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# Synthesis, structural characterization, and computational study of novel (*E*)-N'-(1-*p*-tolylethylidene)furan-2-carbohydrazide



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### HIGHLIGHTS

• Preparation and solid state study of a novel member of an interesting structural class.

• This modeling studies show that the *E*-isomer is the global minimum isomer.

• A rationale for the observed *E*-selectivity is based on strong *E*-*E* dimerization.

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#### ABSTRACT

An efficient synthesis of the novel (*E*)-N'-(1-*p*-tolylethylidene)furan-2-carbohydrazide is described. The molecular structural features were then confirmed by single crystal X-ray diffraction. Quantum chemical calculations including molecular geometry, intermolecular H-bonds, and vibrational frequencies were carried out for the structures to explain stability and geometry using both density functional (DFT/ B3LYP) and the Hartree–Fock (HF) with 6-311+G(d,p) basis set. The calculated structural parameters are presented and compared with their experimental X-ray counterparts. The *E*-isomer is a global minimum on the potential energy surface. However, validation of the computational methods here *via* comparison with the observed X-ray data enabled computational analysis to predict that head-to-tail *E*/*E*-dimer of the observed *E*-isomer has significantly stronger intermolecular hydrogen bonding compared with the non-observed *Z*/*Z*-dimer. It was observed that the stretching mode of N—H and C=O shifted to lower frequencies, due to pairwise intermolecular N—H…O hydrogen bonds. This provides a clear rationale for the isomeric specificity obtained and provides a validation of the optimized method which could be applied to predict structures of other useful carbohydrazides. Generally, it has been concluded that the findings of B3LYP hybrid functional fit better to the observed geometrical and vibrational parameters than the results of the HF.

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### 1. Introduction

Hydrazones possessing an azomethine —NHN=CH— proton represent a key component of organic compounds which have been used in various biological and chemical applications [1]. These compounds can be synthesized under simple reaction conditions at moderate temperature. These materials are normally generated *via* a condensation reaction between an acid hydrazide and aldehydes or ketones, either in the presence or absence of acid catalyst [2,3]. In addition to their own important properties and applications, both *N*-acyl- and *N*-arylhydrazones are vital precursors for

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the synthesis of a wide range of organic compounds including 1,3,4-oxadiazoles derivatives [4–7]. For example, *N*-heterocyclic hydrazones derivatives have received major interest due to their coordination properties which enable them to act as mono- or polydentate ligands towards metal ions, and several such metal complexes have been synthesized and characterized [8]. They also act as precious spectrofluorimetric reagents in metal ion determination in various environments including for Os(VIII), Cd(II), Co(II), and Hg(II) [9]. Furthermore, these compounds may exhibit pharmacological activities. In fact, there is considerable evidence to suggest that the hydrazone moiety present in many derivatives imparts a valuable pharmacophoric character for example for the inhibition of COX, treatment of tuberculosis in combination with

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other drugs, and potential inhibitory activity toward protein tyrosine phosphate from Mycobacterium Tuberculosis [10–12].

Hydrazones that possess acidic hydrogen are identified by their prototropic tautomerism. Therefore, two different geometrical structures are possibly available; *syn-Z* or *anti-E* isomers with different tautomeric forms. Inter and Intra- molecular hydrogen bonds of such compounds and their subsequent influence in generating different supramolecular arrays have been identified [13–15].

Hydrazone-containing compounds have been attracting substantial attention in computational sciences. For example, Guner et al. employed both *ab initio* and DFT methods to investigate cyanobenzaldehyde isonicotinoyl hydrazone [16]. The absorption and fluorescence energies of substituted aryl-1,8-naphthalimide hydrazones was modeled using high level DFT [17]. Also, the structural activity relationships of a series of pyrrole hydrazones were examined as new tuberculosis agents where various computed constitutional, topological, physicochemical and quantum–mechanical descriptors were correlated with their reactivity [18].

In this study, as a part of our ongoing interest in functionalized hydrazides we report the synthesis of (E)-N'-(1-p-tolylethylidene)furan-2-carbohydrazide and comparison of X-ray structural characterization with detailed computational investigations of the structures. In addition, the roles of energy and H-bonding in the subsequent stabilities of the E/Z-geometrical isomers are computationally investigated.

#### 2. Experimental work

#### 2.1. Syntheses and characterization

FTIR spectra was recorded using Shimadzu 8201 spectrophotometer with KBr technique in region 4000–400 cm<sup>-1</sup> that was calibrated by polystyrene. ES–MS and HRMS were recorded on a Micromass LCT orthogonal acceleration time-of-flight mass spectrometer (positive ion mode). <sup>1</sup>H NMR spectra were recorded at 400 MHz and <sup>13</sup>C NMR spectra at 100 MHz on a DPX400 spectrometer. Chemical shifts are denoted in ppm ( $\delta$ ) relative to internal solvent standard.

