Studii şi Cercetări Ştiinţifice
Chimie şi Inginerie Chimică, Biotehnologii, Industrie Alimentară
2020, **21** (2), pp. 195 – 206

Scientific Study & Research
Chemistry & Chemical Engineering, Biotechnology, Food Industry
ISSN 1582-540X

ORIGINAL RESEARCH PAPER

CO-CRYSTAL OF SUCCINIC ACID WITH IMIDAZOLIDIN-2-ONE: CRYSTAL STRUCTURE AND HIRSHFELD SURFACE ANALYSIS

Gerzon E. Delgado[1*], Jines E. Contreras[1], Gustavo Marroquin[2], Joazaizulfazli Jamalis[3], Hernando A. Camargo[4], José A. Henao[5]

[1]University of the Andes, Faculty of Science, Department of Chemistry, Crystallography Laboratory, Mérida 5101, Venezuela
[2]Politecnic National Institute, Higher School of Chemical Engineering and Extractive Industries, Zacatenco 07738, México City, México
[3]University of Technology Malaysia, Faculty of Science, Department of Chemistry, 81310 Johor Bahru, Johor, Malaysia
[4]Santo Tomás University, Faculty of Environmental Chemistry, Bucaramanga, Colombia
[5]Industrial University of Santander, Faculty of Sciences, School of Chemistry, Bucaramanga, Colombia

*Corresponding author: gerzon@ula.ve

Received: July, 12, 2019
Accepted: May, 04, 2020

Abstract: The co-crystal of succinic acid with imidazolidin-2-one was mechanochemically prepared and its structure was studied by powder and single-crystal X-ray diffraction. This compound crystallizes in the triclinic system with space group P-1. The molecular structure and crystal packing are stabilized mainly by intermolecular O--H···O and N--H···O hydrogen bonds interactions, forming a supramolecular assembly with bi-dimensional hydrogen bond networks along the [110] diagonal joined by $C^4_4(22)$ chains and $R^2_2(8)$ amide-acid dimers which running along the *ba* plane. These hydrogen bonds contribute to the stabilization of the crystal structure that packs with an efficiency of 69.1 % in a planar sheet structure similarly to the even diacid co-crystals containing imidazolidin-2-one. Hirshfeld surface analysis was used for visually analyzing intermolecular interactions in the crystal structure.

Keywords: *co-crystals, hydrogen bonding patterns, X-ray diffraction, Hirshfeld surface analysis*

INTRODUCTION

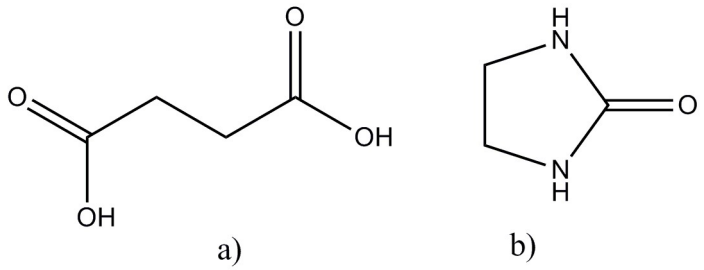
Co-crystals can be described as multicomponent crystals which formed by interactions through molecular-recognition-driven assembly processes between different molecular components that exist in single-component crystalline states [1]. The design of co-crystal based on crystal engineering offers a means for preparing new forms of Active Pharmaceutical Ingredients (API) with improved physicochemical properties (e.g. mechanical properties, melting point, hygroscopic properties, photosensitivity, solubility or bioavailability) [1 – 3].
Two good candidates for formation of supramolecular pharmaceutical co-crystals, due to their interesting noncovalent interactions such as hydrogen bonds, are dicarboxylic acids and cyclic amide compounds. Both types of compounds are used as crystal coformer in pharmaceutical field for enhancing bioavailability and stability of active pharmaceutical ingredients [4 – 7]. In this paper we consider the succinic acid (Succ) and the cyclic amide imidazilidin-2-one (Imdz). The structural formulas of both molecules are presented in Figure 1. Succinic acid is a diprotic, dicarboxylic acid, which is widely used along with its functional derivatives in food technology, pharmaceuticals and cosmetic industry [7 – 8]. Imidazolidin-2-ones and their analogues are widely found in pharmaceuticals, natural alkaloids, and other biologically active compounds [9 – 11]. For the other hand, salt or co-crystal formations can be predicted from the so-called pKa rule [ΔpKa= (pKa(acid)-pKa(base)]. When ΔpKa > 4, ionized acid-base complexes (salts) are observed exclusively and when ΔpKa < -1 non-ionized acid-base complexes (co-crystal) are observed exclusively. For acid-base complexes whose ΔpKa values lie between -1 and 4, the behaviour of "salt-cocrystal continuum" is observed [12]. The pKa value of succinic acid and imidazolidin-2-one are 4.2 and 10.1, respectively. For the Succ-Imdz complex, ΔpKa has been calculated as -5.9, which means that the formation of a co-crystal is expected.
In continuation of our ongoing study on the synthesis and structural characterization of multicomponent crystals [13 – 20], we report the crystal structure and hydrogen bond pattern analysis of the co-crystal formed between a dicarboxylic acid, succinic acid, and a cyclic amide, imidazolidin-2-one. The intermolecular hydrogen bonds in this co-crystal were also studied by means of Hirshfeld surface analysis [21] which is a new tool to study such interactions.

