)	2.6430
C (N82-Ca37)	2.6663
D (N85-Ca38)	2.8508

In addition, previous studies have also mentioned that hydrogen bonding can form between the oxygen atom in urea and hydrogen atom in HA (Kottegoda *et al.*, 2011; Kottegoda *et al.*, 2017). For all the structures considered in this study, the topology analysis indicated that hydrogen bonding existed between oxygen in urea and hydrogen in HA. As shown in Figures 4, 5, 6 and 7, the green path shows the existing bonding between the atoms, while the brown paths denote new bond paths. The dots represent the critical points in the structures, where the point at gradient norm of function value is zero (except at infinity). The orange spheres correspond to (3,-1) critical points, which are called bond critical points, while yellow spheres correspond to (3,+1) critical points that are often named as ring critical points.

**Conclusion**

Our computational study, using Density Functional Theory (DFT), has proved that calcium atom in HA and nitrogen atom in urea can form a new bond as stated in previous experimental studies. The interaction energy between urea and HA were found to range from -1.2245 eV to -0.09719 eV. In addition, the bond lengths between the new bond formed between the nitrogen atom and calcium atom in urea and HA ranged from 2.64 Å to 2.85 Å. Compared with other structures, structure C is the most stable as it has the lowest interaction energy, whereas in terms of bond length, structure B has the shortest bond length. For future studies, this simulation on the combination of urea and HA can be further analysed based on their interactions and efficiency with the soil, such as clay containing kaolinite.

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