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Theoretical Study of the Electronic Properties of the Curcumin Molecule: Using Density Functional Theory

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Abstract

This search aims to study electronic properties of the curcumin moleculewhich exist in two isomers, ketone and enol forms, and the effect of usingdifferent basis setsby relying on density functions theory (DFT) at B3LYP level.

The hydrogen atom transfer from the central methylene (CH_2) group to an oxygen atom to form strong intra-molecular hydrogen (O H) bond causes geometrical changes in two isomers; where the enol form is structure approximately planar but not completely planar for the ketone form.The results showed that the 6-311G+(d,p) basis set gave sat- isfactory results for calculations. As well as the findings of each of the total energy, the energy of the high occupied molecular orbital and energy gap confirm that the isomer ketone is more stable than isomer enol. Also the ketone has a high electron-accepting, as was proven by the values of the energy of lower unoccupied molecular orbital,ionization potential, electron affinity and electronegativity.

Key words:curcumin, electronic properties, stability,DFTcalculations.

دراسة نظرية للخواص الألكترونية لجزيئة الكركمين بأستخدام نظرية دالية الكثافة

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الخلاصة

يهدف البحث الى دراسة الخواص الالكترونية لجزيئة الكركمين والتي توجد في صيغتين أيزوميريتين صيغة الكيتون والأينول وتأثير أستخدام دوال أساس مختلفة من خلال الاعتماد على نظرية دالية الكثافة عند المستوي B3LYP. أنتقال ذرة الهيدروجين من مجموعة الميثيلين المركزية (CH_2) لترتبط بذرة الأوكسجين حتى تشكل أصرة هيدروجينية (O–H) يسبب تغيرات هندسية في شكل الأيزوميرين, حيث شكل الأينول هي تركيب خطي تقريبا ولكن شكل الكيتون ليس خطي تماما. الدالة 6–311G+(d,p) أعطت نتائج مقنعة للحسابات.

كذلك حسابات كل من الطاقة الكلية و طاقة أعلى مدار جزيئي ممتلئ وفجوة الطاقة أكدت أن الكيتون هو الأكثر أستقرارا من الأينول. وأيضا الكيتون لديه قابلية عالية لقبول الألكترونات كما ثبت من خلال قيم كل من طاقة أوطأ

مدار جزيئي غير ممتلئ وجهد التأين والألفة الألكترونية و الكهروسالبية.

الكلمات المفتاحية: الكركمين, الخواص الألكترونية, الأستقرارية, حسابات DFT.

1-Introduction

Curcumin (Fig.1), the mainyellow bioactive component of turmeric, has been reported to possess a variety of medicinalproperties including anticancer, antioxidant,antiarthritic,anti-inflammatory, antiedemicand antitumoractivities [1]. It also hasantimutagenic,anticoagulant, hepatoprotective, antihypercholesterolemic, nephrotonic, antihypertensive,chemoprotective, carminative, depurative, anti-HIV, antimicrobial, and antiparasitic properties [1] [2].Curcumin is a yellow-orange powder that is insoluble in water and etherbut soluble in ethanol, dimethylsulfoxide and acetone.

Curcumin has a melting point of 183°C,molecular formula of $C_{21}H_{20}O_6$ and molecular weight of 368.37 g/mol.Curcumin identified as 1,6-heptadiene-3,5-dione-1,7-bis(4-hydroxy-3-methoxyphenyl)-(1E,6E) or diferuloylmethane [3]

.However,curcumin can exist in at least two tautomeric forms; ketone and enol [4] [5]. The structureof the cur- cuminhasa variety of functional groups including the β-diketo group, carbon–carbon double bonds and phenyl rings containing varying amounts of hydroxyl and methoxy substituents [6] [7].This work elucidates a theoretical study with electronic properties of curcuminmolecule by using density functional theory at B3LYP with various basis sets.

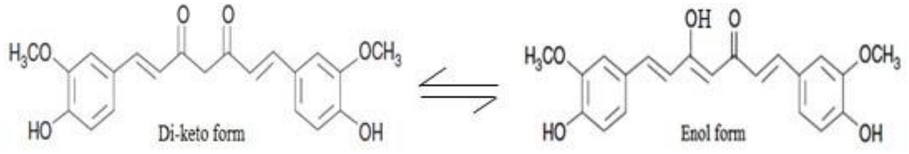

Fig. 1: Structure of curcumin.

