Synthesis and Structural Study of Titanium (IV) Complexes Derivative from 2, 6-; 3,5-and 2,4-dihydroxybenzoic Acid Molecular Modelling Approach

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ABSTRACT **Complex fluorinated titanium (IV) derivative of 2, 6- dihydroxybenzoic acid (L1), 3,5-dihydroxybenzoïc acid (L2) and 2,4-dihydroxybenzoïc acid (L3) are known for their great interest in the dental oral area. They are widely used in the prevention of dental caries. These complexes by spectroscopic methods of analysis (UV-Vis., IR) are synthesized and then characterized. Since the reactivity of a complex depends strongly on its geometry's stability, the most stable geometry of these complexes using molecular modelling is then determined. In order to calculate the steric energy, bond lengths, bond angles and torsion angles data molecular mechanics calculations (MM) using Hyperchem software is performed. For this purpose, the well-known Density Functional Theory calculations (DFT) to study the HOMO and LUMO properties of this complex is used. Both experimental and theoretical showed a distorted octahedral structure around the metal ion Ti (IV).**

Keywords: Titanium complexes, dihydroxybenzoic acid, Synthesis, Characterisation, Molecular mechanics, DFT, stability.

1. INTRODUCTION

Transition metal complexes are known by their biological and pharmacological activities [1-3]. As the complex activity depends on its stability, the study of the complex geometry and the determination of the most stable conformation are very important. Since the difficulty to study this structure by DRX, which requires the obtaining of the complex as a single crystal, the application of molecular modeling proved to be very useful. Corey and Bailar [4] were the first to apply molecular mechanics calculations to transition metals systems. With its success in coordination chemistry, molecular mechanics has become an important tool in this area [5-9]. Most studies of molecular mechanics were applied to conformation calculations, distribution of isomers and steric energy calculations of complexes.

The charges, the coordinates of the atoms are determined using extended Huckel Theory (EHT) [10-12], which has been widely used as a semi-empirical method [13, 14].

The highest occupied molecular orbital energy E_{HOMO}, the lowest unoccupied molecular orbital energy E_{LUMO} and energy gap ΔE are obtained by density-functional theory (DFT) calculations. This method is currently used to determine structural, electronic, and dynamical properties in materials science [15,16].

This research focuses on Ti (IV) complexes for their use in catalysis [17-23], their great activity against dental caries [24] and anticancer [25]. The fluorinated Ti (IV) complex derivative of 2,6-dihydroxybenzoic acid (L1), 3,5-dihydroxybenzoïc acid (L2) and 2,4-dihydroxy benzoic acid (L3) are synthesized. Their structures using spectroscopic analysis methods and molecular modeling calculations are studied.

2. MATERIALS AND METHODS

2.1. Complex synthesis

The complexes using -2, 6-, -3,5- and -2,4- dihydroxybenzoic acids ligands are prepared by dissolving separately, 0.008 mole of ligand and 0.004 mole of TiF_4 in a minimum of acetonitrile. The two solutions obtained by adding the ligand solution on the metal's one is mixed. The two first complexes were prepared without heating, after vigorous stirring for two hours. While the third one is obtained by refluxing for four hours and adding sodium acetate. The complex derived obtained are both an orange solid for the first complex and a yellow one for the second one. The complex derived from L1 is orange while the others are yellow.

2.2. Method of calculation

To optimize the geometry of these complexes and minimize their energies, the molecular mechanics calculations using Hyperchem (Hypercube Inc. Canada) are applied. Calculations were performed using Fletcher Revees algorithm [26,27], MM+ force field. The most stable geometry is determined, which has the less steric energy, bond lengths and bond angles.

Electronics properties of the studied compounds have been studied using density functional theory (DFT) at the B3LYP/6-31G ** levels of theory. The hybrid Becke3-Lee–Yang–Parr (B3LYP) exchange correlation functional was applied for DFT calculations [28].

3. RESULTS AND DISCUSSION

3.1. Experimental study of Ti(IV) complexes

The synthesized complexes are solid and stable in the open air and at room temperature. Their melting points are above 300°C, suggesting a strong bond between the metal and the ligand. The electronic configuration of Ti (IV) is d_0. This suggests diamagnetic property for the three complexes [5,6thèse]. Therefore, the magnetic susceptibility of these complexes is very low and negative. Solubility tests on these complexes reveal that these complexes are insoluble in all common organic solvents except in DMSO or DMF.

The complexes' molar conductivity: elemental analysis and molecular weight are gathered in Table 1. Molar conductivity data indicate that the complexes are non-electrolytic in nature [29,30].

The C, H, O, F and Ti(IV) percentages were determined experimentally; and calculated on the basis of the molar mass calculated from the proposed formulas for the different complexes. The data show a high agreement between the calculated and experimental values, which validates the proposed formulas; [TiF_2(2,6-dihydroxybenzoic acid)$_2$], [TiF_2(3,5-dihydroxybenzoic acid)$_2$] and [TiF_2(2,4-dihydroxybenzoic acid)$_2$]

Table 1. The complexes' molar conductivity: elemental analysis and molecular weight.

