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Sophia J. Makowski, Michael Hörmannsdorfer, Wolfgang Schnick. K₃[C₃N₃(COO)₃] · 2 H₂O - Crystal Structure of a New Alkali Derivative of the Multidentate Ligand Triazine Tricarboxylate. *Journal of Inorganic and General Chemistry / Zeitschrift für anorganische und allgemeine Chemie*, 2010, 636 (15), pp.2584. 10.1002/zaac.201000245 . hal-00599882

HAL Id: hal-00599882

<https://hal.science/hal-00599882>

Submitted on 11 Jun 2011

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Journal:	<i>Zeitschrift für Anorganische und Allgemeine Chemie</i>
Manuscript ID:	zaac.201000245.R1
Wiley - Manuscript type:	Article
Date Submitted by the Author:	19-Jul-2010
Complete List of Authors:	Makowski, Sophia J.; LMU Munich, Chemistry Hörmannsdorfer, Michael; LMU Munich, Chemistry Schnick, Wolfgang; LMU Munich, Chemistry
Keywords:	s-Triazine, Potassium, Carboxylate ligand, Crystal structure

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$K_3[C_3N_3(COO)_3] \cdot 2 H_2O$ – Crystal Structure of a New Alkali Derivative of the Multidentate Ligand Triazine Tricarboxylate

Sophia J. Makowski, Michael Hörmannsdorfer and Wolfgang Schnick*

Keywords: *s*-Triazine; Potassium; Carboxylate ligands; Crystal structure

Abstract. Potassium-1,3,5-triazine-2,4,6-tricarboxylate dihydrate $K_3[C_3N_3(COO)_3] \cdot 2 H_2O$ was obtained by saponification of the respective ethyl ester in aqueous solution under mild conditions and subsequent crystallization at 4 °C. The crystal structure of the molecular salt was elucidated by single-crystal X-ray diffraction ($P \bar{1}$, $a = 6.9663(14)$, $b = 17.485(3)$, $c = 17.560(3)$ pm, $\alpha = 119.73(3)$, $\beta = 91.96(3)$, $\gamma = 93.84(3)^\circ$, $V = 1847.6(6) \cdot 10^6$ pm³, $Z = 6$, $T = 200$ K). Perpendicular to [100] the triazine tricarboxylate and potassium ions are arranged in layers alternating with layers of crystal water molecules. Two thirds of the triazine tricarboxylate units form hexagonal channels being filled with the remaining triazine tricarboxylate molecules. $K_3[C_3N_3(COO)_3] \cdot 2 H_2O$ was additionally investigated by means of FTIR spectroscopy, TG and DTA measurements.

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Introduction

Research in the field of carbon nitrides is mainly focused on the synthesis of two- and three-dimensional networks which can serve as functional materials for a wide field of applications such as catalysis or optoelectronic uses [1-3]. A common approach towards multidimensional networks is the pyrolysis of *s*-triazine (C_3N_3) or *s*-heptazine (C_6N_7) based precursors to induce condensation and thereby generating covalently bound products. A variety of precursors with different functional groups has been utilized in this regard (cf. Scheme 1, **1a-d** and **2a-d**) [4-8].

In general, molecules containing residues that are bound to the *s*-triazine or *s*-heptazine core via C-C bonds (cf. Scheme 1, **1e-f** and **2e-f**) are adverse in this regard. This is due to the strength of the C-C bonds impeding a successful condensation. Furthermore, the synthesis of carbon nitrides necessitates an alternating sequence of carbon and nitrogen both in the precursor and in the resulting polymeric network. Even though such compounds are no suitable precursors for the synthesis of covalently bound true carbon nitrides by condensation reactions they can be regarded as promising linkers in coordination polymers. Metal organic frameworks (MOFs) have been extensively studied in the last years due to their potential applications, e. g. as materials for ion exchange, separation, catalysis or gas storage [9,10]. While numerous MOFs are known in which a hydrocarbon cycle functionalized with several carboxylate groups, e. g. trimesic acid **3** (cf. Scheme 2) [11-13], serves as the linker between inorganic centers the analog *s*-triazine or *s*-heptazine compounds **1f** and **2f** have not been employed for this purpose so far.