2-Methodology

The current study depends on the density functional theory (DFT) approach to investi- gate the electronic properties of the circumin moleculeusing the Becke's three param- eter Lee-Yang-Parr exchange correlation symbolized as (B3LYP) and differences basis sets.The computationswere carried out with Gaussian 09 package of program [8]. According to B3LYP function, the exchange correlation energy is given by [9].

$$E_{\times c}^{B3LYP} = E_{\times c}^{LDA} + a_0(E_{\times}^{HF} - E_{\times}^{LDA}) + a_x(E_{\times}^{GGA} - E_{\times}^{LDA}) + a_c(E_c^{GGA} - E_c^{LDA}) \quad (1)$$

Where the three parameters are = 0.02, =0.72, and = 0.81. LDA, HF and GGA are the local density approximation, Hartree–Fock and generalized gradient approximation, respectively.

The (HOMO), which is the highest energy (outermost) orbital containing electrons, is the orbital acting as an electron donor. On the other hand, the (LUMO), is the lowest energy (innermost) orbital having space to accept electrons [10].

The band gap refers to energy difference between the highest occupied molecular orbital (HOMO) and lowest unoccupied molecular orbital (LUMO) according to the Koopmans' theorem [11]

$$E_g = E_{LUMO} - E_{HOMO} \quad (2)$$

Theionization potential (IP) of a molecule is approximately the negative of the energy of its HOMO. The electron affinity (EA) of a molecule is approximated as the negative of the LUMO energy by applying Koopmans' theorem [12].

According to Koopmans' theorem, the electronegativity can be defined as the negative value for average of the energy levels of the HOMO and LUMO [13] [14] [Parr, *et al*, 1978; Sharpe, 2005]:

The global chemical softness and the chemical hardness(S) are given [15] [10].

3- Results and Discussion

The optimized structures of curcumin isomers in both ketone and enol formshave been published recently by [16]. The optimized of this molecule were performed in the gas state by employing the DFT method using B3LYP function. These forms are shown in Fig.2 by using B3LYP/6-311G+(d,p) level, which is selected because it has a lower total energy as it shown in Table 1. The hydrogen bonding is a really interesting phenomenon and it can drastically change the physical properties of any substances. Therefore, the transition of H-atom between two isomers leads to geometry changes in these isomers; due to form the strong intra-molecular hydrogen bond (enol O-H) which is exists in the middle of structure of the enol form. Moreover, it can be seen from the figures above that the method used to give molecule optimized structures approximately planar in the enol form and not completely planar in the ketone form. The total energy E_T at (a.u) for the isomers of the curcumin molecule, ketone *(trans)* and enol*(cis)*, arepresented in Table 1.This table provides an introduction to the basis set effects. Also, it can be seen fromthis Table that the ketone form presents a lower value for E_T than the enol form, indicating that the ketone structure is more stable than the enol structure.

The 6-311+G(d,p) level is superior to other levels, which is evidenced by the value of the total energy calculated for two forms, total energy of the ketone and enol forms at this basis set are (-1263.9225 a.u and -1263.9147 a.u), respectively.

The difference in stability is such (about 0.0078 a.u).This good agreement with previous study [17] [Naama, *et al*. 2012], which are (-1263.1964 and -1263.1834 a.u), respectively.It is expected that these values are closer to the practical value. It is evident from the data reported in Table 1 for ketone form that the levels STO-3G, 3-21G and 3-21G(d) are not so good as compared to large basis sets, such as, 6-31G(d,p) and 6-311G(d, p) basis sets. Where that the total energy difference between these basis sets and

6-311+G(d,p) basis set are (16.5784 and 7.3122 a.u), respectively, while the total energy difference between 6-311+G(d,p) and 6-31G(d,p) basis sets is 0.327838 a.u, and that goes with second form.Fig. 3 shows the total energy in a.u of the forms under study, the relationship between the total energy and the number of basis sets, and it is clear from figure that the total energy of the ketone is always less than the enol.