Ti(IV) Complex	$\Lambda 0m$ Scm^2 mol^{-1}	Calculated data						Experimental data					
		C %	H %	O %	Ti %	F	Mw_{cal} g/mole	C %	H %	O %	Ti %	F %	Mw_{exp} g/mole
L1	7.40*	42.842	2.556	32.642	12.206	9.69	392.13	43.090	2.551	32.647	12.213	9.490	392.065
L2	0.90	42.842	2.556	32.642	12.206	9.69	392.13	42.790	2.547	32.609	12.214	9.831	392.529
L3	1.18	42.842	2.556	32.642	12.206	9.69	392.13	42.858	2.551	32.650	12.215	9.723	391.990

* in DMF (The others in DMSO)

The IR spectrum of the three complexes compared with those of the free ligand (figure1-3) shows shifts of the C=O band and the OH (hydroxyl) band, suggesting, the participation of these two groups (C=O and OH) in the bonding. L1, L2 and L3act as bidentate ligands. They are linked to Ti(IV) via the carbonyl oxygen of the carboxylic acid group and the oxygen of hydroxyl. Bands around 450cm^{-1}and 597 cm^{-1} regions are attributed respectively to the Ti-O Ti-F stretching vibration [31]. The appearance of these new bands implies that the metal ion Ti (IV) is bonded to fluorides and oxygen.
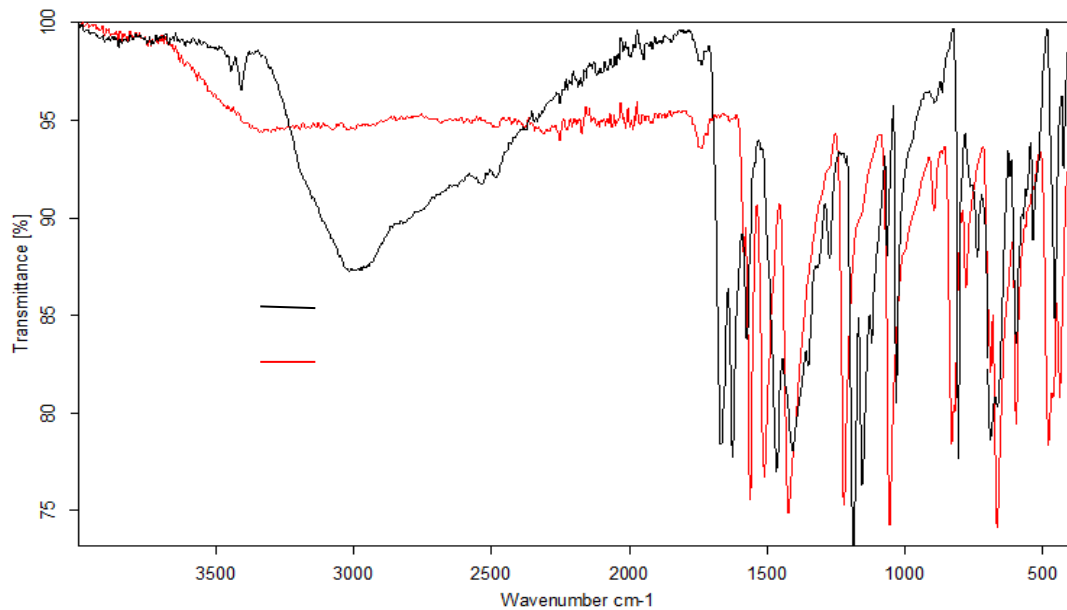
Figure1. IR spectrum in KBr of Ti(IV) complex derivative from dihydroxy-2, 6- benzoic acid
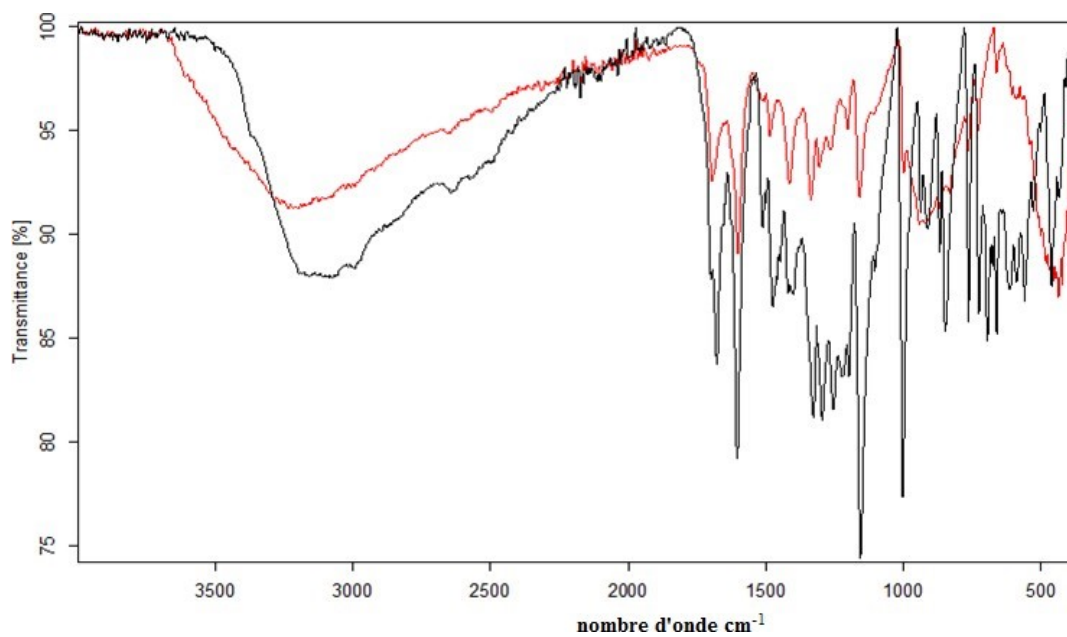   —— ligand
    —— complex

