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Molecules to supermolecules and self assembly: a study of some cocrystals of cyanuric acid

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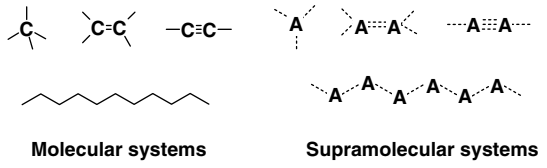
Abstract

The preparation and structure elucidation of cocrystals **1a**, **1b**, **2a**– **4a**, formed from cyanuric acid (**CA**) and the aza-donor compounds 4,7-phenanthroline, 1,7-phenanthroline, phenazine and 1,3-bis(4-pyridyl)propane, respectively, have been reported. While **CA** forms different types of self-assembling modes—monomers (**1a**), dimers (**1b** and **4a**) and infinite tapes (**2a** and **3a**)—the recognition of the constituents, however, is through a triple hydrogen-bonding pattern, consisting of an N–H···N and two C–H···O hydrogen bonds, except in **4a**.

The ability of carbon to use its valency effectively yielding different types of bonding patterns, well defined by geometrical parameters, through hybridization, is fundamental in the studies of molecular synthesis, which leads to the preparation of numerous organic compounds.[1]

Considering the analogy given by Lehn[2] that molecules and intermolecular interactions are for supramolecular synthesis as atoms and bonds are for molecular synthesis,[1] each molecular entity can provide different types of supramolecular assemblies utilizing its molecular recognition capabilities.[3] For example, an entity 'A' as shown in Scheme 1, with three recognition sites, can yield different types of assemblies. Such features are well reflected in the numerous molecular complexes reported in the recent literature, with exotic structural chemistry governed by intermolecular interactions[4] and coordination bonds.[5] In particular, the elegant structures with different types of networks in the form of host–guest assemblies, lamellar sheets, etc., formed by symmetrically substituted molecules such as trimesic acid,[6] pyromellitic acid [7] and trithiocyanuric acid [8] are superb examples not only of marvelous structural features but also for aiding and strengthening fundamental concepts of supramolecular synthesis. Some of the representative structures are shown in Figure 1. Cyanuric acid, **CA**, is another fascinating molecule, which yields a variety of structures,[9] the 'rosette' formed with melamine, being a unique example,[9c] which has been evaluated, very recently, for its bioactivity.[9k]



Scheme 1.

In the majority of cases, in general, the co-crystallizing entities form heteromeric aggregates. However, unlike many other substrates, the recognition pattern of **CA** in its complexes (except in the rosette structure), and so far known in the literature,[9] is quite monotonous with infinite homomeric molecular tapes formed through N–H···O hydrogen bonds, as shown in Scheme 2, including in its coordination assemblies.[10]

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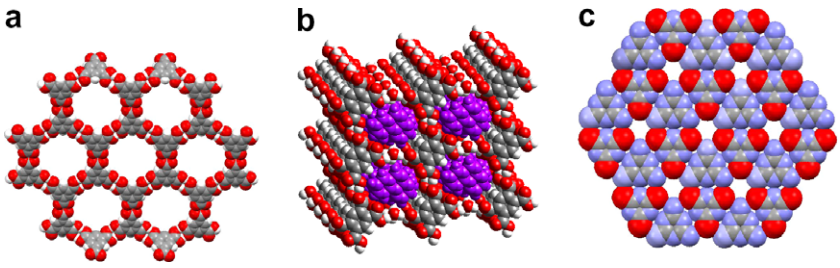
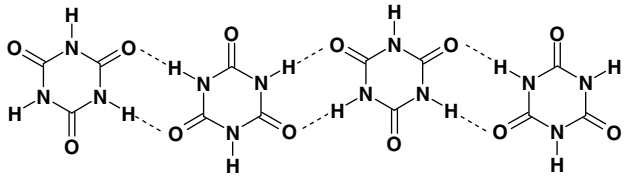


Fig. 1. (a) A hexagonal honeycomb network with cavities in a two-dimensional arrangement in trimesic acid. (b) A square-network mediated channel structure in the molecular complex of pyromellitic acid with various phenanthrolines. (c) The rosette structure of the molecular adduct of cyanuric acid and melamine.