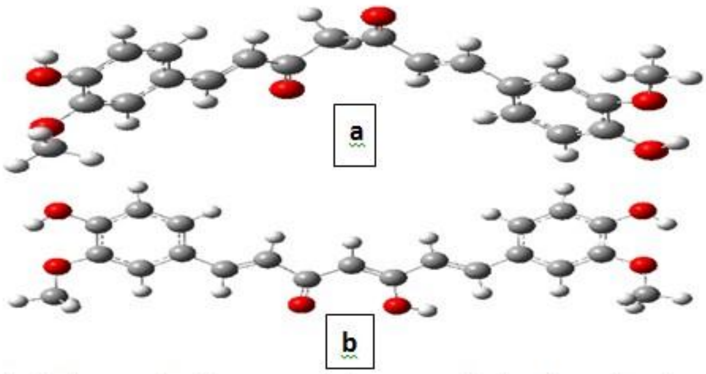

Fig.2: Optimized geometry for curcumin isomers: a- ketone form *(trans)* and b- enol form *(cis)* at the B3LYP/ 6-311+G(d,p) basis set.

Table 1: Total energy of the curcumin isomers.

No.	Basis sets	Total Energy (a.u)	
		Ketone	Enol
1	STO-3G	-1247.3441	-1247.3408
2	3-21G	-1256.6103	-1256.5958
3	3-21G(d)	-1256.6103	-1256.5958
4	6-31G	-1263.2069	-1263.1960
5	6-31G(d)	-1263.5569	-1263.5428
6	6-31G(d,p)	-1263.5947	-1263.5851
7	6-31+G(d,p)	-1263.6477	-1263.6395
8	6-311G	-1263.5181	-1263.5084
9	6-311G(d)	-1263.8556	-1263.8404
10	6-311G(d,p)	-1263.8965	-1263.8876
11	6-311+G(d,p)	-1263.9225	-1263.9147

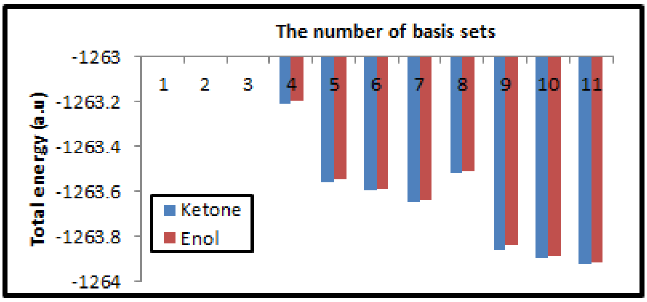

Fig. 3: The total energy of the structures under study as a function of the number of basis sets.

The E_{HOMO},E_{LUMO} and the energy gap (E_{LUMO}-E_{HOMO})for the two forms (keton and enol) in Table 2 are computed by B3LYP density functional theory with many basis sets.As it turns out, the values of the high occupied molecular orbital E_{HOMO} in Table 2 show that the ketone form is more stable than the enol form by (-0.3586eV or -8.2694 Kcal.mol^{-1}) at B3LYP/6-311+G(d,p) level. These results agreed with the result of the total energy, as mentioned earlier.The calculated E_{LUMO} value displayed in Table2 for the ketone form is an indicative that the curcumin molecule has a high electron–accepting character. In fact the smaller the E_{LUMO} value, the greater the electron–accepting character of a compound [18].The energy gap for the two structures ketone and enol ranging about (3.5573-3.9412) eV and (3.2460-3.5154) eV, respectively, and the larger energy gap indicates that the ketone form is better for chemical stability. The differences in the value of energy gap depend on the level used in calculation as depicted in Fig. 4.

Table 2shows us that STO-3G basis set give larger value for energy gap and different values for E_{HOMO} and E_{LUMO} .This may be come from the levelof the basis set is a weak as compared to large basis sets, such as, 6-31G(d) and 6-311G(d,p) levels.Fig. 5 illustrates the shapes of HOMO and LUMO ofcurcumin isomers obtained from the B3LYP/6-311+G(d, p) level of theory calculations from the total self-consistent field density.The change of the form of the isomer from enol to ketone leads to change the map of HOMO and LUMO distribution according to the linear combination of atomic orbitals-molecular orbital (LCAOs-MO), this combination changes the symmetrical point group of the isomer, and therefore, the distribution of the HOMO and LUMO.It is noted that, the positive charges (green color) and the negative charges (red color) in the two isomers are distributed according to the positions of the oxygen and carbon atoms in each structure, and the methoxy group has low contribution only for HOMO of enol.