Figure 2. IR spectrum in KBr of Ti(IV) complex derivative from 3,5- dihydroxybenzoïc acid
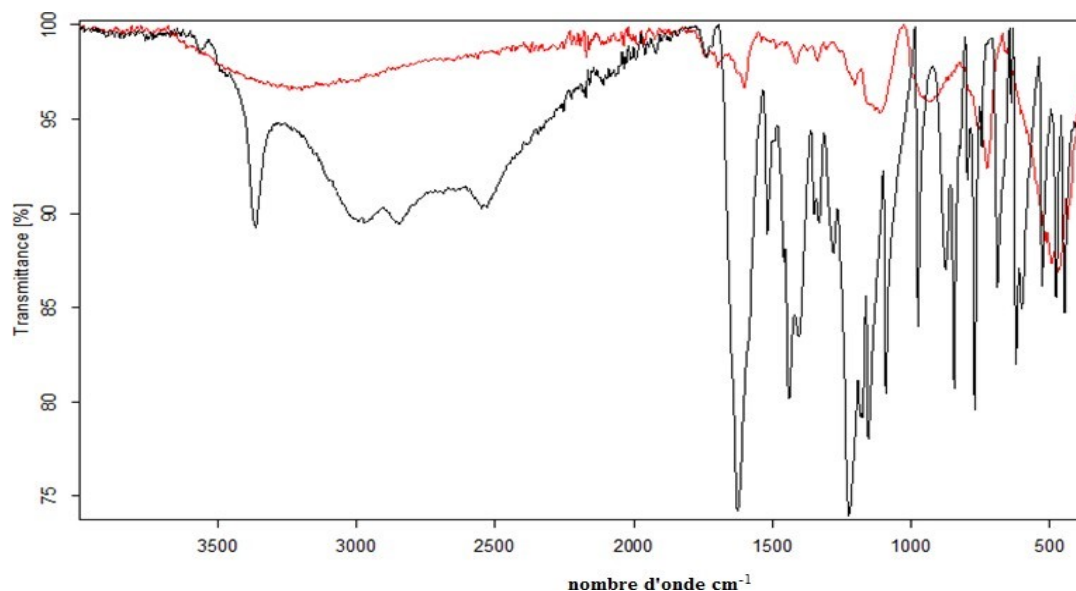   —— ligand
    —— complex

Figure 3. IR spectrum in KBr of Ti(IV) complex derivative from 2,4- dihydroxybenzoïc acid

——— ligand

——— complex

The electronic spectra of the complexes in DMFshow wide bands between 200nm and 400nm, centered on 300 nm; suggesting the existence of an octahedral structure around the metal ion.

3.2. Molecular mechanics calculations

The most stable conformations of the studied complexes are shown in Figures (4-6).

The values of the bond angles and bond lengths are listed in Tables (2-6). These values are more or less different from those of a regular octahedron suggesting a distorted structure for the three complexes.Bond lengths and bond angles obtained by calculation coincide with the crystallographic data [32] and data from the literature [33-35].

3.2.1. [Ti F$_2$ (2,6- dihydroxybenzoic acid) $_2$]

Themost stablegeometryof[TiF$_2$ (2,6- dihydroxybenzoic acid) $_2$](Fig.4) indicates that the ligand isbidentate. The ligand is linkedto the metal ion Ti (IV) by the oxygen of the carboxyl group and the oxygen of the hydroxyl in the ortho position. The two oxygen atoms O(3), O(4) occupy the axial positions while O(6), O(7), F(2) and F(5) are in an equatorial positions. The two fluorine atoms F(2) and F(5) are in cis positions.
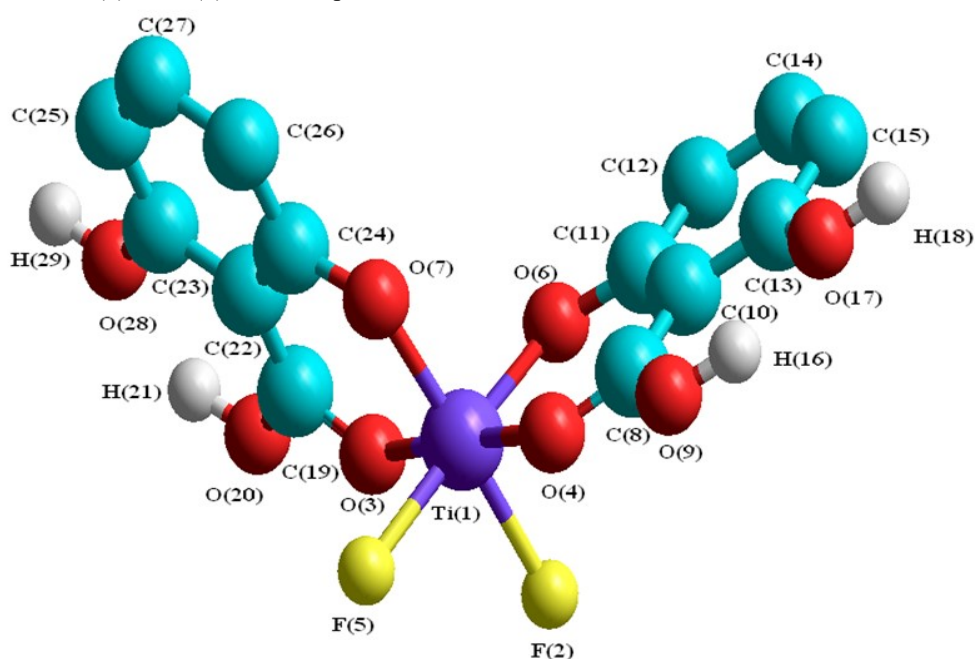