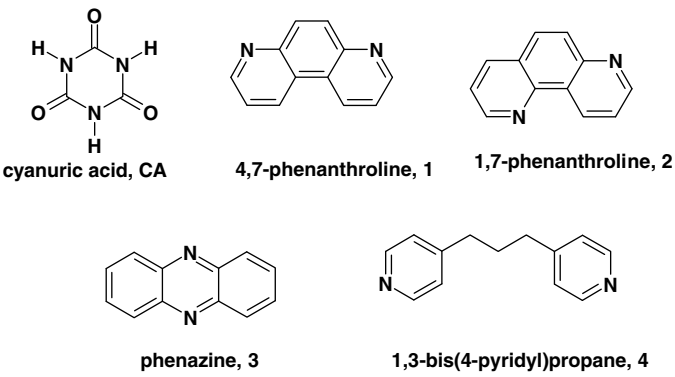
Scheme 2. Molecular tapes formed by **CA** molecules.

Since the number of molecular complexes of **CA** is limited and many of them are solvates[9a] rather than true molecular complexes, perhaps other possible hydrogen-bonded networks of **CA** have not been found yet. This is despite the fact that **CA** has the ability to form different types of hydrogen-bonding networks, as in other supramolecular reagents such as trimesic acid.[6] Hence, the study of a large number of cocrystals to understand and analyze the supramolecular nature of **CA** is required. For this purpose, we have prepared several molecular complexes of **CA** with different aza-donor compounds taking into account the availability of the symmetrically substituted donor groups (–N–H) on **CA**, which can interact with pyridyl –N atoms. Thus, complexes, **1a**, **1b** and **2a**– **4a**, obtained by co-crystallization of **CA** with 4,7-phenanthroline, 1,7-phenanthroline, phenazine and 1,3-bis(4-pyridyl)propane, from an appropriate solvent (see Chart 1), are discussed herein for their supramolecular features with respect to the ability of **CA** to yield different hydrogen-bonding networks.

Co-crystallization of **CA** and **1** from a CH_3OH solution gave single crystals of complex, **1a**, that were suitable for structure determination by X-ray diffraction methods.[11] X-ray analysis revealed that the solvent of crystallization was also embedded in the crystal lattice along with 1:1 ratio of **CA** and **1**, as shown in Figure 2. In three-dimensions, the constituent molecules (**CA** and **1**) arrange to yield a channel structure (see Fig. 2b) with the channels being occupied by molecules of CH_3OH.

The molecular packing analysis showed that **CA** and molecules of **1** interact through a triple hydrogen-bonding pattern (see Fig. 2c), comprising an N–H···N (H···N, 1.98 Å) and two C–H···O hydrogen bonds[12] (H···O, 2.39 and 2.71 Å). Each of three such adjacent supermolecules interacts through a cyclic hydrogen-bonding pattern of N–H···N and C–H···O hydrogen bonds, with H···N and H···O distances being 1.96 and 2.69 Å, respectively.

These trimers are further held together by a single C–H···O hydrogen bond (H···O, 2.43 Å), creating a cavity, in which two CH_3OH molecules reside. These cavities align to yield channels in three-dimensional packing. Thus, in the cocrystals of **1a**, molecules of **CA** exist only in heteromeric form, unlike in the majority of its complexes reported in the literature,[9] wherein **CA** forms only homomeric interactions. Further, it seems that the CH_3OH molecules are strongly bound to the network as loss of solvent molecules was not be observed in thermogravimetric experiments up to 200 °C, suggesting the influence of the solvent for the



reactants	product
CA + 1	**1a.CH_3OH**
CA + 1	**1b.H_2O**
CA + 2	**2a**
CA + 3	**3a**
CA + 4	**4a**

Chart 1.