MATERIALS AND METHODS

All the reagents used were obtained from Sigma-Aldrich (USA) and were used without any further purification.

Synthesis

The co-crystal Succ-Imdz (**I**) was prepared by mixing equimolar amounts, 1.0 mmol, of succinic acid and 2-imidazolidinone in 10 mL of ethanol. The mixture was placed in a reflux system for 1 hour at constant temperature of 343 K. The resultant solution was then left to evaporate slowly at room temperature. Colorless crystals of (**I**) suitable for X-ray diffraction analysis were grown by slow evaporation mp 398 K.



a) b)

Figure 1. *a) Succinic acid (Succ), b) Imidazolidin-2-one (Imdz)*

X-ray powder diffraction

The X-ray powder diffraction patterns for succinic acid (Succ), imidazolidin-2-one (Imdz) and co-crystal (**I**) were collected at room temperature in a Phillips PW-1250 goniometer using monocromatized CuKα radiation. The samples were scanned from 5-55° 2θ, with a step size of 0.02° and counting time of 10s. Silicon was used as an external standard.

X-ray single-crystal crystallography

Colourless needle crystal of the title compound with dimensions 0.52 × 0.21 × 0.12 mm was used for data collection. Diffraction data were collected at 296 (2) K by ω-scan technique on a Rigaku Pilates 200K diffractometer (Rigaku, Japan) equipped with MoKα radiation (λ = 0.71073 Å). The data were corrected for Lorentz-polarization and absorption effects. The crystal structure was solved by direct methods and refined by a full-matrix least-squares calculation on F^2 using the programs SHELXS (version 2018/1) and SHELXL (version 2018/6), respectively. The Cambridge Structural Database (CSD, version 5.40, Aug. 2019) was used for structure analysis.

Hirshfeld surfaces analysis

Hirshfeld surface defines the contour of shape occupied by a molecule in the crystal structure and is constructed basing on the electron distribution calculated as the sum of spherical atom electron densities [21]. Some properties can be plotted on Hirshfeld surface: (i) d_e is the distance from the Hirshfeld surface to the nearest nucleus outside the surface, (ii) d_i is the corresponding distance to the nearest nucleus inside the surface, and (iii) d_{norm} is a normalized contact distance and is the sum of these two (di and de) normalized by the van der Waals radii quantities. Where atoms make intermolecular contacts closer than the sum of their van der Waals radii, these contacts will be highlighted in red on the d_{norm} surface. Longer contacts are blue, and contacts around the sum of van der Waals radii are white [22]. 2D fingerprint plots [23] clearly identify each type of intermolecular interactions. They not only indicate which intermolecular interactions are present, but also the relative area of the surface corresponding to each kind of interaction. The most obvious characteristics of these plots are their pseudo-mirror symmetry about the diagonal where $d_i = d_e$. The pseudo-mirror symmetry of the 2D plots is a direct consequence of the molecule having both donor and acceptor roles in the same intermolecular interaction. Hirshfeld 3D surfaces and the associated 2D

fingerprint information were generated using the program Crystal Explorer (version 2013). All bond lengths to hydrogen were automatically modified to typical standard neutron values (C-H = 1.083 Å, N-H = 1.009 Å and O-H = 0.983 Å). The electrostatic potentials were mapped on the Hirshfeld surfaces using the STO-3G basis set at the level of Hartree-Fock theory over a range of ±0.075 au.

RESULTS AND DISCUSSION

X-ray powder diffraction analysis of (I)

Figure 2 shows the X-ray powder patterns of succinic acid (Succ), 2-imidazolidinone (Imdz) and formed co-crystal (**I**). The difference in X-ray powder patterns showed in Figure indicates the formation of a new compound.