Figure4. The optimized geometry of [Ti F$_2$ (L1)$_2$]

Table2.Some bond lengths for the complex of Ti (IV) derived from 2,6-dihydroxybenzoic acid.

Atoms	Bond lengths (Å)	Atoms	Bond lengths (Å)
Ti(1)-F$_{eq}$(2)	2.044	Ti(1)-F$_{eq}$(5)	2.044
Ti(1)-O$_{ax}$(3)	1.937	Ti(1)-O$_{eq}$(6)	1.931
Ti(1)-O$_{ax}$(4)	1.937	Ti(1)-O$_{eq}$(7)	1.931

Table 3. Some bond angles for the complex of Ti (IV) derived from2,6-dihydroxybenzoic acid.

Atoms	Bond angles (degrees)	Atoms	Bond angles (degrees)
F (2)-Ti(1)-O (3)	89.117	O (4)-Ti(1)-O(6)	89.164
F (2)-Ti(1)-O(4)	89.249	O (4)-Ti(1)-O (7)	90.398
F(2)-Ti(1)-F (5)	87.498	F (5)-Ti(1)-O (6)	177.657
F (2)-Ti(1)-O(6)	90.004	F(5)-Ti(1)-O (7)	89.934
F(2)-Ti(1)-O (7)	117.414	O (6)-Ti(1)-O (7)	92.564
O (3)-Ti(1)-O (4)	117.794	Ti(1)-O(3)-C(19)	129.691
O(3)-Ti(1)-F(5)	89.284	C(8)-O$_{ax}$ (4)-Ti(1)	129.692
O(3)-Ti(1)-O (6)	90.320	Ti(1)-O(6)-C(11)	124.148
O(3)-Ti(1)-O(7)	91.166	C(24)-O(7)-Ti(1)	124.146
O$_{ax}$ (4)-Ti(1)-F(5)	89.162		

3.2.2. [Ti F$_2$ (3,5- dihydroxybenzoic acid) $_2$]

Themost stablegeometryof [TiF$_2$ (3,5- dihydroxybenzoic acid) $_2$] (Fig.5). The ligand is bidentate. It's linked to Ti(IV) by the carboxylic oxygen, the oxygen of hydroxyl in meta position and two fluorine atoms in cis positions.

The study of this structure (Figure.4.2) shows that the fluoride atom F(3) and the oxygen atom O(7) occupy the axial positions. Oxygen atoms O(5), O(6) and O(4) and the fluoride atom F(2), occupy the equatorial positions.
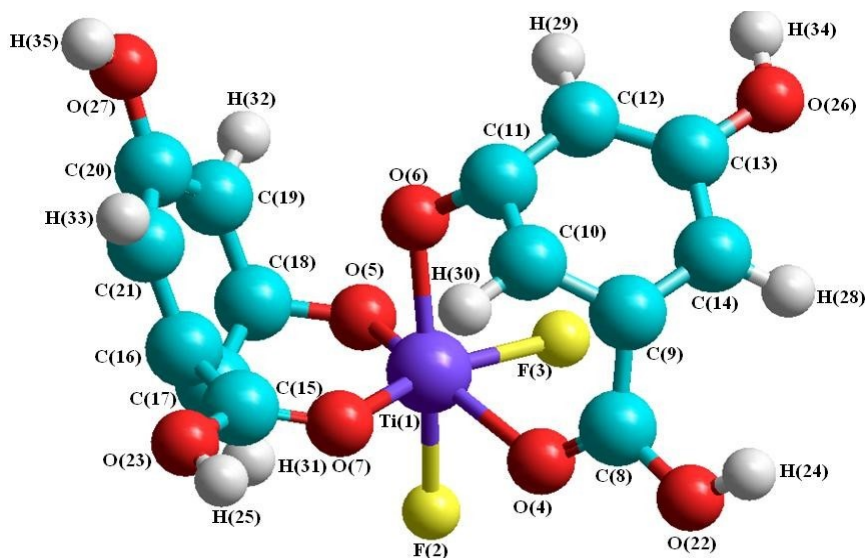

Figure 5. The optimized geometryof [Ti F$_2$ (L2)$_2$].