Table 2: E_{HOMO}, E_{LUMO} and energy gap for curcumin isomers

No.	Basis sets	Ketone		Enol		Energy gap (eV)	
		E_{HOMO} (eV)	E_{LUMO} (eV)	E_{HOMO} (eV)	E_{LUMO} (eV)	Ketone	Enol
1	STO-3G	-3.2942	0.6471	-2.9372	0.5782	3.9413	3.5154
2	3-21G	-5.4729	-1.9157	-5.2648	-1.9380	3.5573	3.3268
3	3-21G(d)	-5.4729	-1.9157	-5.2648	-1.9380	3.5573	3.3268
4	6-31G	-5.8161	-2.1948	-5.4321	-2.1606	3.6212	3.2716
5	6-31G(d)	-5.6446	-1.9823	-5.2757	-1.9529	3.6623	3.3227
6	6-31G(d,p)	-5.6509	-1.9889	-5.2792	-1.9581	3.6621	3.3211
7	6-31+G(d,p)	-5.9940	-2.3948	-5.6294	-2.3834	3.5992	3.2460
8	6-311G	-6.0368	-2.4289	-5.6751	-2.4022	3.6079	3.2729
9	6-311G(d)	-5.8623	-2.2025	-5.5064	-2.1978	3.6599	3.3086
10	6-311G(d,p)	-5.8713	-2.2152	-5.5135	-2.2095	3.6561	3.3040
11	6-311+G(d,p)	-6.0438	-2.4231	-5.6852	-2.4229	3.6207	3.2623

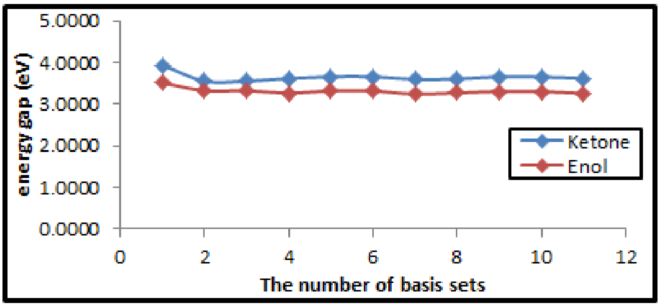

Fig. 4: The energy band gap of two forms, curcumin (ketone) and curcumin (enol), as a function of the number of basis sets.

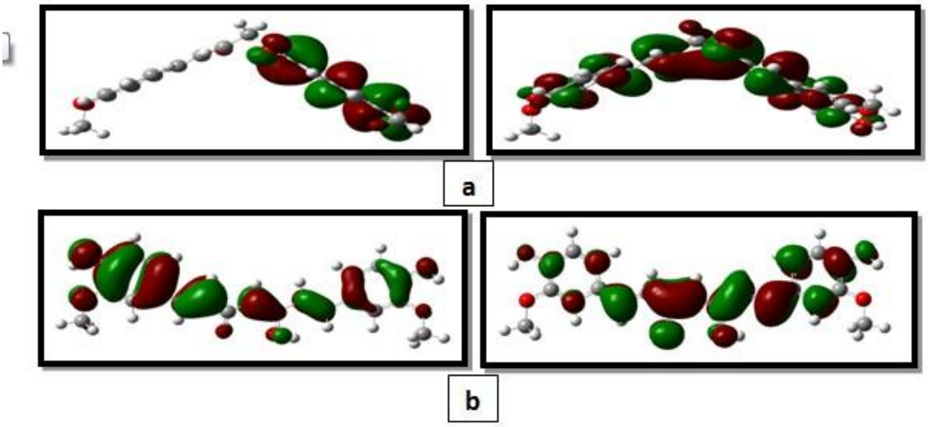

Fig. 5: The distribution of HOMO (left) and LUMO (right) levels for curcumin isomers: a-ketone form and b-enol form.