Furic acid hydrazide (0.0158 mol) and 1-p-tolylethanone (0.0158 mol) were heated under reflux in ethanol (20 ml) for 30 min until a solid precipitate was formed. The mixture was allowed to cool to room temperature and the solvent removed under reduced pressure. The solid was washed successively with cold ethanol, filtered and then recrystallized from cold ethanol to give the pure product in 89% vield and Mp 169–170 °C. IR (KBr) v cm<sup>-1</sup>: 3178 (NH str.), 1151 (N–N), 1658 (C=O), 1507 (C=C), 1561 (N=C), 1134 (C-O). MS (ESI) *m*/*z*: [M+Na)<sup>+</sup>, 265.0], <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>) δ 10.6 (s, 1H, NH), 7.9 (d, *J* = 0.9 Hz, 1H, OCHCH, furan ring), 7.8 (d, J = 7.7 Hz, 2H, aromatic ring), 7.7 (d, J = 8.7 Hz, 2H, aromatic ring), 7.4 (d, J = 3.3 Hz, 1H, OCHCH, furan ring), 6.7 (dd, J = 3.5, 1.7 Hz, 1H, CHCHCH, furan ring), 2.4 (s, 3H, CH<sub>3</sub>), 2.3 (s, 3H, CH<sub>3</sub>). <sup>13</sup>C NMR (100 MHz, CDCl<sub>3</sub>)  $\delta$  162.9 (C=O), 154.3 (C=N), 147.2 (OCHCH, furan ring), 144.3 (OCCH, furan ring), 140.1, 135.0, 129.3, 126.7 (aromatic ring), 115.9 (OCCH, furan ring), 112.6 (OCHCH, furan ring), 21.4 (CH<sub>3</sub>), 13.2 (CH<sub>3</sub>).

#### 2.2. Crystallographic analysis

X-ray single crystal data were collected at 230 K using graphite monochromated Mo K $\alpha \lambda = 0.7107$  Å radiation on a Bruker SMART APEX CCD diffractometer. Data reduction was carried out using SAINT [19] and the structure was solved using SHELXS-97 [20] and showed that there are two molecules of the title compound in the form of a dimer in the asymmetric unit. Full matrix refinement on  $F^2$  was performed with SHELXL-97 [20] and all calculations were carried out using the SHELXTL package [20]. The non-H atoms were refined anisotropically and H atoms were included in calculated positions, except for those bonded to N, which were found by Difference Fourier Methods and refined isotropically. It was necessary to collect the data at 230 K, since flash freezing to 100 K caused the crystal to break up. The crystal data are summarized in Table 1.

#### 3. Computational work

The molecular structures of compounds involved in the study were constructed using Hyperchem 7 [21] and initially optimized at the Semiempirical PM7 Sparkel level of theory implemented in MOPAC09 [22]. Then, using Gaussian 09 package [23], the initially optimized structures were fully optimized at their ground state in the gaseous phase at the DFT/B3LYP and HF level of theories with 6-311+G(d,p) basis set [24,25]. The stationary natures of the fully optimized structures were analytically examined by calculating the harmonic vibrational frequencies at the same level of theories and then zero point energies were estimated. To generate the correct frequencies, the computed vibrational frequencies were scaled by 0.9613 and 0.905 for B3LYP and HF subsequently as reported in literature [26,27]. Electrical Energies of ground state isomers, dimers and rotational states were estimated using single point energy calculations at a higher level of theory; B3LYP/6-311++G(2df,pd)//B3LYB/6-311+G(d,p). Predicted energies were corrected for zero-point vibrational energies. Intermolecular hydrogen bondings and chemical potentials extrema (maximum and minimum) were evaluated at the same level of theories. Atomic charges were calculated using natural population analysis [28]. GaussView and Gapedit programs were used for visualization of structures [29,30].

T-1-1-	4
Table	1

Crystal data and structure refinement of (E)-N'-(1-p-tolylethylidene)furan-2-carbohydrazide.

Parameter	Value
Empirical formula	$C_{14}H_{14}N_2O_2$
Formula weight	242.27
Crystal color	Colorless
Crystal size (mm <sup>3</sup> )	$0.5\times0.5\times0.5$
Crystal system	Triclinic
Space group	P-1
Unit cell dimensions	10.311(7)
a (Å)	11.633(8)
b (Å)	12.480(8)
<i>c</i> (Å)	67.050(12)
$\alpha$ (deg)	74.755(13)
$\beta$ (deg)	64.172(11)
γ (deg)	1232.8(14)
Z	4
D <sub>calculated</sub> (g cm <sup>-3</sup> )	1.305
F(000)	512
$\mu$ Mo K $lpha$ (mm $^{-1}$ )	0.089
T (K)	230(2)
λ (Å)	0.71073
Absorption coefficient (mm <sup>-1</sup> )	0.089
Absorption correction	None
Range of h, k, l	-7/12, -13/14, -11/15
$\theta \min/\max(\deg)$	2.05/26.42
R (int)	0.0403
Completeness to theta = 26.42	96.5%
Reflections collected/unique/	7164/4907
Data/restraints/parameters	4907/0/337
GOF on F <sup>2</sup>	0.902
Final R indices $[I > 2\sigma(I)]R_1$ , $wR_2$	0.0466, 0.1131
R indices (all data) $R_1$ , $wR_2$	0.0732, 0.1210
$\Delta  ho_{ m min}$ , $\Delta  ho_{ m max}$ , $\Delta  ho_{ m rms}$	–0.241 eÅ <sup>-3</sup> , 0.211 eÅ <sup>-3</sup> , 0.05
Refinement number of parameters	337
Refinement number of reflections	4907

#### 4. Results and discussion

#### 4.1. Molecular structures

Preparation of the novel product (*E*)-N'-(1-*p*-tolylethylidene)furan-2-carbohydrazide **3** in its dimeric form; hydrogen complex adduct **4**, was effected through a condensation reaction of furan-2-carbohydrazide **1** and 1-*p*-tolylethanone **2** (Scheme 1). The formation of **3** was confirmed by spectral data (<sup>1</sup>H NMR, <sup>13</sup>C NMR, FTIR, MS) and X-ray crystallography.

