Original Research Article

Solvent Effects on the Cleavage of Emodin's Non H-bonded O-H Link: A Theoretical Study

ABSTRACT

Although Emodin is a well-known natural antioxidant, not much is documented on how the cleavage of its free O-H bond (non-hydrogen bond donor) is affected by solvation. Herein, we report on a Density Functional Theory (DFT) study of solvent effects on the enthalpy of homolytic and heterolytic cleavage of this bond in the most stable conformer of emodin. This cleavage results in the release of an atom of hydrogen from emodin, whatever the mechanism adopted. The B3LYP functional has been associated with the 6-311++G** basis set in this work while solvent effects have been investigated via the IEF-PCM approach. Whereas literature survey indicates that solvation modifies the antioxidant mechanism, our results have shown the contrary for emodin as same mechanism is adopted as we leave the gas to the solvent phase. This observation is peculiar to emodin among the plethora of known antioxidant molecules. Emodin preferentially exerts its antioxidant effect through the homolytic hydrogen atom transfer mechanism.

Keywords: DFT, solvation, emodin, antioxidant properties, NBO analysis

1. INTRODUCTION

Nowadays, it is well established that free radicals are fully responsible for the aging process and are a major cause of endemic diseases (cancer, diabetes, cardiovascular dysfunction, cataract, atherosclerosis, asthma, arthritis) and neurodegenerative disorders (Alzheimer's, Parkinson's diseases, and dementia). These endemic diseases result from the degradation of cellular constituents such as lipids, proteins and DNA as a consequence of the action of reactive oxygen species among which we find free radicals [1-3]. Free radicals are very unstable but reactive substances having at least a free electron in their orbitals [4]. Their presence in an organism is as a result of metabolic reactions which are indispensible in their proper functions. Oxidative stress is a direct consequence of excesses in free radicals in the system. A major solution to these problems is the use of antioxidant substances. These are substances which in small amounts with respect to the substrate are susceptible to oxidation and therefore have the potential to prevent or to slow down the oxidation of the substrate [5, 6]. They generally react according to the different modes of their acidic hydrogen atom transfer: hydrogen atom transfer (HAT), single-electron transfer followed by proton transfer (SET-PT), and sequential proton loss electron transfer (SPLET) (see scheme 1). They also react through their chelating ability (or oxidation inhibitory effect) towards metallic ions. The stability of the resultant entity depends on hydrogen bonds, resonance and conjugation effects. It is in this perspective that free OH bonds have been the principal focus of this work. It is noteworthy here that the antioxidant under study (emodin) is an antiviral agent of the anthraquinone family which can be isolated from *rumex abissinicus* [7].

Emodin is a well-known natural product capable of many biological activities. It serves as an active ingredient in the manufacture of certain pharmaceuticals and as an additive in the fabrication of certain cosmetics [8, 9]. It is also used as a purgative, antipyretic, antiviral agent, etc. At industrial level, it plays the role of oxidative degradation of polymers, auto-oxidation of fuels and is responsible for the loss of elasticity of rubber and plastics [7-10]. Many research works have been carried out on emodin given its biological importance. Among these, radical scavenging capacity has been extensively reported. Although recent studies [7,10] showed that emodin has inhibitory potentials for superoxide radicals, the mechanisms involved are not fully understood. Gas phase theoretical studies based on structure-activity relationships (SAR) of emodin which were undertaken [8, 9] to understand its antioxidant properties revealed the most stable conformer that is presented in Fig. 1. This is a justification of our choice on emodin conformer investigated in this research endeavor. By these same studies, the free OH group not involved in H-bond formation was shown to be largely responsible for the antioxidant property of emodin.

Despite the volume of theoretical work carried out by researchers on emodin, the hydrogen atom transfer mechanism has not yet been established for this molecule. This hydrogen atom transfer by antioxidants could be achieved via heterolytic fission of the O-H bond or by sequential proton loss-electron transfer and single electron transfer-proton transfer reactions as mention above.