In known *s*-triazine and *s*-heptazine based linkers such as *s*-triazine-2,4,6-tris(4-pyridyl) **4** [14,15], *s*-triazine-2,4,6-triyl-tribenzoic acid **5** [16-20] or *s*-heptazine-2,5,8-triyl-tribenzoic acid **6** [20,21] (cf. Scheme 2) the *s*-triazine or *s*-heptazine cores, respectively, only provide the threefold symmetry but do not contribute to metal coordination. In contrast in **1f** and **2f** both the carboxylate groups and the nitrogen atoms of the ring can be regarded as coordination positions.

The *s*-heptazine compound **2f** has not been mentioned in the literature so far whereas the synthesis of **1f** by a multistep reaction via the respective ethyl ester and potassium salt has already been described over 50 years ago [22]. However, no structural characterization of the product or any intermediate has been performed and since then only very little research regarding triazine tricarbonyl acid or its salts has been carried out until 2002 when Dunbar et al. reported the crystal structure and magnetic properties of $K\{Fe(1,3,5\text{-triazine-2,4,6-tricarboxylate})(H_2O)_2\} \cdot 2 H_2O$ [23].

To the best of our knowledge no crystal structure of any other salt of triazine tricarbonyl acid has been described so far. However, regarding the potential application of triazine tricarboxylate as a multidentate ligand a deeper understanding of its

1
2 coordination behavior towards various metal ions is of great interest. In this contribution we report on synthesis and crystal
3 structure of potassium triazine tricarboxylate dihydrate as a further example of a structurally characterized triazine
4 tricarboxylate and thereby providing further insight into the coordination properties of this linker.
5
6
7

8 **Results and Discussion**

9 *Crystal Structure*

10
11 Potassium triazine tricarboxylate crystallizes as a dihydrate in the triclinic space group $P\bar{1}$ with six formula units in the
12 unit cell. Crystallographic data and details of the structure refinement are summarized in Table 1. The crystal structure
13 comprises triazine tricarboxylate $[C_3N_3(COO)_3]^{3-}$ and potassium ions and crystal water molecules (cf. Figure 1).
14

15
16 The triazine tricarboxylate ions are nearly planar with only the carboxylate groups being slightly rotated out of plane so that
17 the anions exhibit molecular symmetry C_3 . The substituents cause an increase of the adjacent angles ($N1-C1-N3 = 124.5^\circ$)
18 while the remaining angles of the *s*-triazine core are accordingly reduced ($C1-N1-C2 = 115.5^\circ$). In accordance with
19 expectation the bond distances of both the C-N bonds within the ring (133–134 pm) and the C-O bonds of the carboxylate
20 groups (124–125 pm) correspond to conjugated double bonds while the C-C bond lengths of 153–154 pm resemble those of
21 single bonds (cf. Table 2).

22
23 The triazine tricarboxylate ions, the potassium atoms and water molecules are arranged in an AA'BB' type stacking pattern
24 perpendicular to [100] (cf. Figure 2) with the A and A' layers consisting of the triazine tricarboxylate and potassium ions and
25 the crystal water molecules being located in the intermediate B and B' layers. Within the A and A' layers the triazine
26 tricarboxylate ions are not coplanar but are slightly tilted out of the *bc*-plane. Perpendicular to [100] the triazine
27 tricarboxylate units form two different kinds of columns. One third of the columns consist solely of molecules B (cf. Figure
28 1) with the molecules of two adjacent layers A and A' being rotated by 60° within the plane. In the remaining columns
29 molecules A and C alternate and are rotated by 30° . These columns form hexagonal channels around the B columns (cf.
30 Figure 3).

31
32 The interlayer distance of 347 pm between two triazine tricarboxylate layers is in the expected range for molecular *s*-
33 triazine derivatives [1,24,25]. Between the layers the triazine tricarboxylate units are interconnected by a network of medium
34 strong [26] hydrogen bonds (cf. Table 3) via the carboxylate groups. All crystal water molecules are part of the hydrogen
35 bonding network although due to the strong disorder of one oxygen atom (O24) no hydrogen bond can be clearly assigned to
36 the linked hydrogen atom H11.