The ionization potential IP and electron affinity EA are reported in Table 3.It is clear from this Table the functions (1, 2 and 3) are given the results opposed. It is believed that these functions are weak and the function STO-3G is weakest. The IP values computed for ketone and enol forms are 6.0438eV and 5.6852eV, respectively, and the EA values calculated are 2.4231eV and 2.4229eV, respectively, at the 6-311G+(d,p) basis set. These values indicatethat the enol form has high ability to donate the electron while the ketone form has high ability to accept electron.The results of ionization potential and electron affinity for both ketone and enol form are drawn in Fig. 6 and Fig. 7, respectively.

Table 3: IP and EA for curcumin isomers.

No.	Basis Sets	IP (eV)		EA (eV)	
		Ketone	Enol	Ketone	Enol
1	STO-3G	3.2942	2.9372	-0.6471	-0.5782
2	3-21G	5.4729	5.2648	1.9157	1.9380
3	3-21G(d)	5.4729	5.2648	1.9157	1.9380
4	6-31G	5.8161	5.4321	2.1948	2.1606
5	6-31G(d)	5.6446	5.2757	1.9823	1.9529
6	6-31G(d,p)	5.6509	5.2792	1.9889	1.9581
7	6-31+G(d,p)	5.9940	5.6294	2.3948	2.3834
8	6-311G	6.0368	5.6751	2.4289	2.4022
9	6-311G(d)	5.8623	5.5064	2.2025	2.1978
10	6-311G(d,p)	5.8713	5.5135	2.2152	2.2095
11	6-311+G(d,p)	6.0438	5.6852	2.4231	2.4229

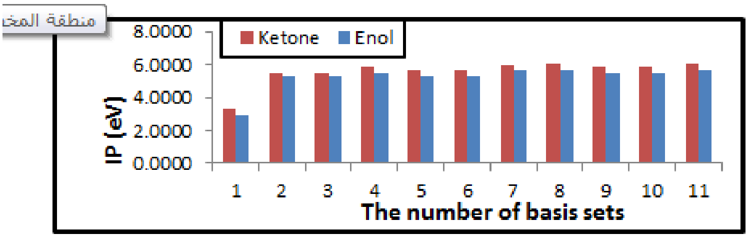

Fig. 6: The ionization potential of structures under study as a function of the number of basis sets.

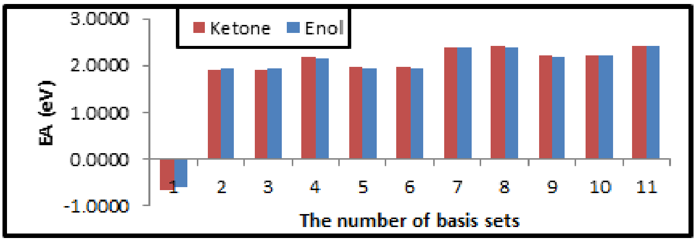

Fig. 7: The electron affinity of structures under study as a function of the number of basis sets.

The results of chemical hardness (η), chemical softness (S), electronegativity (χ) and chemical potential (K) are represented in Table 4. The chemical hardness of the ketone is larger than the chemical hardness of the enol. This suggests that the ketone form is closer to the properties of the solid material, so hard to break bonds. These results correspond to the result of forbidden energy gap, which was for the ketone is largest, as mentioned previously. On the other hand, the enol form is softer than the ketone form. The results of these properties are agreed with the previous study [19], which for two forms, ketone and enol, are (3.06 and 2.81 eV and 0.16 and 0.17 eV), respectively. The η and S for keton and enol are shown in Fig. 8 and Fig. 9, respectively. Fig.10shows the relation between the electronegativity and the number of basis sets. It is obvious from this figure that the ketone form has electronegativity higher than that of the enol form, so that this means small chemical potential and more chemical reactivity, which corresponding with the results of the E_{LUMO} as reported previously. This suggests that the ketone form is very reactive in nature.These results has been found in a good agreement with literature study [19], which has 4.03 eV for ketone type and 3.89 eV for enol type.

Table 4: The values of some electronic properties for the two forms, ketone and enol.