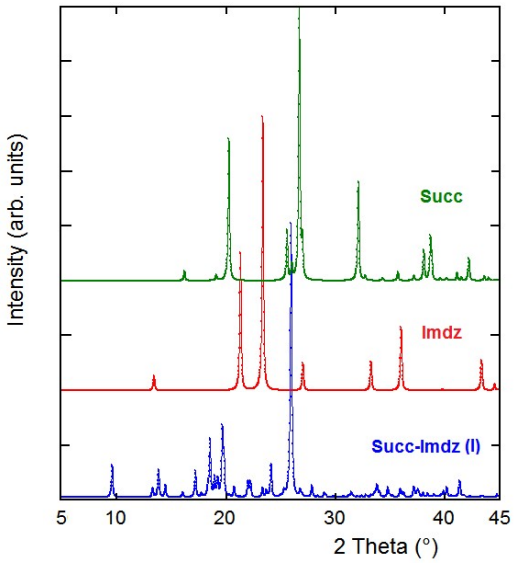


Figure 2. *X-ray powder diffraction patterns for succinic acid, imidazolidin-2-one and co-crystal (**I**)*

The 20 first measured reflections, of the powder pattern (**I**), were completely indexed using the program DICVOL (version 2004), which gave a solution in a triclinic cell with parameters *a*= 5.51 Å, *b*= 9.65 Å, *c*= 13.30 Å, α= 106.0°, β= 90.8°, γ= 96.0° in a *P*-type cell. In order to confirm the unit cell parameters, a Le Bail refinement of the whole diffraction pattern without structural was carried out using the Fullprof program (version 2018/12). Figure 3 shows a very good fit between the observed and calculated patterns.

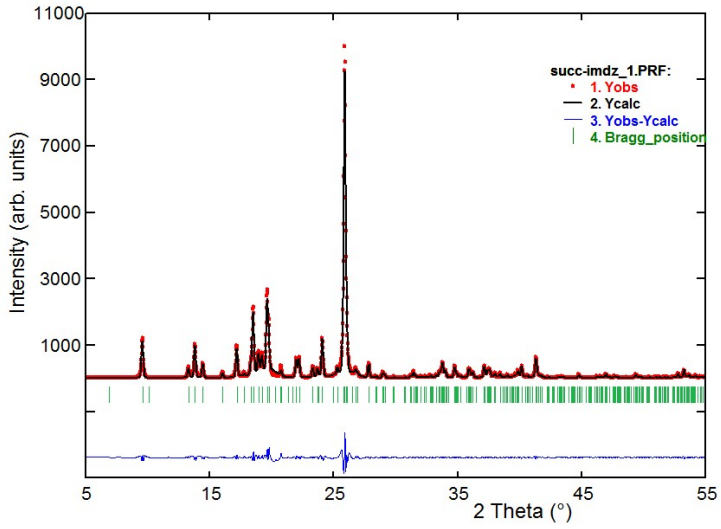


Figure 3. *Le Bail refinement plot for the co-crystal* ***(I)***

Single-crystal X-ray diffraction study of (I)

All H atoms were placed at calculated positions and treated using the riding model, with C-H distances of 0.97-0.98 Å, N-H distances of 0.86 Å, and O-H distances of 0.82 Å. The U_{iso} (H) parameters were fixed at 1.2 U_{eq} (C, N, and O). Figure 4 shows the molecular structure and the atom-labeling scheme of (**I**).

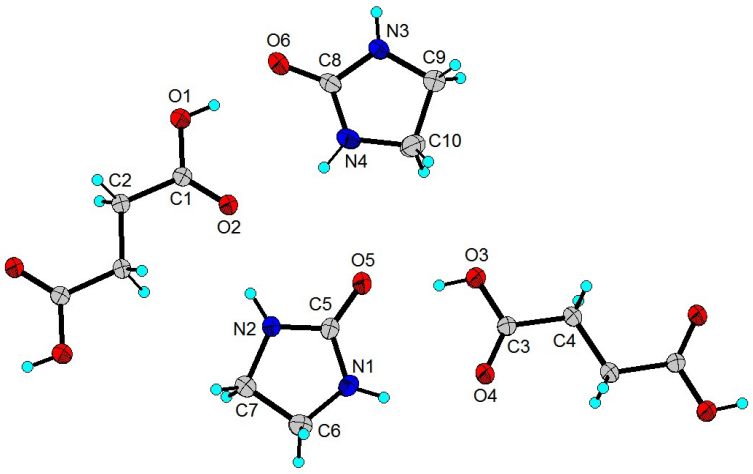


Figure 4. *The molecular structure of* ***(I)****, showing the atomic numbering scheme (displacement ellipsoids are drawn at 25 % probability level; H atoms are shown as spheres of arbitrary radii)*

Table 1 shows the crystallographic data and structure refinement parameters and Table 2 shows selected geometrical parameters for (**I**). Crystallographic data for the structure have been deposited with the Cambridge Crystallographic Data Centre (CCDC-1554342).