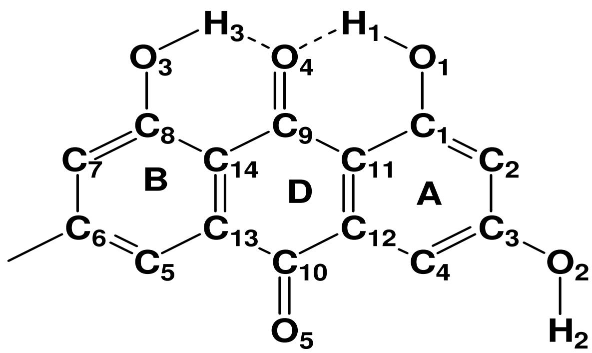


Fig. 1. Structure of the most stable conformer of emodin [8, 9]

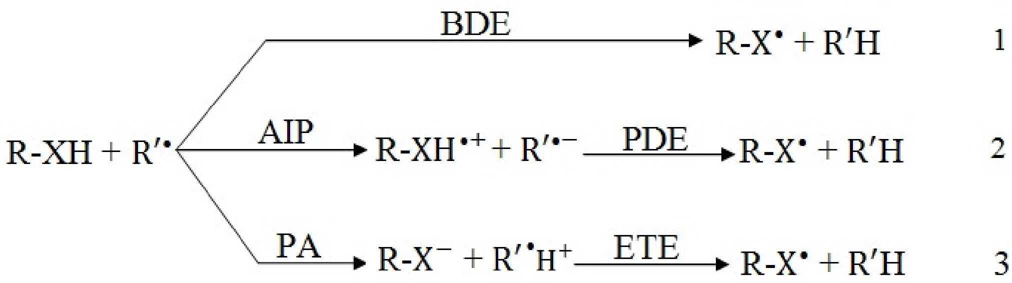
The main focus of this work is on solvent effects especially as most biological and chemical processes take place in solution and since solvation play a determinant role on the mechanism of certain processes. Investigating solvent effects on the cleavage of the free O-H bond in emodin involves the Bond Dissociation Energy (BDE) studies. The DFT method was chosen for this work because it takes better account of electronic correlation that is necessary for a good estimate of BDE and a good description of the radicalizing species. The DFT/B3LYP level of theory has been used since it gives better BDE results compared to other methods [11, 12]. Solvent effects were studied via the Integral Equation Formalism Polarizable Continuum Model (IEF-PCM) in benzene, methanol acetonitrile and water. The IEF-PCM is characterized by good, precise and accurate results with less computation efforts required [13-15]. The solvents were chosen based on the increasing order of their dielectric constants from benzene to water.

2. COMPUTATIONAL METHODS

All quantum chemical calculations have been performed using the Gaussian 09W computational package [16]. The Gaussian 09W software employs the Gaussian-type orbitals in speeding up calculations [17-20]. The restricted Kohn-Sham approach has been preferred to unrestricted approach for these calculations in order to minimize spin contamination and to increase precision on energy evaluations [7, 12]. The GaussView 5.0.8 graphical user interface has been used for pre and post processing of molecular data. The molecular geometry of emodin, radicals and ions in each medium, have been optimized using B3LYP/6-311++G(d,p) level of theory without constraints of any kind. Vibrational frequencies have been calculated at the same level of theory as that used for geometry optimization and no imaginary frequencies were found, ascertaining that the optimized structures are minima on their potential energy surfaces. To obtain very precise results, we chose the large Pople-style basis set 6-311++G(d,p). In order to determine partial charges, second order perturbation or interaction energies and orbital occupations, natural bond orbitals (NBO) analyses were performed on each molecule studied. Solvent contributions were accounted for by means of the IEF-PCM method. This method assumes a homogeneous distribution of the solvent on the entire surface of the aqueous solution [21-24].

Free radicals can be deactivated in reactions involving antioxidants according to three mechanisms: Hydrogen Atom Transfer (HAT), Sequential Proton Loss Electron Transfer (SPLET) and Single Electron Transfer followed by Proton Transfer (SET-PT) as illustrated in **scheme 1**. Some antioxidant parameters or descriptors related to these antioxidant mechanisms are defined as follows: Bond Dissociation Enthalpy (BDE – for the HAT mechanism), Proton Affinity and Electron Transfer Enthalpy (PA and ETE –

for the SPLET mechanism), Adiabatic Ionization Potential and Proton Dissociation Enthalpy (AIP and PDE–for the SET-PT mechanism) [25-28].