No.	Basis sets	η (eV)		S (eV)		χ (eV)		K (eV)	
		Ketone	Enol	Ketone	Enol	Ketone	Enol	Ketone	Enol
1	STO-3G	1.9706	1.7577	0.2537	0.2845	1.3235	1.1795	-1.3235	-1.1795
2	3-21G	1.7786	1.6634	0.2811	0.3006	3.6943	3.6014	-3.6943	-3.6014
3	3-21G(d)	1.7786	1.6634	0.2811	0.3006	3.6943	3.6014	-3.6943	-3.6014
4	6-31G	1.8106	1.6358	0.2761	0.3057	4.0055	3.7963	-4.0055	-3.7963
منطقة الم	1G(d)	1.8312	1.6614	0.2731	0.3010	3.8135	3.6143	-3.8135	-3.6143
6	6-31G(d,p)	1.8310	1.6606	0.2731	0.3011	3.8199	3.6187	-3.8199	-3.6187
7	6-31+G(d,p)	1.7996	1.6230	0.2778	0.3081	4.1944	4.0064	-4.1944	-4.0064
8	6-311G	1.8040	1.6365	0.2772	0.3055	4.2328	4.0387	-4.2328	-4.0387
9	6-311G(d)	1.8299	1.6543	0.2732	0.3022	4.0324	3.8521	-4.0324	-3.8521
10	6-311G(d,p)	1.8280	1.6520	0.2735	0.3027	4.0433	3.8615	-4.0433	-3.8615
11	6-311+G(d,p)	1.8103	1.6312	0.2762	0.3065	4.2335	4.0540	-4.2335	-4.0540

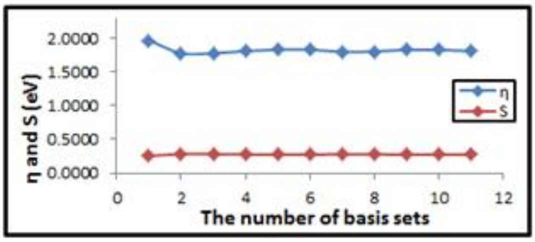

Fig. 8: The chemical hardness and softness of ketone form as a function of the number of basis sets.

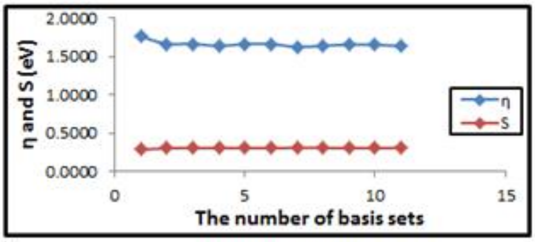

Fig. 9: The chemical hardness and softness of enol form as a function of the

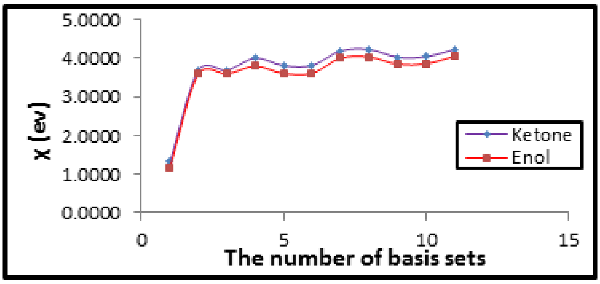

Fig. 10: The electronegativity of structures under study as a function of the number of basis sets.

4- Conclusions

1- The presence of intra-molecular hydrogen bonds leads to change the geometrical opti- mization of the structure, where the enol isomer has approximately planar form while the ketone isomer has not completely planar form.

2- Depending on the values of the electronic properties (total energy E_T, energy gap and E_{HOMO}), that the ketone form (*trans*) is more stable than the enol form (*cis*).

3- The results of E_{LUMO} ,χ, IP and EA confirm the rich electron-accepting of the ketone form.

4- The natural ketone form is more active than the enol isomer of curcumin dye.

5- The 6-31G, 6-31G(d), 6-31G(d,p), 6-31G+(d,p), 6-311G, 6-311G(d), 6-311G(d,p), 6-311 G+(d,p) basis sets were almost convergence in the results whereas the 3-21G and 3-21G(d) basis sets were perfectly similar in the results, while the STO-3G basis set showed undesirable results as compared to other basis sets.

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