Table 4. Some bond lengths for the complex of Ti (IV) derived from3,5-dihydroxybenzoic acid.

Atoms	bond lengths (Å)	Atoms	bond lengths (Å)
Ti(1)-F(2)	2.0548	Ti(1)-O(5)	1.9827
Ti(1)-F(3)	2.0550	Ti(1)-O(6)	1.9759
Ti(1)-O(4)	1.9848	Ti(1)-O(7)	1.9770

Table 5. Some bond angles for the complex of Ti (IV) derived from3,5-dihydroxybenzoic acid.

Atoms	Bond angles (degrees)	Atoms	Bond angles (degrees)
F(2)-Ti(1)-F(3)	81.453	F(3)-Ti(1)-O(4)	80.671
F(2)-Ti(1)-O(4)	75.390	F(3)-Ti(1)-O(5)	75.990
F(2)-Ti(1)-O(5)	81.573	F(3)-Ti(1)-O(6)	89.798
F(2)-Ti(1)-O(6)	160.125	F(3)-Ti(1)-O(7)	161.643
O(4)-Ti(1)-O(5)	149.277	O(4)-Ti(1)-O(6)	120.933
O(4)-Ti(1)-O(7)	81.317	O(5)-Ti(1)-O(6)	78.956
O(5)-Ti(1)-O(7)	122.117	O(6)-Ti(1)-O(7)	96.437

3.2.3. [Ti F_2 (2,4- dihydroxybenzoic acid) $_2$]

The most stable geometry of [TiF$_2$ (2,4- dihydroxybenzoic acid) $_2$] (Fig.6). The ligand is bidentate, it is bonded to the metal ion Ti(IV) by carboxylic oxygen and by oxygen of hydroxyl in the ortho position. Oxygen atoms O(2) and O(3) occupy axial positions; whereas the two fluoride atoms F(4) and F(6), oxygen atoms O(5) and O(7) are in equatorial positions. The two fluoride atoms F(4) and F(6) are in cis position.
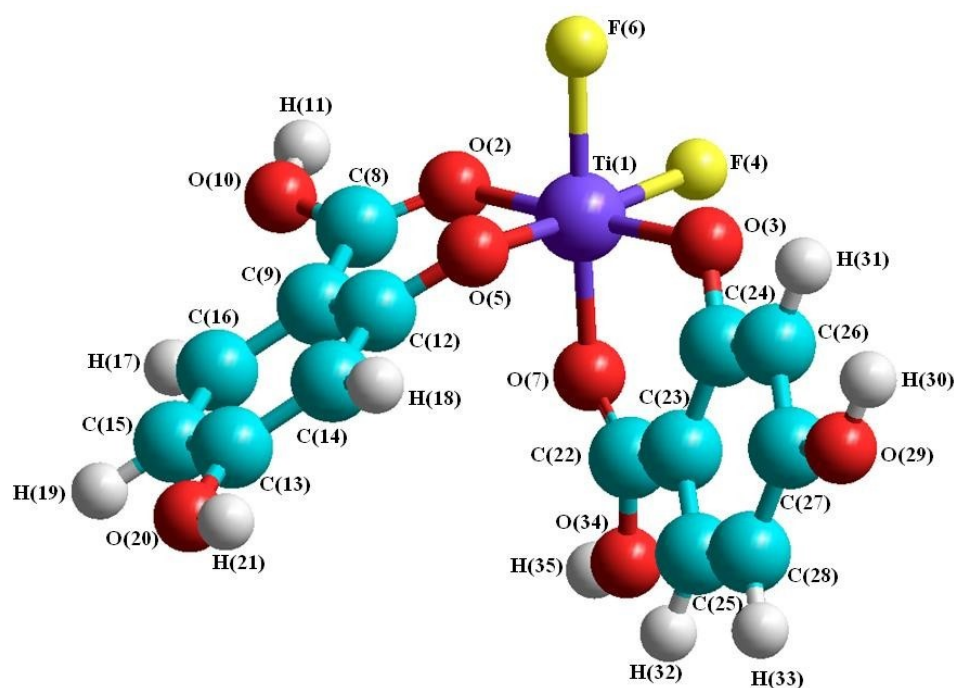

Figure 6. The optimized geometry of [Ti F$_2$ (L3)$_2$]

Table 6. Some bond lengths for the complex of Ti (IV) derived from 2,4-dihydroxybenzoic acid.

Atoms	bond lengths (Å)	Atoms	bond lengths (Å)
Ti(1)-O(2)	1.9445	Ti(1)-O(5)	1.9428
Ti(1)-O(3)	1.9421	Ti(1)-F(6)	2.0463
Ti(1)-F(4)	2.0461	Ti(1)-O(7)	1.9443

Table 7. Some bond angles for the complex of Ti (IV) derived from 2,4-dihydroxybenzoic acid.