Scheme 1: Mechanism of hydrogen atom transfer [25-28]

where R-XH represents an antioxidant, X may be O, C, N or S and R' represents the reactive radicalizing species. The mechanism adopted depends on the reaction medium of the antioxidant [26, 28, 29]. The reaction in **equation 1**, with BDE as the characteristic property, preferentially occurs in the gas phase and in non-polar solvents. In polar solvents, SPLET mechanism (that characterizes **equation 3**) is more appropriate. This process is a form of sequential transfer that begins with the departure of a proton from the antioxidant to the reactive radicalising species, controlled by PA and followed by electron transfer from the proton-deficient antioxidant to the protonic reactive radical; this stage is characterized by ETE. The second form of hydrogen atom heterolytic transfert which starts by electron transfert (characterized by IP) and followed by proton transfert (which is studied by PDE) [6, 30, 31]. Thus, the determination of the afore-mentioned properties will facilitate the follow-up and proper understanding of the mechanisms of hydrogen atom transfer. The antioxidant parameters mentioned above are calculated as described below [32-34]:

BDE is a thermodynamic parameter used in characterizing the strength of a chemical bond as shown in equations 4 and 5.

$$RX - H \rightarrow RX^{\bullet} + H^{\bullet} \qquad (4)$$

$$BDE = \Delta_f H^{\circ}(RX^{\bullet}) + \Delta_f H^{\circ}(H^{\bullet}) - \Delta_f H^{\circ}(RX - H) \qquad (5)$$

where $\Delta_f H^{\circ}(i)$ is the enthalpy of formation of the species i.

AIP is the energy necessary to pull out one electron from the antioxidant molecule (equations 6 and 7).

$$RX - H \rightarrow (RX - H)^{\bullet +} + e^{-} \qquad (6)$$

$$AIP = \Delta_f H^{\circ}((RX - H)^{\bullet +}) + \Delta_f H^{\circ}(e^{-}) - \Delta_f H^{\circ}(RX - H) \qquad (7)$$

PDE is the energy responsible for the dissociation a proton from a radical cationic species (equations 8 and 9).

$$(RX - H)^{\bullet +} \rightarrow RX^{\bullet} + H^{+} \qquad (8)$$

$$PDE = \Delta_f H(RX^{\bullet}) + \Delta_f H(H^{+}) - \Delta_f H\left((RX - H)^{\bullet +}\right) \quad 9$$

PA is the proton dissociation energy of a substance (equations (10 and 11).

$$RX - H \rightarrow RX^{-} + H^{+} \quad 10$$

$$PA = \Delta_f H°(RX^{-}) + \Delta_f H°(H^{+}) - \Delta_f H°(RX - H) \quad 11$$

ETE is the energy required to remove one electron from an anionic species (equations 12 and 13).

$$RX^{-} \rightarrow RX^{\bullet} + e^{-} \quad 12$$

$$ETE = \Delta_f H(RX^{\bullet}) + \Delta_f H(e^{-}) - \Delta_f H(RX^{-}) \quad 13$$

3. RESULTS AND DISCUSSION

3.1 Solvation effects on geometrical parameters

The values of selected bond lengths and angles of the most stable conformer of emodin in the various media investigated are presented in **table 1**. Insignificant changes have been observed between the lengths of equivalent C-C bonds in rings A and B in the gas phase; the minimum and maximum discrepancies being 0.001 and 0.008 Å respectively. The C_9-C_{14} and C_9-C_{11} bonds, adjacent to the carbonyl group C_9=O_4 are shorter than the C_{10}-C_{13} and C_{10}-C_{12} bonds by 0.032 and 0.042 Å respectively. These differences can be explained by the fact that the C_9=O_4 group is engaged in the formation of the hydrogen bonds, $O_3H_3…O_4$ and $O_1H_1…O_4$. The C_9=O_4 bond being longer than the C_{10}=O_5 bond by 0.042 Å, can also be attributed to the involvement of the former in the formation of these hydrogen bonds. Similar observations are made in the case of C_8-O_3 and C_1-O_1 bond lengths, which are each longer than the C_3-O_2 bond.