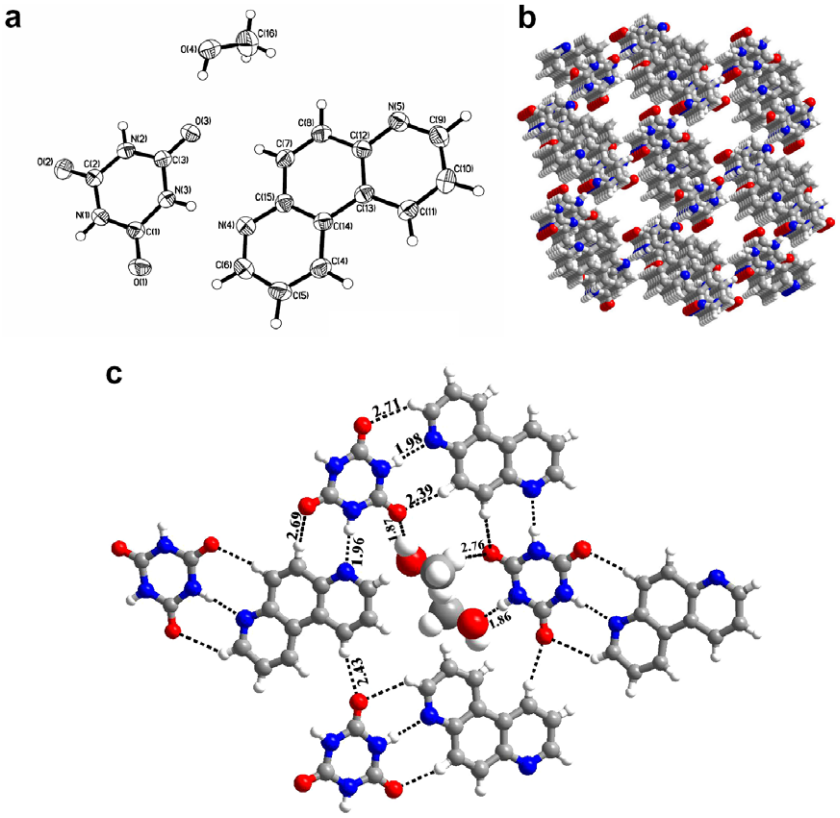


Fig. 2. (a) ORTEP structure of the asymmetric unit in the molecular complex, **1a**. (b) Three-dimensional arrangement of molecules of **CA** and **1** (viewed down *a*-axis) forming channel structure (solvent molecules in the channels have been omitted for clarity). (c) H-bonded network in two-dimensions with cavities being occupied by CH_3OH molecules.