Table 1. *Crystal data, data collection and structure refinement of* ***(I)***

Chemical formula	$C_4H_6O_4$, 2($C_3H_6N_2O$)	**CCDC**	1554342
Formula weight	290.28	**Radiation (MoKα)**	λ = 0.71073 Å
Crystal system	Triclinic	**θ range [°]**	3.1-25.3
Space group	*P*-1 (No. 2)	**hkl range**	-6 ≤h≤ 6
***a* [Å]**	5.5556(4)		-10 ≤k≤ 11
***b* [Å]**	9.6621(7)		-16 ≤ l≤ 16
***c* [Å]**	13.3406(9)	**Reflections**	
α [°]	106.09(1)	**Collected**	9822
β [°]	90.823(9)	**Unique (Rint)**	2487 (0.053)
γ [°]	95.981(1)	**With I > 2σ(I)**	1420
V [Å^3]	683.62(9)	**Refinement method**	Full-matrix on F^2
Z	2	**Number of parameters**	183
dx [g·cm^{-3}]	1.410	**R(F^2) [I > 2σ(I)]**	0.0621
F [000]	308	**wR(F^2) [I > 2σ(I)]**	0.1735
μ [mm^{-1}]	0.117	**Goodness of fit on F^2**	1.00
Crystal size [mm]	0.52 x 0.21 x 0.12	**Max/min Δρ [e·Å^{-3}]**	0.42/-0.26

Table 2. *Selected geometrical parameters (Å, °) for* ***(I)***

C1-O1	1.302(4)	**C1-O2**	1.200(4)
C3-O3	1.290(4)	**C3-O4**	1.202(4)
C5-O5	1.254(4)	**C8-O6**	1.241(3)
N1-C5	1.333(4)	**N2-C5**	1.339(4)
N3-C8	1.349(4)	**N4-C8**	1.320(4)
O1-C1-O2	123.5(3)	**O3-C3-O4**	123.5(3)
N1-C5-N2	109.5(2)	**N3-C8-N4**	108.3(3)

A search in the Cambridge Structural Database (CSD, version 5.40, Aug. 2019) shows 10 adducts containing imidazolidin-2-one with carboxylic acids; all co-crystals. In this work, the multicomponent compound imidazolidin-2-one succinate (**I**) can be classified as a co-crystal as predicted by the pKa rule [12]. The co-crystal (**I**) crystallizes in the triclinic space group P-1. The asymmetric unit consists of two half molecules of succinic, where the other half of each molecules are generated by inversion symmetry, and two molecules of imidazolidin-2-one. The C-O distances indicated the no-ionized character of the acid groups, which show the neutrality of both molecules in the crystal.
The molecular structure and crystal packing are stabilized mainly by six intermolecular hydrogen bonds, two of type O--H···O and 4 of type N--H···O (Table 3). The intermolecular hydrogen bonds act as follows: O1---H1···O6 and N4---H4···O2 connect one succinic with a imidazolidin-2-one molecule forming a cycle with a typical $R^2_2(8)$ acid-amide heterosynthon [23]. Similarly, the hydrogen bonds O3---H3A···O6 and N1---H1···O4 form a new heterosynthon of the type $R^2_2(8)$. These rings are connected by chains $C^4_4(22)$ along the *ba* plane forming planar sheets. The two interactions N2---H2···O2 and N3---H3···O4 connect these heterosynthons with new acid molecules forming a macrocycle between 4 molecules of acid and amides, described by the graph-set motif $R^6_8(34)$. All these interactions are shows in Figure 5. Figure 6 shows as discrete sheets of molecules extend in layers along the [110] direction. These hydrogen bonds contribute to the stabilization of the crystal structure that packs with an efficiency of 69.1 %.

Table 3. *Hydrogen bonds geometry (Å, º)*

D--H···A	D--H	H···A	D···A	D--H···A	Symmetry codes
O1---H1···O6	0.82	1.740	2.547 (3)	167	-
N4---H4···O2	0.86	2.320	3.099 (4)	150	-
O3---H3A···O5	0.82	1.740	2.546 (3)	166	-
N1---H1···O4	0.86	2.300	2.912 (5)	145	-
N2---H2···O2	0.86	2.130	2.909 (3)	150	-
N3---H3···O4	0.86	2.140	2.947 (4)	156	1+x, 1+y, z

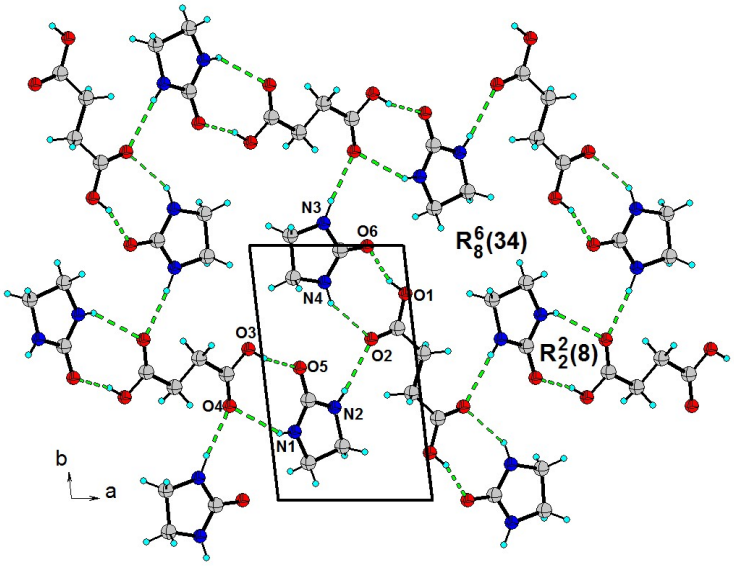


Figure 5. *A portion of the crystal packing shows all intermolecular (O--H···O) and intramolecular (N--H···O) hydrogen bonds formed in* ***(I)***