The O_1-H_1 and O_3-H_3 bonds are almost having similar lengths, and are both longer than the O_2-H_2 bond. This is attributable to the involvement of the hydrogen atoms H_1 and H_3 in hydrogen bond formation. The lengths of the hydrogen bonds $O_3H_3…O_4$ and $O_1H_1…O_4$ are nearly the same (1.70Å), explaining the similarity in bond lengths between the O_1-H_1 and O_3-H_3 bonds. The angles of these hydrogen bonds are approximately 146^{o}, which is a clear indication that these hydrogen bonds are moderately strong according to the Jeffrey's classification of hydrogen bonds [35].

Table 1. Some lengths (Å) and angles (degrees) of connections of the optimized geometry of the most stable conformer of the emodin

Ring	Bond	Gas	Benzene	Methanol	Acetonitrile	Water
	Bond lengths					
Ring A	**C_1-C_2**	1.4	1.4	1.4	1.4	1.4
	C_2-C_3	1.39	1.39	1.39	1.39	1.39

	C_3-C_4	1.4	1.4	1.4	1.41	1.41
	C_4-C_{12}	1.38	1.38	1.38	1.38	1.38
	C_1-C_{11}	1.42	1.42	1.42	1.42	1.42
	C_{11}-C_{12}	1.41	1.42	1.42	1.42	1.42
Ring D	**C_9-C_{11}**	1.45	1.45	1.45	1.45	1.45
	C_9-C_{14}	1.46	1.46	1.46	1.46	1.46
	C_{10}-C_{12}	1.5	1.5	1.5	1.5	1.5
	C_{10}-C_{13}	1.49	1.49	1.49	1.49	1.49
Ring B	**C_8-C_7**	1.4	1.4	1.4	1.4	1.4
	C_5-C_6	1.41	1.41	1.41	1.41	1.41
	C_7-C_6	1.39	1.39	1.39	1.39	1.39
	C_5-C_{13}	1.38	1.39	1.39	1.39	1.39
	C_8-C_{14}	1.42	1.41	1.41	1.41	1.41
	C_{13}-C_{14}	1.42	1.42	1.42	1.42	1.42
	C_6-C_{15}	1.51	1.51	1.51	1.51	1.51
	C_1-O_1	1.34	1.34	1.34	1.34	1.34
	C_3-O_2	1.36	1.36	1.36	1.36	1.36
	C_8-O_3	1.34	1.34	1.34	1.34	1.34
	C_9-O_4	1.26	1.26	1.26	1.26	1.26
	C_{10}-O_5	1.22	1.22	1.22	1.22	1.22
	O_1-H_1	0.99	0.99	0.99	0.99	0.99
	O_2-H_2	0.96	0.97	0.97	0.97	0.97
	O_3-H_3	0.99	0.99	0.99	0.99	0.99
	O_1H_1…O_4	1.7	1.69	1.69	1.69	1.69
	O_3H_3…O_4	1.7	1.69	1.69	1.69	1.69
	Bond angles					
	O_1-H_1…O_4	146.5	146.7	147	147	147

O_3-H_3…O_4	146.1	146.4	146.6	146.7	146.6
C_8-O_3-H_3	107.3	107.2	107.1	107.1	107.1
C_1-O_1-H_1	107.4	107.3	107.1	107.1	107.1
C_3-O_2-H_2	110.1	110.4	110.7	110.8	110.7

However, our results have shown that inter-atomic distances remain virtually unchanged from gas to solvent phases. In a general, bond lengths like bond angles almost do not change with solvation. It has been found that hydrogen bond lengths decrease as solvent permittivity increases meanwhile, hydrogen bond angles increase slightly. This predicts that the stability of emodin increases with solvent permittivity, since the decrease in hydrogen bond length increases molecular stability enormously.