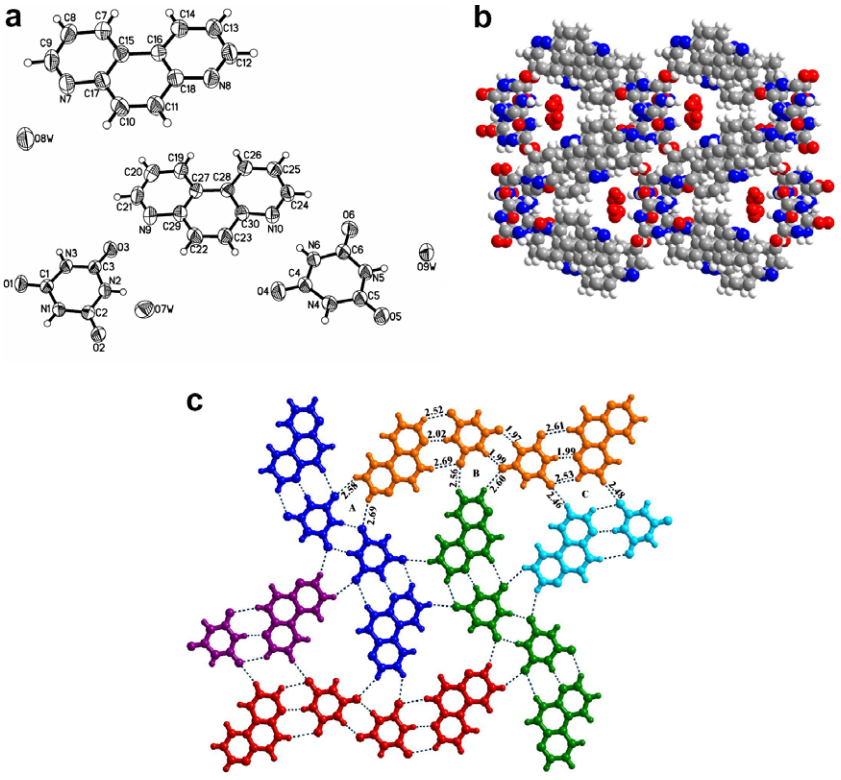


Fig. 3. (a) ORTEP structure of the contents in the asymmetric unit in the complex, **1b**. (b) Three-dimensional arrangement of the molecules in the crystal structure of **1b**, with channels being occupied by water molecules. (c) Intermolecular interactions between **CA** and molecules of **1**.

observed topology in the assembly. This was further confirmed from the observation of totally different network in the cocrystals, **1b**, of **CA** and **1** obtained from water, wherein water molecules were also present in the crystal lattice.[11]

In **1b**, the composition of the constituents was in the ratio of 2:2:3, as shown in Figure 3a. In the three-dimensional arrangement, a channel structure, as observed in **1a**, was formed, with channels being occupied by water molecules (Fig. 3b). However, the arrangement of the molecules around the channels and also in two-dimensions was quite different in **1a** and **1b**, although the basic recognition unit remained the same—a triplet hydrogen-bond pattern with N–H···N (H···N, 2.02 Å) and C–H···O (H···O, 2.52 and 2.69 Å) hydrogen bonds. Two such adjacent supermolecules are held together by cyclic N–H···O hydrogen bonds (H···O, 1.97 and 1.99 Å) formed between the **CA** molecules, leading to the formation of dimers of **CA**.

Thus, a quartet assembly of two molecules of each **CA** and **1** is formed. Such adjacent quartets (shown in different colours in Fig. 3c) are further held together by different types of C–H···O hydrogen bonds constituting void space. As a result, a channel structure is obtained through three-dimensional packing with water molecules occupying the channels (see Fig. 3b). The water molecules exist within the channels as chains (see Fig. 4).

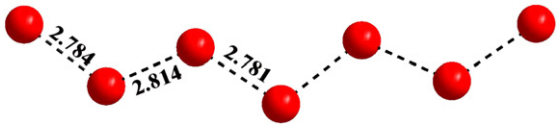


Fig. 4. O···O Interactions in the water chains formed in the crystal structure, **1b**.

Thus, from **1a** to **1b**, we observe the transformation of **CA** molecules from monomers to dimers and significantly, such dimers are not known in the other crystal structures of complexes/adducts of **CA**.

In contrast, when **1** was replaced by 1,7-phenanthroline, **2**, molecular complex, **2a**,[11] was obtained, with a triple hydrogen-bonding pattern between **CA** and **2**, as observed in **1a** and **1b**, but with an entirely different assembly in both three-dimensional arrangement and molecular arrangement within the sheets. The packing of the molecules is shown in Figure 5.

Within a typical sheet, **CA** molecules in **2a**, exist as infinite tapes with the adjacent molecules being held together by cyclic N–H···O hydrogen bonds. The H···O distances are 1.79 and 1.98 Å. Each molecule in this chain is attached to a molecule of **2** through three hydrogen bonds, one N–H···N (H···N, 1.85 Å) and two C–H···O (H···O, 2.29 and 2.81 Å) similar to the interactions observed in **1a** and **1b**.