The 3D molecular structure of **4** is depicted in Fig. 1a and b; **1a** represents the experimental X-ray crystal structure with the numbering scheme while **1b** displays the optimized DFT(B3LYP)/6311+G(d,p) geometrical structure. Fig. 2 displays the orientation of the two molecules of **3** (the dimeric form **4**) in the asymmetric unit of X-ray crystal viewed along the *c*-axis, where the red dotted lines represent the hydrogen bonds.

Selected geometrical parameters; bond lengths and bending angles, for **4** optimized as described above along with their experimental counterparts are tabulated in Table 2. Our calculations showed that both B3LYP and HF results are in good agreement with their X-ray counterparts. This should validate our choice of level of theory employed in this study of investigating such compounds. Evidently, computed bond distances and bond angles are nicely correlated with their experimental counterparts with regression factors ( $R^2$ ) of (0.9928, 0.9685) and (0.9907, 0.9858) for DFT and HF respectively. The DFT correlations are depicted graphically and shown in (Fig. 3a and b).

The DFT/B3LYP results are in better agreement with the experimental ones than those obtained by the HF level. Therefore, and considering that the DFT/B3LYP satisfactorily takes into account electron correlation contributions which are essential to investigate highly conjugated and systems of lone electron pairs, the DFT/B3LYP method was further employed in this study [31].

In **4**, the experimental bond distances of N2–C6 and N4–C20 are equal to 128.4(2), 128.3(2). The corresponding B3LYP and HF values are (129 pm, 129 pm) and (126 pm, 126 pm), respectively, clearly, indicating the double bond nature of the two bonds. The N1–N2 bond length is 137.5(19) pm, 136.4 pm and 135.8 pm as it is predicted by X-ray, DFT and HF, respectively, while the N3–N4 bond distance is found 137.9(2) pm, 136.4 pm and 135.8 pm by the same aforementioned experimental and theoretical methods, respectively. These data suggest a single bond between the nitrogen atoms. Theoretical calculations showed that the hydrogen atoms H1 and H3 were equidistant to each of N1 and N3 atoms (102.9 pm and 100.4 pm by the DFT and HF, respectively), while the corresponding X-ray distances are 90.5(19) pm and 91.5(17) pm.

Geometrical parameters showed that the hydrazone moieties between C8 and O2 and between C22 and O4 are effectively planar and atoms are in trans-position in each of the two parts. Furan rings of the dimer are slightly twisted away from the hydrazone plans, forming a torsional planes 10.9° for each C2—C1—N1—N2 and C16—C8—N2—N1. Besides, the furan moieties are found slightly deviate from planarity with each other, with a C2—O1—C16—O3 torsion of 5.8°. The phenyl moieties are in anti orientation with each other, (C9—C13—C27—C23 torsion angle of 80.5°), adopting the well-known dorsal geometry with the N2—C6—C8—C9 and N4—C20—C22—C27 torsional planes of 28.9° for each with the hydrazone moieties.

#### 4.2. Geometrical Isomers

Due to the double bond geometry and the restricted rotation around the N2=C6 bond, compound **3** was expected to exhibit E/Z-stereoisomerism, and the synthesis might lead to form therefore of both isomers. However, only the *E*-form around N2=C6 and thus its dimeric E/E adduct were obtained. Accordingly, calculations on the hypothetical Z/Z-adduct in addition to the *Z*-rotamer and the E/Z-rotational transition structures at the same level of theory DFT(B3LYP)/6-311+G(d,p) were performed.

Figures and Cartesian coordinates of both the Z-isomer and the rotational transition structure around N2=C6 double bond at the B3LYP/6-311+G(d,p) level of theory are reported in supplementary materials, Figs. S1 and S2, respectively. The most important feature of the rotational transition structure is the perfect planarity of C6-N2-N1 moiety (180.0°) and the presence of one imaginary symmetrical bending vibrational mode at  $v = -385.7 \text{ cm}^{-1}$  centered at N2 atom. In addition, the calculated bond distances N1-N2 and N2-C6 are 129.3 pm and 126.3 pm respectively, i.e. about 7.1 pm and 2.7 pm shorter than the DFT/B3LYP-based lengths of the corresponding bond distances in the *E*-rotamer (*E*/ E-dimer). The DFT calculations showed that the hydrazone and furanyl moieties in the Z/Z-dimer are in perfect planarity while the phenyl moieties are parallel to each other, adopting anti orientation with the skeleton of the Z-rotamer that constitute the Z/Z-adduct. In a similar manner to the hydrazone moieties in the E-rotamer and thus its E/E-adduct, the geometrical parameters of the Z-rotamer and thus its Z/Z-adduct showed that the hydrazone moieties between C8 and O2 and between C22 and O4 are effectively planar but atoms are in cis-position in each of the two constituent parts. One last thing is worth indicating here is that the bond lengths of N1-C5 and N3-C19 in all geometries involved in the study are shorter than the typical N-C single bond and longer than a typical N=C bond, revealing the presence of the hyperconjucation in the hydrazone moieties.