Atoms	Bond angles (degrees)	Atoms	Bond angles (degrees)
O(2)-Ti(1)-O(3)	178.673	O(3)-Ti(1)-O(5)	89.075
O(2)-Ti(1)-F(4)	89.945	O(3)-Ti(1)-F(6)	89.423
O(2)-Ti(1)-O(5)	91.226	O(3)-Ti(1)-O(7)	91.796
O(2)-Ti(1)-F(6)	89.293	F(4)-Ti(1)-O(5)	175.784
O(2)-Ti(1)-O(7)	89.462	F(4)-Ti(1)-F(6)	87.224
O(3)-Ti(1)-F(4)	89.664	F(4)-Ti(1)-O(7)	88.781
O(5)-Ti(1)-F(6)	88.740	F(6)-Ti(1)-O(7)	175.817
O(5)-Ti(1)-O(7)	95.279		

3.3. Degrees of distortion

The complexes' distortion degrees according to the following equation are calculated [36]:

$$\Delta l = \left(\frac{1}{n}\right)\sum\left[\frac{(R_i - R)}{R}\right]^2 \qquad ()$$

Δl is the degree of distortion, R the distance of the M-X bond (X atom bound to the metal ion), R is the average MX distances and n is the number of bonds around the central atom.

The data are listed in Table 8 and show that the complexes have a low distortion.

Table 8. Complexes' distortion degrees.

Complex	central metal	distortion ($\Delta l.10^4$)
[Ti F$_2$ (L1)$_2$]	Ti(IV)	7.022
[Ti F$_2$ (L2)$_2$]	Ti(IV)	6.292
[Ti F$_2$ (L3)$_2$]	Ti(IV)	6.003

3.4. Density Functional theory calculations

Electronic properties depend essentially on the ground and excited states. The highest occupied molecular orbital (HOMO) and the lowest unoccupied molecular orbital (LUMO) displayed typical behavior for such molecules in the ground and excited states. The gap energy is calculated by the difference between HOMO and LUMO energies (table 9).

Table 9. The E$_{HOMO}$, E$_{LUMO}$ and ΔE energies of the studied complexs obtained by B3LYP / 6-31G**.

Complexes	E_{HOMO} (ev)	E_{LUMO} (ev)	ΔE (ev)
$[Ti\ F_2\ (L1)_2]$	3.556	4.359	0.803
$[Ti\ F_2\ (L2)_2]$	3.938	4.414	0.476
$[Ti\ F_2\ (L3)_2]$	3.905	4.216	0.311

The spatial distributions of HOMO-LUMO are shown in Fig.3. According to DFT calculation, in the of molecule the HOMO orbital spreads over the whole element., while the LUMO orbital is localized mainly on the fluoride, benzene derivative rings. Whereas HOMO is distributed commonly in whole skeleton of molecule.

The energy gap between the molecular orbitals HOMO and LUMO is a critical parameter for determining molecular electrical transport properties because it measures electronic conductivity. The HOMO and LUMO orbitals are also called boundary orbitals because they are at the outer limits of the electrons of a molecule. The border orbital gap is used to characterize the chemical reactivity and kinetic stability of a molecule [37].

The most stable structure is defined by the largest energy gap between HOMO and LUMO. Obtaining energy gaps between HOMO and LUMO demonstrate high-load mobility in the compound studied. Furthermore, by studying the values of the molecular gap border of complexes carried in Table 9.It is notice that [Ti F2 (2.6-dihydroxybenzoic acid)₂] presents a large energy gap, so it presents the most stable structure. This confirms the results obtained by molecular mechanics. The narrow energy gap between HOMO and LUMO facilitates intramolecular load transfer [38].

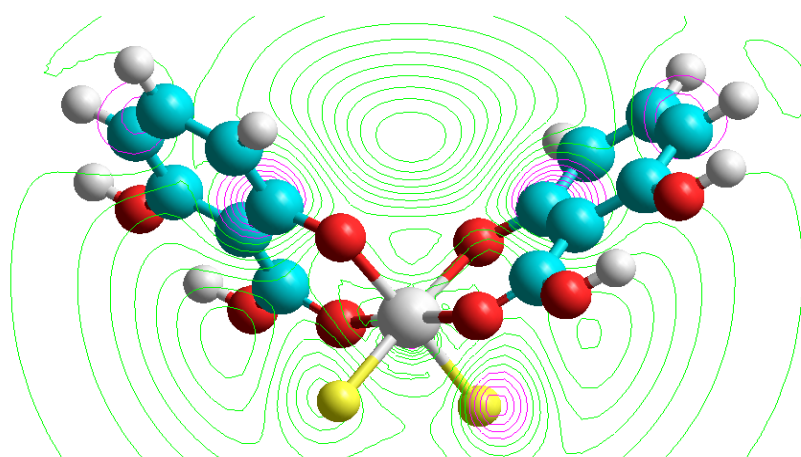The spatial distributions of HOMO-LUMO are illustrated by the Figures (7-9).