Thus, a band of molecules of **2**, intercalated by a molecular tape of **CA** is formed, which is further arranged in such a manner that each **CA** tape is intercepted by two layers of molecules of **2** as shown in Figure 5b.

The situation is similar even in the co-crystallization experiments of **CA** with phenazine, **3**, except for the fact that in the resultant molecular adduct, **3a**,[11] molecules of **CA** and **3** are arranged, alternately, within a sheet structure, as shown in Figure 5c. However, when the co-crystallization was carried out with 1,3-bis(4-pyridyl)propane, **4**, the structure obtained for the cocrystals, **4a**,[11] exhibited features similar to the structure of **1b** forming dimers of **CA** as described below.

In the structure of **4a**, primary recognition between **CA** and **4** is established through N–H···N hydrogen bonding

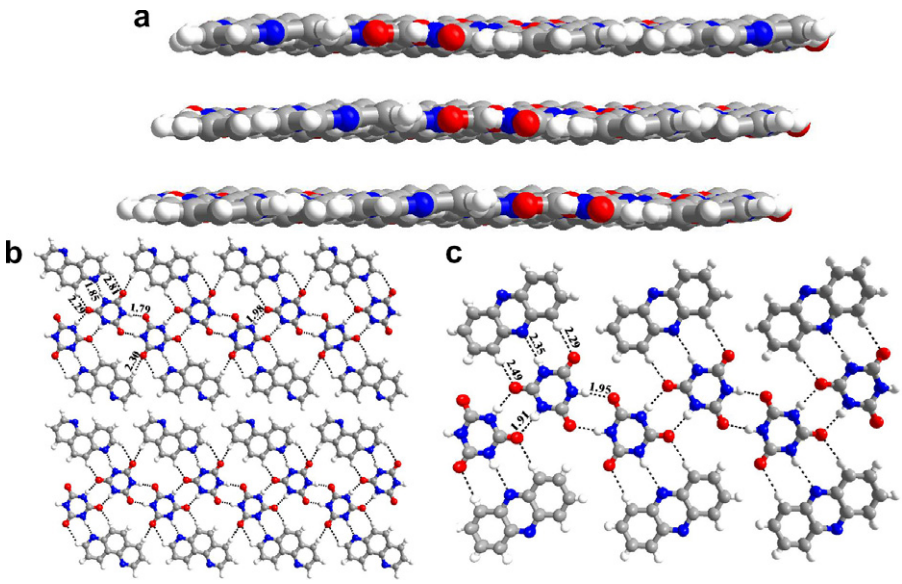


Fig. 5. (a) Stacked sheet structure in the crystal structure of adduct, **2a**. (b) Arrangement of the molecules of **CA** and **2** in a typical two-dimensional sheet structure of complex, **2a**. (c) Arrangement of the molecules of **CA** and **3** in a two-dimensional sheet of complex, **3a**.