#### 4.3. Energy calculations

Energies of the *E*/*Z*-geometrical isomers, *E*/*E*-dimer, *Z*/*Z*-dimer, frontier orbitals and their dipole moments are listed in Table 3. Our calculations predict that target compound **3** and its *Z*-rotamer are ground states where the *E*-form is the global minimum on the potential energy surface (PES). Evidently, the total energy of each isomer is lower than the energy sum of its constituent monomers. The energy difference ( $\Delta \epsilon$ ) in kcal mol<sup>-1</sup> between the two isomers



Scheme 1. Synthesis of (E)-N'-(1-p-tolylethylidene)furan-2-carbohydrazide.



**Fig. 1**. (a) The experimental geometric structure of the title compound at the unit cell in its dimeric form, (b) the theoretical geometrical structure, Mullikan charges (red color) and the hydrogen bonds in pm as predicted by B3LYP/6-311+G(d,p) level of theory. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

indicates that the *Z*-form is less stable than the *E*-form by 1.19 kcal mol<sup>-1</sup>. In the case of the dimers, the energy difference between the *E*/*E*-dimer and the *Z*/*Z*-dimer is remarkably enhanced to 7.66 kcal mol<sup>-1</sup>.

The energy barrier between E/Z-geometrical isomers ( $\Delta \varepsilon_b$ ) is estimated as the energy difference between  $\varepsilon_{isomer}$  and  $\varepsilon_{TS}$ . Accordingly,  $\Delta \varepsilon_b$  between *E*-isomer and *TS* measures 34.16 kcal mol<sup>-1</sup>, while its value is 32.97 kcal mol<sup>-1</sup> in the case of the *Z*-isomer, and thus a net energy difference of 1.19 kcal mol<sup>-1</sup> between the E/Z rotamers. In subsequent calculations, the computed energies were corrected to zero-point energy calculations. Transition structure was tackled using quadratic synchronous transit (QST2) with the same B3LYP/6-311++G(2df,pd)//B3LYP/6-311+G(d,p) level of theories. The stationary point was verified as first order saddle point, and thus the energy barrier between the E/Z-geometrical isomers was calculated. Which Minima does the transition structure connect has been identified by means of internal reaction coordinate (IRC) with a maximum number of 30 points on each



**Fig. 2.** Crystal packing (*E*)-N'-(1-*p*-tolylethylidene)furan-2-carbohydrazide viewed along the *a*-axis showing the pairwise intermolecular N–H···O hydrogen bondings in red colors. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

#### Table 2

Selected experimental and computed bond distances (pm) and bond angles (°) of the E/E-dimer of (E)-N'-(1-p-tolylethylidene)furan-2-carbohydrazide at B3LYP/6-311+G(d,p) and HF/6-311+G(d,p) levels of theories.

Bond	Bond Distance/pm			Angle	Bond angle/°			
	X-ray	B3LYP	HF		X-ray	B3LYP	HF	
C5-N1	135.2(2)	136.6	135	C5-N1-N2	121.4(15)	122.1	122.3	
C5—02	123.1(19)	123.5	120.6	C5-N1-H1N	114(11)	114.3	114.9	
C5-C1	147(2)	147.4	148.3	N2-N1-H1N	124.5(11)	123.3	122.4	
C1-C2	134.2(2)	137.2	134.9	C6-N2-N1	117.8(14)	119.1	119.3	
C1-01	136.8(19)	137.2	135	C2-C1-01	109(15)	109.2	109.7	
01–C4	135(2)	134.9	132.7	C2-C1-C5	137.9(16)	137	136.6	
C3-C2	141.3(3)	142.5	143.3	01–C1–C5	113.0(14)	113.1	113.7	
N1-N2	137.5(19)	136.4	135.8	C1-C2-C3	107.1(15)	107	106.1	
N2-C6	128.4(2)	129	126	C1-C2-H2	126.4	125.4	126.2	
C6–C7	148.8(2)	150.9	151.1	C3-C2-H2	126.4	125.4	127.7	
C6–C8	147.8(2)	148.5	149.4	C4–C3–C2	106.3(16)	106	105.3	
C8–C13	139.1(2)	140.1	138.8	C3-C4-01	111.1(16)	110.8	111.2	
C13–C12	137.8(2)	139.3	138.7	02-C5-N1	120.0(16)	119.7	120	
C8–C9	139.3(2)	140.5	139.3	02-C5-C1	120.4(15)	120.3	119.6	
C9–C10	137.5(2)	138.8	138.1	N1-C5-C1	119.6(15)	120	120.3	
C11–C14	151.1(2)	150.9	151	N2-C6-C8	116.0(15)	115.7	115.9	
O3-C18	134.9(2)	134.9	132.7	N2-C6-C7	124.3(15)	124.1	124.3	
03–C15	137.1(2)	137.2	135	C8–C6–C7	119.7(15)	120.2	119.8	
C15–C16	137.2(2)	137.2	134.9	C6-C7-H7	109.5	111	110.9	
C16–C17	140.4(3)	142.5	143.3	C13-C8-C9	117.1(16)	117.7	118	
C15–C19	146.9(2)	147.3	148.3	C13-C8-C6	121.7(16)	121.6	121.4	
C19-04	122.9(19)	123.5	120.6	С10-С9-Н9	119.5	120.2	119.9	
C19–N3	135.1(2)	136.9	135	C12-C11-C14	121.3(2)	121.4	121.5	
N3-N4	137.9(2)	136.4	135.8	C10-C11-C14	121.6(2)	121	120.8	
N4-C20	128.3(2)	129	126	C12-C13-C8	121.2(18)	121	120.9	
C20-C21	148.9(2)	150.9	151.1	C18-03-C-15	106.3(14)	107.3	107.7	
C20–C22	148.3(2)	148.5	149.4	C19-N3-N4	120.4(15)	120.1	122.3	
C22–C23	139.1(2)	140.1	138.8	C19-N3-H(3N)	116.4(10)	116.3	114.9	
C25–C28	150.5(2)	150.8	151	N4—N3—H(3N)	123.1(10)	123.3	122.5	
C22–C27	138.5(2)	140.5	139.3	C20-N4-N3	118.4(15)	119.6	119.3	
N3—H(3N)	91.5(17)	102.9	100.4	C16-C15-O3	109.1(16)	109.2	109.7	
N1-H(1N)	90.5(19)	102.9	100.4	C16-C15-C19	137.4(16)	137	136.6	
H(3N)· · · O2	202.7(18)	191.6	204.4	03-C15-C19	113.1(15)	112.7	113.7	
H(1N)· · · O4	208.7(19)	191.6	204.4	C15-C16-C17	106.8(16)	106.7	106.1	
N1···04	298.8(2)	293.7	303.6	$N1-H(1N)\cdots O(4)$	174.2(16)	170.7	168.8	
N3···02	292.4(2)	293.7	303.5	N3—H(3N)···O(2)	166.3(15)	170.7	168.8	