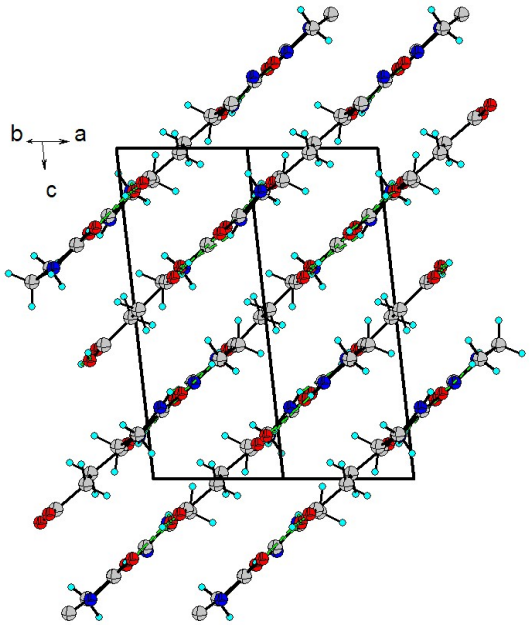


Figure 6. *A portion of the crystal packing along the [110] direction showing the dicrete sheets forming a bi-dimiensional network in the structure of* ***(I)***

Regarding similar structures, a search in the Cambridge Structural Database (CSD, version 5.40, Aug. 2019) shows 6 adducts containing succinic acid with imidazole derivatives (Table 4). Both charged (salts) and neutral (co-crystals) structures are presented with different types of structure without following a pattern of hydrogen bonds.

Table 4. *Hydrogen bond patterns in multicomponent crystals formed between succinic acid and imidazole derivatives retrieved from the CSD-database*

CSD refcode	Acid	Crystal type	Supramolecular synthons	Structure type	Ref.
VURCUH	dimethyl-H-imidazol	salt	$C^1_1(7)D^2_3(10)$	2D chain	[4]
BOTTEK01	2-methylimidazol	salt	$C^2_2(8)$	2D sheet	[5]
HOLNIG	4-methylimidazol	co-crystal	$C^2_2(8)C^2_2(14)$	2D sheet	[25]
MEQPON	imidazole	salt	$C^2_2(11)$	2D sheet	[26]
VARHUS	benzimidazole	co-crystal		3D sheet	[27]
VORCOV	2,2'-bi(H-imidazole)	co-crystal	$C^2_2(11)$	3D sheet	[28]
this work	imidazolidin-2-one	co-crystal	$R^2_2(8)C^4_4(22)R^6_8(38)$	2D sheet	(**I**)

A new CSD search revealed five organic compounds in which both imidazolidin-2-one and aliphatic dicarboxylic acid moieties are present. These results are listed in Table 5. In this case it can be seen how all these structures crystallize in neutral form as co-crystals, what was expected because the ΔpKa values. In all structures heterosynthons of the type $R^2_2(8)$ are formed.

Table 5. *Hydrogen bond patterns in imidazolidin-2-one with aliphatic dicarboxylic acids (HOO-(CH_2)n-COOH m(n+2)=2-7, retrieved from the CSD-database.*

CSD refcode	m= (n+2)	Acid: amide	Acid	ΔpKa	Supramolecular synthons	Structure type	Ref.
UHADAJ	2	1:2	oxalic	-8.8	$R^2_2(8)C^2_2(8)R^6_8(30)$	planar sheet	[4]
UHADOX	3	1:1	malonic	-7.3	$R^2_2(8)C^4_4(18)$	chain	[4]
this work	4	1:2	succinic	-5.9	$R^2_2(8)C^4_4(22)R^6_8(34)$	planar sheet	(**I**)
UHADUD	5	1:3	glutaric	-5.8	$R^2_2(8)C^2_2(12)$	chain	[5]
UHADIR	6	1:2	adipic	-5.7	$R^2_2(8)C^2_2(13)R^6_8(38)$	planar sheet	[5]
UHAFAL	7	1:1	pimelic	-5.6	$R^2_2(8)C^4_4(28)$	chain	[5]

The even adducts with dicarboxylic acids (m= 2, 4, 6) crystallized in an amide (1:2) acid ratio. For these compounds amide-acid-amide interactions produce rings which are connected by chains forming planar sheet structures. Also they form, macrocycles between acid and amide molecules, described by the graph-set motif $R^6_8(30)$, $R^6_8(34)$ and $R^6_8(38)$ for m= 2, 4, 6, respectively. Figure 7 shows these trends.
The odd adducts with dicarboxylic acids (m= 3, 5, 7) crystallized in an amide: acid ratio of 1:1 and 1:3 with chains of alternate acid and amide molecules, forming in all cases chain structures.