3.2 Solvent effects on energetic properties

The values of the energetic parameters: thermal energy, E_{therm}, free energy, ΔG°, zero point energy, ZPE, and energy gap, $\Delta E_{HOMO-LUMO}$ of emodin in various media are listed in **table 2**. From the values in **Table 2,** slight reductions in E_{therm}, ΔG and ZPE are observed on going from the gas phase to benzene and from benzene to the polar solvents. The values of these parameters remain nearly the same from one polar solvent (methanol, acetonitrile and water) to another. The greatest reduction in each of these parameters from gas to solvent phases occurs in the case of water; for instance, a maximum reduction of about 33 kJ/mol in thermal energy is observed as the gas phase molecule passes into an aqueous medium. Similar reductions of about 36 and 2 kJ/mol for free energy and ZPE respectively are equally observed. This can be explained by the fact that emodin-solvent interactions in non-polar aprotic solvents are Van der Waals in nature, whereas in polar solvents they are hydrogen-bridge in nature (more intense than the former). Thus, at 0 and 298.15 K, the stability of emodin increases slightly with the permittivity of the medium. This trend is similar to the slight increase in hydrogen bond strength with permittivity of the medium as discussed in **section 3.1**.

HOMO-LUMO energy gaps are generally used to describe molecular reactivity. It is well established that, the smaller the energy gap, the more reactive is a molecule [36, 37]. The values of emodin's HOMO-LUMO energy gaps are presented in **table 2**. It can be seen that these values remain virtually unchanged from gas to solvent media, which indicates that the global reactivity of this molecule is almost not affected by solvation.

Table 2. Values of some energetic parameters describing the stability of the emodin, obtained by DFT/B3LYP/6-311++G(d,p)

Parameters	Gas	Benzene (ε = 2.28) [27]	Methanol (ε = 32.70)	Acetonitrile (ε = 36.60)[27]	Water (ε = 78.40)[27]
E_{therm}	-2504862	-2504877	-2504894	-2504894	-2504895
ΔG° (kJ/mol)	-2504400	-2504417	-2504436	-2504437	-2504436
ZPE (kJ/mol)	577	576	575	575	575
E_{HOMO} (eV)	-6.75	-6.74	-6.74	-6.74	-6.74
E_{LUMO} (eV)	-3.37	-3.38	-3.39	-3.39	-3.39
$\Delta E_{HOMO-LUMO}$	3.37	3.36	3.35	3.35	3.35

3.3 Solvation of particle transfer mechanism

In this work, the gas-phase proton (H^+) and electron (e^-) enthalpies (H) used are respectively 6.197 and 3.145 kJ/mol [38]. The latter represents the integrated heat capacity at 298.15 K for ideal gas, $H(H^+)$ = (5/2)RT, while the former is obtained from the Fermi-Dirac statistical mechanic equations. We used the experimentally determined solvation enthalpies of the hydrogen atom H(H•) in benzene, methanol, acetonitrile and water (**Table 3**). In gas phase, the average value of $\Delta_f H°(H^\bullet)$ (5 kJ/mol) obtained from [17] was used. The solvation enthalpies of H^+ and e^- in various solvents have been computed at IEF-PCM/6-311++G(d, p) level and the results obtained are in good agreement with experimental values. The solvation enthalpies listed in **Table 3** have been computed as enthalpy changes of the following processes [39]:

$$solvent_{(solv)} + H^+(g) \rightarrow solvent - H^+_{(solv)} \qquad 14$$

$$solvent_{(solv)} + e^-(g) \rightarrow solvent^-_{(solv)} \qquad 15$$

Our values of $\Delta_f H°(H)$ and those reported in the literature calculated at the same level of theory are nearly the same in all solvents used.

Table 3. Solvation enthalpies of hydrogen atom ($\Delta_f H^\circ_{solv}(H^\bullet)$), proton ($\Delta_f H^\circ_{solv}(H+)$) and electron ($\Delta_f H^\circ_{solv}(e^-)$) in kJ/mol

Solvent	ε^a	$\Delta_f H^\circ_{solv}(H^\bullet)$	$\Delta_f H^\circ_{solv}(H+)$		$\Delta_f H^\circ_{solv}(e^-)$	
		a	This work	a	This work	a
Benzene	2.28	6.4	-878	-894	-14	-7
Methanol	32.7	5.0	-1016	-1038	-88.6	-86
Acetonitrile	35.69	5.0	-1060	-1031	-130	-95
Water	78.38	-4.0	-984.4	-1022	-131.2	-105

a from Ref. [27]

Presented in **Table 4** are the values (in kJ/mol) of BDE, IP, PA, PDE and ETE, parameters that describe the mechanisms of antioxidant particle transfer.