side of the path and step size  $0.3 \text{ amu}^{-0.5}$  bohr between points where geometries were optimized at each point along the reaction path. Fig. 4 roughly depicts the DFT/B3LYP estimated energy profile of the *E*/*Z*-isomers and the transition state between them.

### 4.4. Hydrogen bonding

Intermolecular and intramolecular H-bonding plays a crucial role in determining molecular shapes, properties/functions, and reactivity of the system [32]. The single crystal X-ray structure of **3** reveals the pairwise N—H $\cdots$ O intermolecular H-bonding (IHB) interactions between two molecules as it is already illustrated in Fig. 1(a) and (b).

The experimentally determined  $H \cdots O$  distances in the N1—H1 $\cdots$ O4 and N3—H3 $\cdots$ O2 moieties are 208.7(19) and 202.7 (18) pm, respectively, slightly longer than the DFT (191.6 pm) and HF (204.4 pm) computed values at the given basis set (Table 2). Obviously, both the experimental and computed distances of the



**Fig. 3.** (a) Correlation graphs of the calculated DFT and experimental molecular bond distances of the title compound. (b) Correlation graphs of calculated DFT and experimental molecular bond angles of the title compound.

#### Table 3

Total energy ( $\epsilon$  + *ZPE*); Energy of frontier orbital's ( $\epsilon_{HOMO}$ ,  $\epsilon_{LUMO}$ ), electric dipole moment ( $\mu$ ), of *E*/*Z*-geometrical isomers of the targeted compound and their transition state (*TS*) calculated at the B3LYP/6-311++G(2df,pd)//B3LYP/6-311+G(d,p) level of theory.

Isomer	$\varepsilon + ZPE_{(hartree)}$	$\epsilon_{HOMO}~(eV)$	$\epsilon_{LUMO}~(eV)$	$\mu_{(D)}$
Е	-801.845974	-6.2110	-1.7462	4.9998
TS	-801.791531	-6.0859	-1.8670	3.9198
Ζ	-801.844073	-6.4235	-1.4553	4.8302
E/E-Adduct	-1603.710958	-6.0856	-1.8281	0.0552
Z/Z-Adduct	-1603.698753	-6.0407	-1.3734	0.0001

H-bonds in the dimeric form are significantly shorter than the van der Waals radius of the  $0 \cdots H$  bond (290 pm), but they are still longer than a typical 0—H covalent distance or the sum of their covalent radii of about 130 pm [33]. The calculated N—H—O angles associated with the H-bonds, N1—H1…O4 and N3—H3…O2 were found to be slightly less than 180° and are in very good agreement with their observed counterparts (Table 2).

H-bond's energy, which can easily be attained by both experimental (vibrational spectroscopic [26,34], X-ray crystallographic [35-37] and Neutron diffraction [38,39] methods) and computational approaches, is well accepted measurable quantity employed to describe the strength of the bond.  $\Delta \varepsilon_{HB}$ , the change in energy associated with the formation of IHB, is evaluated using equation 1 as the energy difference between the HB complex and its constituent molecules, where *n* is the number of hydrogen bonds exist in the dimer,  $\varepsilon_{adduct}$  is the electronic energy of the dimer and  $\varepsilon_{monomer}$ is the electronic energy of our respective molecule [40]. In our work, both *emonomer* and *eadduct* were computed at B3LYP/ 6-311++g(2df,pd)//B3LYP/6-311+G(d,p), and then corrected to zero-point vibrational energies. The computed energies predicted H-bond energy of 5.96 kcal mol<sup>-1</sup>, giving rise to an adduct stabilization energy due to hydrogen bonding by 11.93 kcal mol<sup>-1</sup> compared to our targeted molecule.