Figure 7. HOMO and LUMO plots of $[Ti\ F_2\ (L1)_2]$.
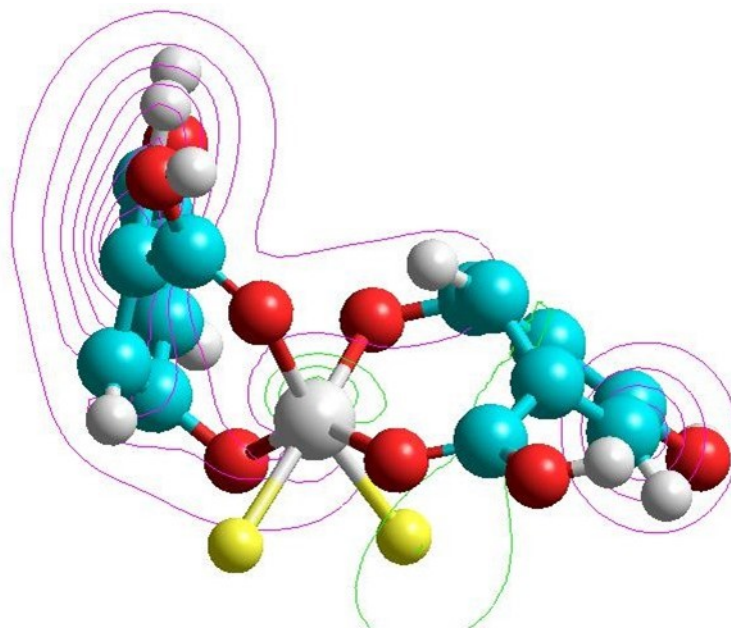
Figure 8. HOMO and LUMO plots of [Ti F_2 (L2)$_2$].
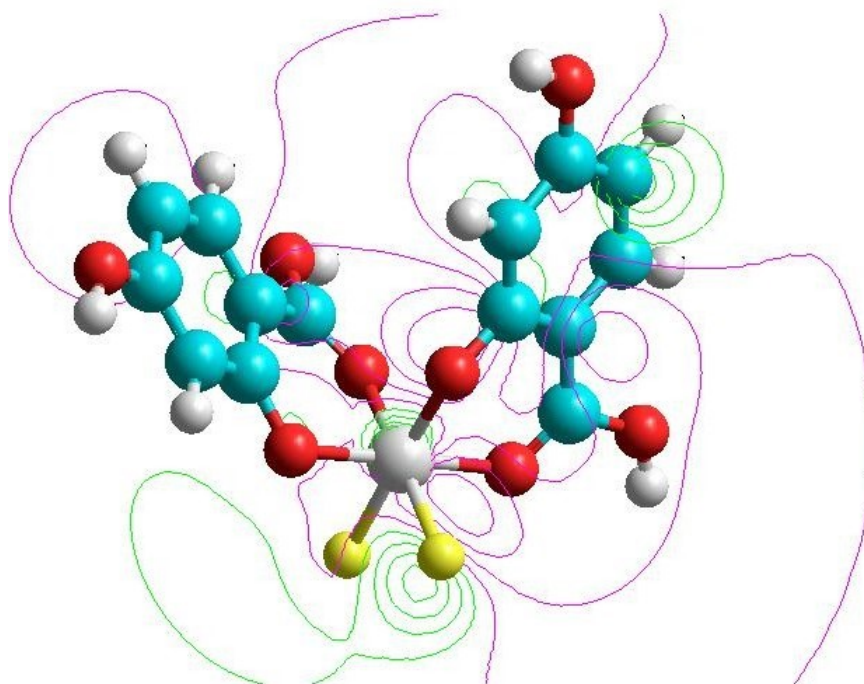
Figure 9. HOMO and LUMO plots of [Ti F_2 (L3)$_2$].

4. CONCLUSION

In this work, titanium (IV) complexes derived from 2,6-; 3,5- and 2,4-dihydroxybenzoic acid are synthesized. Such complexes are subject of characterization by spectroscopic methods of analysis (IR, UV-Visible, NMR and micro-analysis) to determine their structures. Their molar conductivity to study the electrolytic nature of these complexes are determined.

The obtained complexes are solid and stable in air and at room temperature. Their melting points are high (>300°C). Data of molar conductivity of Ti(IV) complexes in DMF and DMSO indicate that they are non-electrolytic.

The study of these complexes' IR spectra of shows that the metal is bonded to two fluorine atoms and oxygens of hydroxyl and carboxyl clusters. The ligands are bidentate.

The complexes' study by electronic absorption spectrophotometry (UV-Visible, indicates distorted octahedral geometry around the metal ion (Ti(IV)).

These results aim to propose the following formulas for the different synthesized complexes: [Ti F_2 (2,6-hydroxybenzoic acid)$_2$], [Ti F_2(3,5-hydroxybenzoic acid)$_2$] and [Ti F_2 (2,4-hydroxybenzoic acid)$_2$].

Theoretical study of the Ti (IV) complexes structures, using Hyperchem software, aims to determine their most stable geometries, bond angles and bond lengths. The HOMO, LUMO and gap energies using DFT method are calculated. These calculations show that complexes have a large energy gap, so they have stable structures and great activity. Results obtained by theoretical study reproduce as well as possible those obtained by the experimental study. The data obtained by molecular mechanics calculation and fall within the same range with those found in literature and crystallographic.