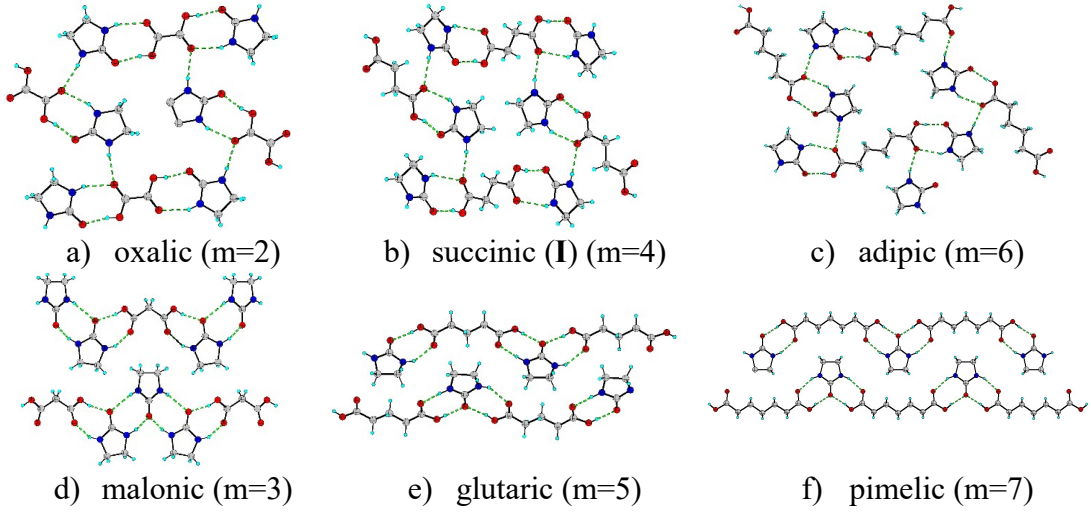


Figure 7. *Planar sheet structures (even aliphatic dicarboxylic acids) vs chain structures (odd aliphatic dicarboxylic acids)*

Hirshfeld surfaces analysis

In order to visualize the intercontacts in the molecular structure, the Hirshfeld surface analysis was carried out for the title molecule. The Hirshfeld surface of (**I**) mapped over a d_{norm} range of -0.5 to 1.5 Å is illustrated in Figure 8. The dominant interaction between the amino hydrogen and carboxylic oxygen atoms in (**I**) can be seen as bright red spots. The d_{norm} surfaces plot of (**I**) is consistent with the analysis of the packing patterns as discussed in the X-ray crystal structure analysis.
The combination of d_e and d_i in the form of two-dimensional fingerprint plot gives the summary of intermolecular contacts in the crystal lattice. The fingerprint plots of the co-crystal imidazolidin-2-one succinate (**I**) are shown in Figure 9. It is evident from the fingerprint plots of this compound that O···H (43.1 %) and H···H (40.2 %) intercontacts play a central crucial role in the stabilization of molecules in the crystal structure.

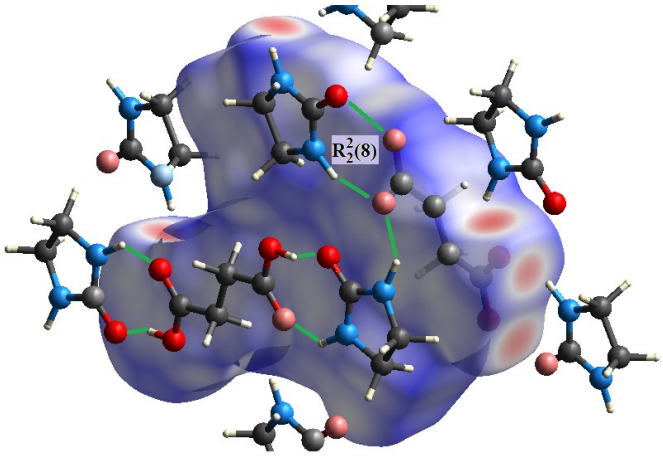


Figure 8. *Hirshfeld surface mapped with d_{norm} for (**I**) visualizing the intercontacts of both molecules in co-crystal*