Fig. 4. Energy profile of E/Z-geometrical isomers predicted by B3LYP/6-311+G(d,p).

$$\Delta \varepsilon_{HB} = \left(\frac{\varepsilon_{\text{adduct}} - \sum_{i} \varepsilon_{\text{monomer}}}{n}\right) \tag{1}$$

Similarly, calculations on the hypothetical *Z*-rotamer and its *Z*/ *Z*-adduct at the same level of theory DFT(B3LYP)/6-311+G(d,p) were then performed. Calculations showed that the H···O distance in each the N1—H(1N)···O4 and N3—H(3N)···O2 H-bonds is 191.9 pm, indicating that the HB-distance in the *Z*/*Z*-form is 0.3 pm longer than its corresponding DFT(B3LYP) value in the *E*/ *E*-form. Fig. 5 displays the molecular structure of the *Z*/*Z*-dimer where the pairwise hydrogen bonds and the selected atomic charges are given in red colors.

Energy calculations predicted that  $\Delta \varepsilon_{HB}$  of the Z/Z-dimer is 3.33 kcal mol<sup>-1</sup>, revealing a stabilization energy of 6.66 kcal mol<sup>-1</sup>. Accordingly, the hydrogen bond stabilization energy factor stabilized the E/E-dimer by 5.27 kcal mol<sup>-1</sup> more than its stabilization energy of the Z/Z-dimer. This finding is practically means that each single one of the H-bonding of *E*/*E*-dimer is more stable than that of the Z/Z-complex by 2.64 kcal mol<sup>-1</sup>. Since the energy difference (stabilization energy) between the two adducts is 7.66 kcal  $mol^{-1}$ , all other probable factors contribution in stabilizing the E/E-adduct over the Z/Z-adduct is 2.39 kcal mol<sup>-1</sup>. This implies that the hydrogen bonds play a crucial role in the stability of such stereoisomer-adducts. Therefore, one could rationalize that the stereo-selectivity of the reaction and thus the formation of E-rotamer and its dimeric-adduct rather than the Z-rotamer and its dimeric-adduct in the crystal structure is basically referred to hydrogen-bonding stabilization energy. This result is in great consistent with literature where the intermolecular N-H--O and N-H--N hydrogen bonds in E-acylhydrazone compounds stabilized the crystal structure whether the hydrogen bonds occur in a repeating unit to form a polymer or in a self-dimer complex as our *E*-dimer [41–45]. Nevertheless, the hydrogen bond geometrical parameters; D-H, D-H. A and D-H-A (N-H, N-H···O, and N-H-O, respectively) of our complex are slightly differ from those predicted by others, most probably, due to the type of bonding among hydrazone moieties to form a dimer rather than a polymer in the crystal lattice in addition to the influence of the attached substituent to the N=C moiety.

Mullikan distribution charges (Figs. 1b and 5) provide reasonable explanation regarding the relative weakness of the Z/Z-dimer hydrogen bonds. For instance the charges on N1, H1 and O4 are -0.270, 0.414 and -0.22, respectively, in the Z/Z-dimer (Fig. 5), while the corresponding charges on H, N and O atoms in the E/E-dimer (Fig. 1b) are -0.134, 0.419 and -0.289, respectively. As a natural result of this variety of N, H and O charges, a stronger N1…H1 bonding interaction in the Z/Z-dimer on the expense of the O4…H1



**Fig. 5.** Theoretical geometrical structure of the Z/Z-dimer, Mullikan charges (red color) and hydrogen bonds (blue color) in pm as predicted by B3LYP/6-311+G(d,p) level of theory. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

hydrogen bonding would be resulted, and thus a weaker HB interaction in the Z/Z-dimer than what is observed in case of the E/Edimer.

#### 4.5. Harmonic frequencies

Based on optimized geometries, the vibrational modes of frequency of the targeted compound **3** and its dimeric form **4** were computed at the B3LYP and HF level of theories at the assigned basis set and then compared to their corresponding observed FTIR values. Each of the included structures has proved to be minimum on the PES due to inexistence of any imaginary vibrational modes in the calculated IR spectra of each of the investigated structures. The most characteristic vibrational bands (observed and computed) that have been selected for both the E-monomer and its dimeric form along with their calculated relative intensities are listed in Table 4. The vibrational bands assignments were accomplished by using Gauss-View molecular visualization program. The vibrational modes of frequencies predicted by the DFT/B3LYP level of theory of the dimer are in better agreement with the experimental values ( $R^2 = 0.9991$ ) than those have been predicted of the *E*-monomer ( $R^2$  = 0.9086). This result is in complete accordance with the X-ray finding that the dimeric form of the titled compound is the one that is predominant in the solid state rather than the monomeric form. The relative deviation of the values predicted for the E/E-dimer is 0.74% while it is 1.31% in the case of the E-monomer. The vibrational modes predicted by the HF/6-311+G(d,p) level of theory and scaled by 0.905 are either overestimate or lower estimate the corresponding observed FT-IR values, reporting a relative deviation of 2.09%. Relative deviation is usually calculated using Eq. (2) where N is the number of vibrational modes involved in calculations, or in general, the number of times the calculations are made [46,47].