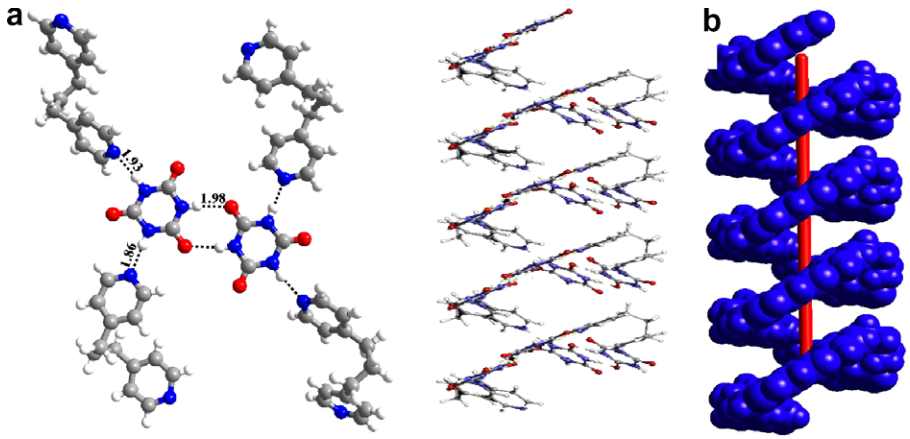


Fig. 6. (a) Recognition features in the molecular complex, **4a**. Helical arrangement of molecules through hydrogen bonds (b) in ball and stick mode and in a close packing pattern.

with the H···N bonds being 1.86 and 1.93 Å, as shown in Figure 6a. Further, the adjacent units are held together by cyclic N–H···O hydrogen bonds (H···O, 1.98 Å) formed between **CA** molecules, leading to the formation of dimers of **CA**. In addition, unlike in **1a** and **1b**, the interaction between **CA** and **4** is only through a single N–H···N hydrogen bond rather than triplet hydrogen bonds, and also, interestingly, the assembly forms a helical structure in three-dimensional arrangement (see Fig. 6b), perhaps being facilitated by the flexible geometry of **4**.

Thus, through the complexes, **1a**, **1b** and **2a**– **4a**, we are able to explore the different types of hydrogen-bonding patterns of **CA**, which indeed directed variations in the three-dimensional arrangement in these complexes. This study also signifies the importance of the combinatorial-type synthesis of supramolecular assemblies of each molecular entity to unravel the many possible structural features and molecular recognition features. Such information would be quite useful in further target-oriented supramolecular synthesis and also in many computational studies concerning intermolecular interactions such as molecular simulations for polymorph predictions and crystal structure predictions.

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Supplementary data

Crystallographic Information Files (CIFs), tables of complete crystal data and intermolecular interactions, ORTEPs of **2a**–**4a** and expanded Figures of 5c. Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.tetlet.2008.03.143.

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11. Crystal data. (**1a**) $C_{16}H_{15}N_5O_4$, monoclinic, $P2_1/n$, $a = 7.199(3)$, $b = 17.072(2)$, $c = 12.839(1)$ Å, $\beta = 94.00(2)°$, $R = 0.0449$, CCDC 668944. (**1b**) $C_{30}H_{28}N_{10}O_9$, monoclinic, $P2_1/c$, $a = 13.251(2)$, $b = 17.228(2)$, $c = 14.042(2)$ Å, $\beta = 102.49(3)°$, $R = 0.0535$, CCDC 668945. (**2a**) $C_{15}H_{11}N_5O_3$, triclinic, $P\bar{1}$, $a = 4.816(2)$ $b = 10.434(4)$ $c = 14.040(6)$ Å, $\alpha = 81.07(2)$, $\beta = 89.49(1)$, $\gamma = 77.72(4)°$, $R = 0.0827$, CCDC 668948. (**3a**) $C_{18}H_{14}N_8O_6$, triclinic, $P\bar{1}$, $a = 5.989(1)$, $b = 7.366(1)$, $c = 10.408(2)$ Å, $\alpha = 87.14(1)$, $\beta = 86.00(1)$, $\gamma = 84.73(3)°$, $R = 0.0638$, CCDC 668947. (**4a**) $C_{16}H_{17}N_5O_3$, monoclinic, $P2_1/c$, $a = 6.666(1)$, $b = 8.110(1)$, $c = 28.824(3)$ Å, $\beta = 90.19(2)°$, $R = 0.0495$, CCDC 668946.
12. For the characteristics and structure directing features of C–H···O hydrogen bonds, see: Desiraju, G. R.; Steiner, T. *The Weak Hydrogen Bond in Structural Chemistry and Biology*; Oxford University Press: Oxford, 1999.