Table 4. Values of BDE, AIP, PDE, PA and ETE properties (in kJ/mol) in the studied mediums, obtained by DFT/B3LYP/6-311++G(d,p)

Medium	**BDE**	**AIP**	**PDE**	**PA**	**ETE**
Gas	371.52	738.15	910.20	1339.20	354.15
Benzene	372.48	679.30	754.30	1006.30	427.30
Methanol	370.45	536.40	639.97	757.92	418.40
Acetonitrile	370.45	529.00	639.81	755.81	413.00
Water	370.45	517.60	635.14	747.14	405.60

<u>3.3.1 Hydrogen atom transfer</u>

The values of BDE for homolytic cleavage obtained by different mechanisms are presented in **Table 5**, along with gas phase results found in the literature [8, 9]. In **table 5**, bond dissociation enthalpies calculated by the HAT, SET-PT and SPLET mechanisms are represented by BDE, BDE_{e-p} and BDE_{p-e} respectively. It is clear from this table that the gas phase BDE value obtained in this work is in very good agreement with that obtained from literature [8, 9]. This table also shows that the BDE due to homolytic fission is lower than BDE_{e-p} and BDE_{p-e} in all media. This led us to the conclusion that hydrogen atom transfer by emodin occurs almost exclusively by the homolytic mechanism in all media. The effect of solvation on the value of BDE is relatively insignificant since it has changed **approximately only by 1 kJ/mol from the gas** to the solvent phases. On the other hand, the values of BDE_{e-p} and BDE_{p-e} have witnessed a reduction of about 540 kJ/mol, as media permittivity increases. This could be due to the fact that AIP and PA, which are the rate determining properties of the two heterolytic mechanisms, are very sensitive to solvation; as evidenced in table 4. Although the BDE_{p-e} and BDE_{e-p} values are identical, a comparison of AIP and PA shows that the electron-proton sequential transfer has priority over the reverse mechanism. It is equally obvious in this table that AIP and PA are each higher than the BDE in all media investigated; which justifies the preference of the homolytic mechanism over heterolytic.

Table 5. Values of BDEs (in kJ/mol) in various media, obtained by B3LYP/6-311++G(d,p)

	BDE			**BDE_{e-p}**	**BDE_{p-e}**
	This work	[8]	[9]		
Gas	371.52	371.12	371.12	1693.34	1693.34
Benzene	372.48	_	_	1433.60	1433.60
Methanol	370.45	_	_	1176.37	1176.37
Acetonitrile	370.45	_	_	1168.81	1168.81
Water	370.45	_	_	1152.74	1152.74

3.3.2 Single electron transfer followed by proton transfer

Here, the main property studied is AIP. Our gas phase AIP value (783.15 kJ/mol) is in better agreement with that obtained by [8] (775.81 kJ/mol), than that obtained by [9] (662.33 kJ/mol). Since these researchers performed their calculations with G03, the differences between their AIP values and that obtained in the present study are certainly due to different software versions. The trend in our AIP values in the various media investigated is shown in **Fig. 2**.

From **Fig. 2**, it can be seen that the AIP values change considerably with media polarities. AIP decreases as media permittivities increase. This parameter has dropped by a maximum of 220.55kJ/mol from the gas phase to the aqueous solution, showing that solvation has an impact on the electron transfer process. AIP values are found to be higher than ETE values. This can be explained by the fact that the neutral form of emodin is more stable and consequently less reactive than its deprotonated form. The ETE value is found to increase when solvation effects are considered.