References
[1] M.J.M. Campbell, Coord. Chem. Rev., 1975, 16, 279.
[2] W. Henderson, L J. McCaffreyu and B.K. Nicholson, J. Chem. Soc. Dalton Trans., 2000, 16, 2753.
[3] A.E. Liberta and D.X. West, Biometals,1992, 5, 121.
[4] E.J. Corey and J.C. Bailar, J. Am. Chem. Soc., 1959, 81, 2620.
[5] Z. Zizi, A.Benghalem, L. Benmeni, S.M. Al-Asquar and M. M. Mostafa, Int. J. Chem., 2007, 17,57.
[6] Z. Zizi, M. M. Mostafa and A. Benghalem, Mansoura J. Chem., 2005, 32(1), 167.
[7] Z. ZIZI; A. Benghalem; A. M. Summam and M.M. MOSTAFA, Inter. J. Chem., 2004, Vol.14(4).
[8] I. Aoues and Z. Zizi, Bull. Chem. Soc. Ethiop., 2018, 32(3), 571.
[9] R.D. Hancock, Acc. Chem. Res., 1990, 23, 253.
[10] R. Hoffman, J. Chem. Phys., 1963, 39,1397.
[11] A.B. Anderson and R. Hoffman, J. Chem. Phys., 1974, 60, 4271.
[12] G. Calzaferri, L. Fross and I. Kamber, J. Chem. Phys., 1989, 93, 5366.
[13] E. Clementi and C. Roetti, Roothan- Hrtree-fock Atomic Wavefunction, Atomic Data and Nuclear Data Tables, 1974,14, 177.
[14] M. H. Prosnec, C. Janiak and H.H. Brintzinger, Organometallics, 1992, 11, 4036.
[15] A. F. Jalbout, B. Trzaskowski, A. J. Hameed, J. Organomet. Chem., 691 (2006) 4589.
[16] A.F. Jalbout, A. J. Hameed, B. Trzaskowski, J. Organomet. Chem., 2007,692, 1039.
[17] Y. Qian, J. Huang, M.D. Bala, B. Lian, H. Zhang and H. Zhang, *Chem. Rev.*, 2003, 103, 2633.
[18] R. Beckhause and C. Santamaria, *J. Organomet. Chem.*, 2001, 617, 81.
[19] E. Manek, D. Hinz and G. Meyer, *Coord. Chem. Rev.*, 1997, 164, 5.
[20] J.C. Vites and M.M. Lynam, *Coord. Chem. Rev.*, 1995, 138, 71.
[21] R.O. Duthaler and A. Hafner, *Chem. Rev.*, 1992, 92, 807.
[22] B.K. Keppler, C. Friese, H.G. Moritz, H. Vongerichten and E. Vogel, *Struct. Bond.*, 1991, 78, 98.
[23] M.J. Go, J.M. Lee, K.M. Lee, C.H. Oh, K.H. Park, S.H. Kim, M. Kim, H.R. Park, M.H. Park, Y. Kim and J. Lee, *Polyhedron.*, 2014, 67, 286.
[24. C. Finidori, World Intellectual Property Organization,WO/01/005797, 2001.
[25]. A. Rajini, M. Nookaraju, I.A.K. Reddy, N. Venkatathri,Journal of Saudi Chemical Society., 2017, 21, S77–S85.
[26]. P.P. Cobri, A.C. Massabni, A.G. Moreira, F.J. Medrano, M.G. Jasiulionisand C.M. Costa-Neto, Can. J. of Chem.,2005, 83(2), 104.
[27] I. Brudzinska, Y. Mikata, M. Obata and C.S. Ohtsuki, *Bioorg. Med.* (Print),2004, 14(10), 2533.
[28] C. Lee, W. Yang, R. G. Parr, Phys. Rev. B 37 (1988) 785; A.D. Becke, J. Chem. Phys. 98 (1993) 5648; T.A. Keith, R.F.W. Bader, *Chem. Phys. Lett.* 194 (1992) 1.
[29] W. J. Geyary., *Coord.Chem.Rev.*, 7(1971), 1-81.
[30] D. X. West et L.D.Borowy, *Trans.Met.Chem.*,16(1991),5.
[31] S. Geoge, Infrared and Raman Characteristic Group Frenquencies (Tables and Charts), 3ème edition, (2001), p305-311.
[32] J. Giraudet, thèse de doctorat, Université Blaise Pascal, (2002) 22.
[33] M.J. Go, J.M. Lee, K.M. Lee, C.H. Oh, K.H. Park, S.H. Kim, M. Kim, H.R. Park, M.H. Park, Y. Kim, J. Lee, Polyhedron, 67 (2014) 286.
[34] L. Brohan et J.M. Nunzi, Action Concertée Energie (PE1),(2004).
[35] J.L. Lamboy, A. Pasquale, A.L .Rheingold et E. Meléndez, Inorg. Chim.Acta., 360(6) (2007) 2115-2120.
[36] Q. Wang, X. Xu et X. Wang, *Acta Cryst.*, C49(1993),464-467.
[37] I. Fleming, *Frontier Orbitals and Organic Chemical Reactions*, John Wiley & Sons, New York, (1976).
[38] N. C. Handy, P. E. Maslen, R. D. Amos, J. S. Andrews, C.W. Murry, G. J. Laming, *Chem. Phys. Lett.*,197(1992),506-515.