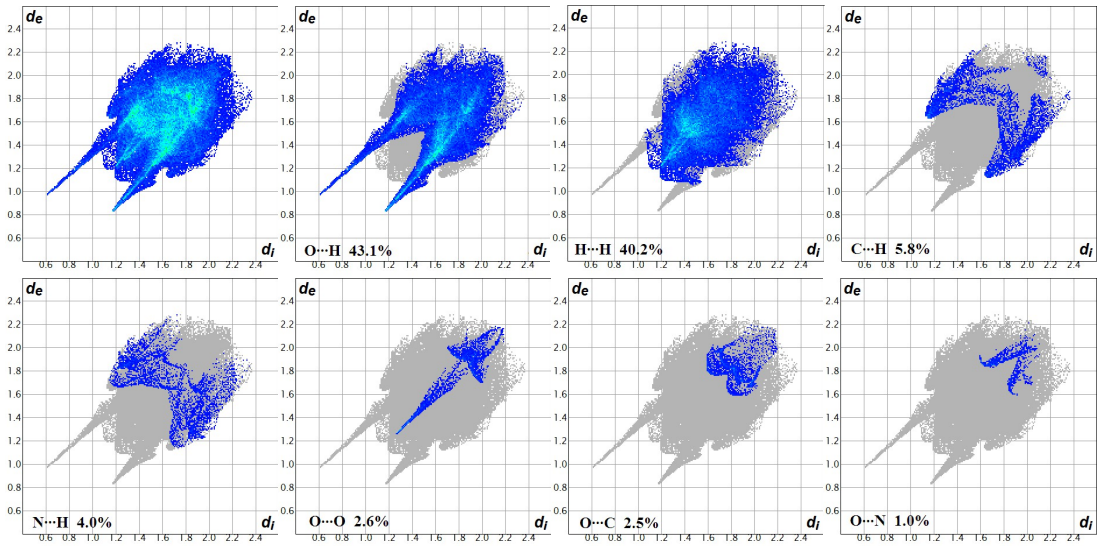


Figure 9. *2D fingerprints for* ***(I)***

CONCLUSIONS

The co-crystal formed between succinic acid and imidazolidin-2-one was synthesised mechanochemically and its structure was solved based on the single-crystal X-ray data. The crystal belongs to triclinic system. Crystal structure results and Hirshfeld surface analysis shows how the supramolecular structure of (**I**) is built up from self-assembly of molecules via O---H···O and N---H···O interactions, which contribute to the stabilization of the crystal structure that packs with an efficiency of 69.1 % in a planar sheet structure fashion.

ACKNOWLEDGEMENTS

This work was supported by CDCHT-ULA (grant C-1972-16-08-B), FONACIT (grant LAB-97000821).

REFERENCES

1. Desiraju, G.R.: Crystal and co-crystal, *CrystEngComm*, **2003**, **5** (82), 466-467;
2. Aakeröy, C.B., Salmon, D.J.: Building co-crystals with molecular sense and supramolecular sensibility, *CrystEngComm*, **2005**, **7** (72), 439-448;
3. Vishweshwar, P., McMahon, J.A., Bis, J.A., Zaworotko, M.J.: Pharmaceutical co-crystals, *Journal of Pharmaceutical Sciences*, **2006**, **95** (3), 499-516;
4. Callear, S.K., Hursthouse, M.B., Threlfall, T.L.: Co-crystallisation of organic α,ω-dicarboxylic acids with the cyclic amides 2-pyrrolidinone and 2-imidazolidinone, *CrystEngComm*, **2009**, **11** (8), 1609-1614;
5. Callear, S.K., Hursthouse, M.B., Threlfall, T.L.: A systematic study of the crystallization products of a series of dicarboxylic acids with imidazole derivatives, *CrystEngComm*, **2010**, **12** (3), 898-908.