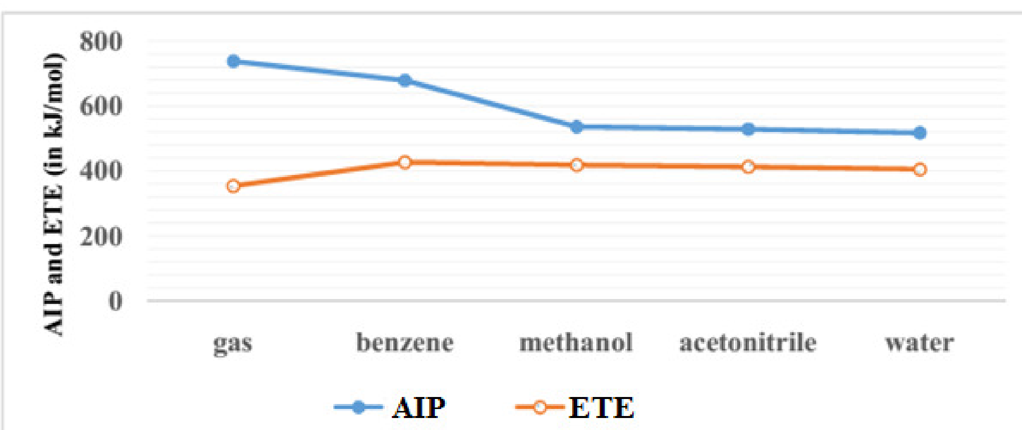


Fig. 2. IP and ETE variation of the emodin in the study mediums, obtained by DFT/B3LYP/6-311++G(d,p) method

3.3.3 Sequential proton loss electron transfer

The main property that determines the rate of SPLET is PA. **Fig. 3** shows the variation of this property in the various study media. It is obvious from the Fig. that PA decreases as solvent permittivity increases, but remains fairly constant in the polar solvents. PA has reduced by a maximum of 592.06 kJ/mol from the gas phase to the aqueous solution. The trend shown by BDE_{p-e} is similar to that shown by PA, since the former is calculated using the latter. It is also noticed that the values of PA are relatively higher than those of PDE. This is explainable based on the fact that the neutral form of emodin is more acidic than its ionized form.

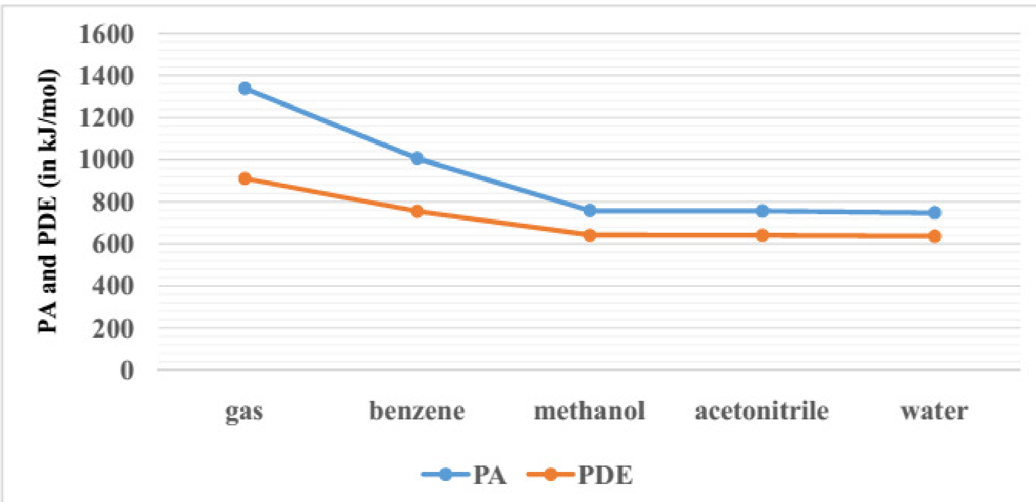


Fig. 3. Variation of PA and PDE of emodin in the different media, obtained by the DFT/B3LYP/6-311++G(dp) method