Relative deviation 
$$= \frac{1}{N} \left( \sum_{i=1}^{N} \left| \frac{\text{theoritical value} - \text{experimental value}}{\text{experimental value}} \right| \right)$$
(2)

As it is clear from Table 4 that the DFT computed N—H stretching band of the dimeric form ( $v = 3183.2 \text{ cm}^{-1}$ ) is considerably lowered than that of the monomer ( $v = 3387.0 \text{ cm}^{-1}$ ) calculated at the same level of theory, but in pretty good agreement with the FTIR finding ( $v = 3178.0 \text{ cm}^{-1}$ ). The difference between the two calculated values (203.8 cm<sup>-1</sup>) could be attributed here to the impact of the N—H···O intermolecular hydrogen bonding. The electrostatic H···O interaction weakened the N—H bond due to electronegativity difference where oxygen atom is more electronegative than nitrogen atom.

The C=O band of the E/E-dimer appeared at  $v = 1645.6 \text{ cm}^{-1}$ , 12.8 cm<sup>-1</sup> lower than the corresponding observed value and 25.5 cm<sup>-1</sup> lower than that of the monomer ( $v = 1670.8 \text{ cm}^{-1}$ ). This behavior could be referred to the dimerization that resulted as a consequence of IHB. The dimerization weakened the C=O bond, lowering the stretching force constant, which in turn negatively influenced the symmetrical stretching frequency of the carbonyl bond.

It is observed that the rocking (in-plane) and the wagging (outof-plane) bending bands have not been significantly influenced, since the rocking and wagging bands of both the title compound and its dimeric form are, nearly, equal. One of the most characteristic bending bands is the strong band; out-of-plane bending, that appears at 809.2 cm<sup>-1</sup> (in case of *E*-monomer) and 819.6 cm<sup>-1</sup> (in case of the *E*/*E*-dimer) due to para-substitution in the phenyl

#### Table 4

Comparison of the selected observed and the scaled calculated vibrational spectra and their intensities (Inten, km mol<sup>-1</sup>) of (*E*)-N<sup>-</sup>(1-*p*-tolylethylidene)furan-2-carbohydrazide and its dimeric form at the given level of theories.