6. Patel, J.R., Carlton, R.A., Needham, T.E., Chichester, C.O., Vogt, F.G.: Preparation, structural analysis, and properties of tenoxicam cocrystals, *International Journal of Pharmaceutics*, **2012**, **436** (1-2), 685-706;
7. Lin, H.L., Wu, T.K., Lin, S.Y.: Screening and characterization of cocrystal formation of metaxalone with short-chain dicarboxylic acids induced by solvent-assisted grinding approach, *Thermochimica Acta*, **2014**, **575** (1), 313-321;
8. Fulias¸ A., Vlase, G., Vlase, T., Suta, L.M., Soica, C., Ledeti, I.: Screening and characterization of cocrystal formation between carbamazepine and succinic acid, *Journal of Thermal Analysis and Calorimetry*, **2015**, **121** (3), 1081-1086;
9. Lee, K.C., Venkateswararao, E., Sharma, V.K., Jung, S.H.: Investigation of amino acid conjugates of (S)-1-[1-(4-aminobenzoyl)-2,3-dihydro-1H-indol-6-sulfonyl]-4-phenyl-imidazolidin-2-one as water soluble anticancer prodrugs, *European Journal of Medicinal Chemistry*, **2014**, **80** (6), 439-446;
10. Yousry A. Ammar, Y.A., El-Sharief , M.A.M., Ghorab, M.M., Mohamed, Y.A., Ragab, A., Abbas, S.Y.: New imidazolidineiminothione, imidazolidin-2-one and imidazoquinoxaline derivatives: Synthesis and evaluation of antibacterial and antifungal activities, *Current Organic Synthesis*, **2016**, **13** (3), 466-475;
11. Casnati, A., Motti, E., Mancuso, R., Gabriele, B., Della Ca, N.: Recent advances in the catalytic synthesis of imidazolidin-2-ones and benzimidazolidin-2-ones, *Catalysts*, **2019**, **9** (1), 28(44);
12. Cruz-Cabeza, A.J.: Acid-base crystalline complexes and the pKa rule, *CrystEngComm*, **2012**, **14** (20), 6362-6365;
13. Belandria, L.M., Mora, A.J., Delgado, G.E., Briceño, A.: 4-Carboxypiperidinium 1-carboxycyclobutane-1-carboxylate, *Acta Crystallographica Section C: Structural Chemistry*, **2012**, **C68** (2), 088-091;
14. Mora, A.J., Belandria, L.M., Ávila, E.E., Seijas, L.E., Delgado, G.E., Miró, A., Almeida, R., Brunelli, M., Fitch, A.N.: Investigating the stability of double head to tail dimers and ribbons in multicomponent crystals of *cis*-4-aminocyclohexanecarboxilic acid with water and oxalic acid, *Crystal Growth & Design*, **2013**, **13** (5), 1849-1860;
15. Belandria, L.M., Mora, A.J., González, T., Delgado, G.E.; Hydrogen bond patterns in 3-carboxypiperidinium semi-oxalate monohydrate, *Avances en Química*, **2013**, **8** (1), 3-7;
16. Delgado, G.E., Varela, K.N., Mora, A.J., Bruno-Colmenárez, J., Atencio, R.: Synthesis, thermal studies, spectroscopy characterization and crystal structure of nicotinamidium oxamate, *Molecular Crystals and Liquid Crystals*, **2015**, **609** (1), 218-227;
17. Chacón, C., Bruno-Colmenárez, J., Jamalis, J., Delgado, G.E.: Synthesis, thermal studies and crystal structure of 4-aminopyridinium semi-oxalate hemihydrate, *Scientific Study & Research: Chemistry & Chemical Engineering, Biotechnology, Food Industry*, **2017**, **18** (2), 111-119;
18. Delgado, G.E., Belandria, L.M., Mora, A.J., Bruno, J., Marroquín, G.: Synthesis and structural characterization of the 1:1 proton transfer salt of malonic acid with p-chloroaniline, *Tchê Química Journal*, **2017**, **14** (28), 66-71;
19. Mora, A.J., Belandria, L.M., Delgado, G.E., Seijas, L.E., Lunar, A., Almeida, R.: Non-covalent interactions in the multicomponent crystal of 1-aminocyclopentane carboxylic acid, oxalic acid and water: A crystallographic and theoretical approach, *Acta Crystallographica Section B: Structural Science*, **2017**, **73** (10), 968-980;
20. Flores, J.A., Delgado, G.E., Jamalis, J., Henao, J.A.: Molecular complex 1:1 of malonic acid with 2-aminopyridine: Crystal structure and Hirshfeld surface analysis, *Tchê Química Journal*, **2019**, **16** (31), 347-352;
21. Spackman, M.A., Jayatilaka, D.: Hirshfeld surface analysis, *CrystEngComm*, **2009**, **11** (1), 19-32;
22. McKinnon, J.J., Jayatilaka, D., Spackman, M.A.: Towards quantitative analysis of intermolecular interactions with Hirshfeld surfaces, *Chemical Communications*, **2007**, **37** (1), 3814-3816;
23. Spackman, M.A., McKinnon, J.J.: Fingerprinting intermolecular interactions in molecular crystals, *CrystEngComm*, **2002**, **4** (66), 378-392.
24. Etter, M.C.: Encoding and decoding hydrogen-bond patterns of organic compounds, *Accounts of Chemical Research,* **1990**, **23** (4), 120-126.
25. Du, G., Liu, Z., Chu, Q., Li, Z. Zhang, S.: bis(4-methylimidazolium) succinate succinic acid solvate, *Acta Crystallographica Section E: Crystallographic Communication*, **2009**, **65** (3), o607-o608;

26. MacDonald, J.C., Dorrestein, P.C., Pilley, M.M. Design of supramolecular layers via self-assembly of imidazole and carboxylic acids, *Crystal Growth & Design*, **2001**, **1** (1), 29-38;
27. Trivedi, D.R., Ballabh, A., Dastidar, P. Supramolecular assemblies in salts and co-crystals of imidazoles with dicarboxylic acids, *CrystEngComm*, **2003**, **5** (64), 358-367;
28. Gao, X.L., Lu, L.P., Zhu, M.L. The crucial role of C--H···O and C=O···π interactions in the building of three-dimensional structures of dicarboxylic acid–biimidazole compounds, *Acta Crystallographica Section C: Crystal Structure Communications*, **2009**, **65** (4), 123-127.