3.4 Effects of solvation on the OH bond orbital occupation and charge

NBO analysis provides a deeper insight into atomic charge distribution, charge transfer and inter-orbital interactions [36]. NBO parameters for the molecule studied are presented in **table 6**. From this table, it is clear that the charge difference between oxygen and hydrogen, $|q_O|-|q_H|$ remains constant from gas phase through the polar solvents. This can be attributed to the fact that both atoms of the free OH bond interact with the molecules of each solvent leading to the formation of emodin-solvent hydrogen bonds. The charge transferred from emodin's oxygen to the solvent's (methanol or water) hydrogen is replaced by charge transferred from the solvent's oxygen to the substrate's acidic hydrogen. However, a reduction in this charge difference is observed from gas phase to the nonpolar solvent (benzene). This reduction is attributable to the fact that emodin-solvent charge transfer is made only from the emodin's oxygen to the benzene hydrogens; the reverse transfer rendered impossible by the steric hindrance of the benzene ring.

The preceding observations are supported by the OH bond occupation in the different media investigated, which increases from gas phase to benzene, but remains almost the same from gas phase to the polar solvents.

Table 6. Values of atomic charge, charge differences and orbital occupancy of free OH bond in the investigated media

	Gas	Benzene	Methanol	Acetonitrile	water
Atoms	**Atomic charge** (in coulomb)				
O_2	-0.686	-0.683	-0.704	-0.704	-0.702
H_2	0.474	0.481	0.492	0.492	0.493
$\lvert q_O \rvert - \lvert q_H \rvert$	0.212	0.202	0.212	0.212	0.209
Bond			**Occupation, Q_{ij}**		
O_2-H_2	1.98556	1.98899	1.98561	1.98558	1.98536

3.5 Diffuse and polarized bases, and multiple division effect of valence atomic orbitals

The effects of diffuse and polarized bases, as well as multiple division effect of valence atomic orbitals have been studied only on BDE which characterizes the HAT mechanism for the antioxidant activity of emodin. This analysis has only been made on BDE because HAT is the most preferred antioxidant mechanism by emodin. The BDE values calculated with some Pople-typed basis sets along with their absolute relative values ($|\Delta BDE|$) obtained by comparison with the BDE value calculated with 6-311++G(d,p), are listed in **table 7**. Also present in this table, is the BDE value (371.52 kJ/mol) obtained by 6-311++G(d,p) in gas phase.

Clearly from **table 7**, the atomic orbital valence diffusion and their triple division do not practically affect the BDE value. In both cases, a BDE increment of less than 1 kJ/mol is observed. Indeed, the diffuse functions take account of a greater orbital occupation in a given area of space. These functions are essential in calculations involving transition metals and anionic systems; because the transition metal atoms have "d" orbitals which tend to be diffuse. The free electron of the anionic system could be far away from the rest of the electron density. However, the valence atomic orbital polarization especially those of hydrogen atoms, affect in a considerable manner, the energy of the O-H bond dissociation. The resulting variations are shown here to be higher than 10 kJ/mol and may reached 16.93 kJ/mol in the case of hydrogen atoms. It can be concluded that atomic orbital polarization, particularly, that of hydrogen atom is essential in determining the computational time for the X-H bond BDE. It is worth noting that these results are in agreement with the literature observations.

Table 7. BDE and ΔBDE values (in kJ/mol) of certain basis sets, relative to 6-311++G(d,p) in gas phase

	6-311++G**	6-311+G**	6-311G**	6-311++G*	6-311++G	6-311G	6-31++G**
BDE	371.52	372.39	371.78	354.59	360.99	359.51	371.17
$\lvert\Delta BDE\rvert$	0.00	0.87	0.26	16.93	10.53	12.01	0.35

4. CONCLUSION

Our results have revealed that solvation does not significantly affect the bond lengths and angles in emodin, but has a slightly appreciable impact on hydrogen bonds rendering them moderately strong. The stability of emodin from energetic studies increases slightly with solvent polarity. This result implies that the substrate-solvent interactions in this molecule are of Van der Waals type in non-polar solvents and of hydrogen bond type in polar solvents. The hydrogen atom homolytic transfer process has been identified as the dominating antioxidant mechanism of emodin in all media. The BDE value obtained in this work is in agreement with those obtained by [8, 9] in the gas phase. Our results have shown that diffusion and triple division of valence atomic orbitals do not influence the calculated BDE values in an appreciable manner, whereas they are significantly affected by polarization.

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