Assignments of the selected bands	B3LYP/6-311+G(d,p)				HF/6-311+G(d,p)		FT-IR
	Monomer		Dimer		•		$(cm^{-1})$
	v	Inten	v	Inten	v	Inten	
	$(cm^{-1})$	km mol <sup>-1</sup>	$(cm^{-1})$	km mol <sup>-1</sup>	$(cm^{-1})$	km mol <sup>-1</sup>	
v (N1—H, N3—H) sym. str.	3387.0	18.96	3182.2	1887.3	3350.1	984.51	3178.0 vs
v (C2–H) sym. str.	3119.9	1.79	3169.6	10.0	3136.5	3.12	3175.0 m
v (Furan ring C3—H, C4—H) sym. str.	3147.2	0.10	3145.8	0.26	3104.7	0.84	3175.0 w
v (Furan ring C3—H, C4—H) asym. str.	3119.9	1.79	3119.1	5.01	3076.9	0.41	3125.0 w
v (C12–H12, C13–H13) sym. str.	3073.3	16.09	3080.0	12.15	3040.2	4.40	3085.0 m
v (C9—H9, C10—H10) asym. str.	3037.0	14.57	3075.0	2.91	3016.1	16.51	3080.0 w
v (C9–H9, C10–H10) sym. str.	3059.4	2.66	3073.5	12.15	3005.2	17.25	3075.4 w
v (C7—H7a, C7—H7b, C7—H7c) asym. str.	3022.0	9.59	2974.5	9.51	3008.8	37.45	2985.0 m
v (C14—H14a, C14—H14b, C14—H14c) asym. str.	2954.4	16.84	2953.9	20.64	2882.9	23.94	2985.0 m
v (C14—H14a, C14—H14b, C14—H14c) sym. str.	2905.1	34.64	2903.6	74.46	2864.0	55.41	2910.0 m
v (C7—H7a, C7—H7b, C7—H7c) sym. str.	2897.3	10.37	2917.3	6.36	2881.9	5.59	2911.6 w
$v$ (C=O) sym. str. + $\rho$ (N-H) rock	1659.8	581.27	1627.6	2308.0	1692.0	2303.31	1658.4 vs
$\nu$ (Ph ring C=C) sym. str. + $\beta$ (Ph ring C-H) bend	1592.3	19.80	1594.1	10.27	1631.3	10.85	1561.3 s
$v$ (C6=N2)sym. str. + $v$ (Ph ring C=C) asym. str. + $\beta$ (Ph ring C-H) bend + $\beta$ (N-H)	1572.9	1.51	1595.8	35.73	1716.7	362.70	1561.3 s
Dena (France size C. C) server start & C (France size C. U) has 1	1520.2	44.02	1500.0	114.0	1500 5	1 42 45	1501.2
V (Furan ring C=C) asym. str. + $\beta$ (Furan ring C=H) bend	1539.2	44.03	1500.0	114.0	1589.5	142.45	1501.3 \$
v (Ph ring C=C) asym. str. + $\beta$ (Ph ring C=H) bend	1526.9	1.73	1622.4	10.27	15/9.5	5.90	1507.0 m
$\rho$ (N1-H, N3-H) fock.	-	-	1632.4	2308.0	1527.0	89.44	1658.0 VS
$\rho$ (Ph ring C9–H, C10–H, C12–H, C13–H) rock.	1486.3	8.27	1510.5	85.5	1511.8	14.89	1561.2 S
$\rho$ (N1—H, N3—H) rock.	1455.2	0.81	14/2.9	2.18	1462.6	506.77	1491.2 W
v (Furan ring $C=C$ ) sym. str.	1434.6	108.16	1451.0	311.31	1441.6	311.90	14/4./ s
$\rho$ (H–C4=C3–H), $\rho$ (H–C1/=C18–H) rock.	1367.2	/1.33	13/3.2	310.17	1369.9	0.03	1383.2 s
$\beta$ (C14–H14a, C14–H14b, C14–H14c) bend	1359.3	0.34	1358.9	0.16	1361.6	0.25	1370.0 w
$\beta$ (C7–H7a, C7–H7b, C7–H7c) bend.	1350.6	17.92	1360.2	36.39	1385.4	28.43	1367.9 s
$\nu$ (C5–N1) sym. str. + $\nu$ (Furan ring C2–C3) str. + $\beta$ (Furan ring C–H) bend + $\beta$ (N–H) bend	1311.5	288.00	1337.0	386.49	1361.2	506.77	1303.1 s
$\rho$ (H-C9-C10-H), $\rho$ (H-C23-C24-H) rock.	1286.2	4.30	1286.9	7.46	1308.4	0.78	1299.5 w
v (C6–C8, C20–C22) svm. str.	1263.9	130.95	1263.9	159.68	1281.4	0.53	1270.0 s
v (C25-C28, C11-C14) sym. str.	1184.8	2.16	1223.0	0.57	1189.6	60.98	1218.0 w
$\rho$ (Furan ring C4–H. C3–H. C2–H) rock.	1197.2	4.09	1223.0	6.83	1228.0	0.03	1210.0 w
$\zeta$ (Ph ring C9-H C10-H) sciss	1163.2	3 38	1203.0	0.23	1195.2	26.62	1183.8 w
v (Furan ring C—O) asym. str. + $\beta$ (Furan ring C4—H) bend	1158.2	63.96	1158.7	84.07	1180.3	1.29	1134.0 s
$\gamma$ (N–N) sym str + $\beta$ (N–H) bend + $\beta$ (Furan ring C4–H) bend	1131.6	196.80	1129.4	234 18	1137.5	3 78	1134 0 s
$\gamma$ (Furan ring C-O) sym str + $\beta$ (Furan ring C4-H) bend + $\gamma$ (N-N) s + $\beta$ (Ph ring	1106.8	56 79	1109	25.05	1122.4	101.81	1076.3 m
C9–H) bend	110010	00110	1100	20100		101101	10,000
$\omega$ (Ph ring C—H) wag	809.2	38.79	819.6	49.03	833.7	49.58	881.6 m
ω (N1—H, N3—H) wag	-	-	779.5	118.7	767.9	98.68	817.3 m
$\tau$ (N1–H, N3–H) twist.	-	-	755.4	1.39	744.7	1.08	758.2 s
ω (C4—H + C3—H + C2—H) wag.	742.0	73.08	740.9	78.02	734.7	2.07	758.2 s
ω (N1—H, N3—H) wag.	735.8	13.84	726.6	2.31	705.9	6.43	716.1w

v :stretching frequency, sym. str.: symmetrical stretching, asym. str.: asymmetrical stretching,  $\rho$ : rocking,  $\beta$ :bending,  $\zeta$ :scissoring,  $\tau$ : twisting,  $\omega$ : wagging. The signs vs, s, m, and w stand for very strong, strong, medium and weak band intensities, respectively.

moieties according to DFT calculations. The corresponding observed band appears at 818.8 cm<sup>-1</sup>.

In general, the stretching bands of both the (E)-N'-(1-p-tolyle-thylidene)furan-2-carbohydrazide and its E/E-dimeric form are varied irregularly with no obvious trend.

## 5. Conclusion

(*E*)-N'-(1-*p*-tolylethylidene)furan-2-carbohydrazide has been synthesized and characterized by means of FTIR, NMR, MS and single crystal X-ray crystallography. It also was subjected to computational investigations utilizing both HF and DFT/B3LYP model with 6-311+G(d,p) as a basis set. The level of theories employed have produced precise correlations with the experimental findings in terms of geometrical and vibrational parameters. This verifies the appropriateness of our choice of level of theories and the suitability of the DFT/B3LYP in such calculations to a better extent than the HF model. Hydrogen bonds and energy calculations have provided insight on the reason behind the stereospecificity of the reaction; production restriction on the *E*-rotamer and thus its *E*/*E*-adduct, only. Our calculations showed that H-bonds of the E/E-adduct are more stable than those of the Z/Z-adduct by 5.27 kcal mol<sup>-1</sup>, i.e. the thermodynamic stability of E/E-dimer is implicitly explained.

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#### Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.molstruc. 2013.08.008.

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