37
38 The potassium ions are coordinated in the form of irregular polyhedrons by four to six oxygen atoms of water molecules
39 and carboxylate groups and by one nitrogen atom of the triazine rings. The triazine tricarboxylate units serve as tridentate
40 ligands and coordinate the K^+ atoms via the O-N-O entities (cf. Figure 1) with the K^+ atom being slightly shifted towards one
41 of the oxygen atoms. The coordination sphere is completed by the oxygen atoms of further triazine tricarboxylate units and
42 water molecules. The K-O distances (273–297 pm) are in accordance with the sum of the ionic radii [27] while the K-N
43 distances (278–282 pm) are relatively short compared to the potassium salts of other *s*-triazine or *s*-heptazine compounds
44 [28–30]. In $K\{Fe(1,3,5\text{-triazine-2,4,6-tricarboxylate})(H_2O)_2\} \cdot 2H_2O$ the Fe atoms are coordinated by an O-N-O unit in a
45 similar way as in the title compound with a short Fe-N distance of 212 pm while the potassium ions are coordinated solely
46 by oxygen atoms and the K-O distances are comparable in both compounds. Hence in both triazine tricarboxylate salts a
47 strong contribution of the *s*-triazine core to metal coordination is observed so that the triazine tricarboxylate unit can be
48 regarded as an interesting linker for coordination networks potentially allowing other linkage motifs than those observed in
49 MOFs which contain trimesic acid as the organic linker.

49 *Vibrational Spectroscopy*

50
51 Potassium triazine tricarboxylate dihydrate was analyzed by FTIR spectroscopy. All signals in the spectrum can be
52 attributed to vibrations of the triazine tricarboxylate entities and water molecules, respectively (cf. Figure 4). The bending
53 and stretching vibrations of the *s*-triazine ring lead to a characteristic absorption band at 740 cm^{-1} and a group of signals at
54 $1300\text{--}1660\text{ cm}^{-1}$, respectively. In the range between 1300 and 1660 cm^{-1} the stretching vibrations of the carboxylate groups
55 can be observed as well. The broad band at $3000\text{--}3600\text{ cm}^{-1}$ can be attributed to the OH stretching vibrations of the crystal
56 water molecules and in accordance with the crystal structure the red-shift of the $\nu(\text{OH})$ signals corresponds to medium strong
57 hydrogen bonds [26].

58 *Thermal Behavior*

59
60 TG and DTA curves of potassium triazine tricarboxylate dihydrate are displayed in Figure 5. In the temperature range
between 65 and 150°C the crystal water molecules are released (mass loss *observed*: 10.9 %, *calculated*: 9.9 %) and the so
obtained dehydrated compound is thermally stable up to 325°C . The decomposition of the sample starts with a mass loss of

17 % accompanied by a sharp endothermic signal at 325–390 °C, probably due to a partial decarboxylation, and proceeds with a slow and steady mass loss at higher temperatures.

Conclusions

We have reported on the crystal structure and thermal behavior of potassium triazine tricarboxylate dihydrate. Triazine tricarboxylate represents a multidentate ligand which can be regarded as the *s*-triazine analog of trimesic acid and hence as a promising linker for metal organic frameworks but only one triazine tricarboxylate salt has been structurally characterized so far. This study has expanded the investigations of this class of compounds to a new salt and thereby provides further insight into the coordination properties of triazine tricarboxylate. The presented crystal structure shows that the nitrogen atoms of the *s*-triazine cycle exhibit a strong interaction with the potassium ions and that the coordination of metal ions via the O-N-O units of the triazine tricarboxylate entities is a recurring binding motif for this ligand. Because of the differing coordination properties compared to trimesic acid triazine tricarboxylate seems to be an interesting linker for coordination networks and with the observed high thermal stability of $K_3[C_3N_3(COO)_3]$ an important condition for syntheses of three-dimensional networks at elevated temperatures is fulfilled.

Experimental Section

Syntheses

Potassium triazine tricarboxylate dihydrate was synthesized according to the procedure described in [22,31] by saponification of the respective triethyl ester. To prepare the triethyl ester dry HCl was conducted through ethyl cyanofornate (20.0 g, 202 mmol, Aldrich, 99 %) under argon until the trimerization product started to precipitate. Then the conversion was completed by cooling the reaction to 4 °C over night. The product was filtered, washed with cold water and dried at 75 °C yielding 7.15 g (24.1 mmol, 36 %) triethyl-*s*-triazine-2,4,6-tricarboxylate as colorless needles.

Elemental analysis (wt. %): N 14.22 (calc. 14.13), C 47.20 (calc. 48.47), H 4.88 (calc. 5.08).

Small amounts of the triethyl ester (100 mg, 0.34 mmol) were added to 3.5 ml of a 1 M aqueous solution of KOH while cooling with an ice bath. The reaction was stirred until the ester was completely dissolved and then 25 ml ethanol was poured into the solution to precipitate the potassium salt. The product was filtered, washed with ethanol and dried at 75 °C to obtain 103 mg (0.28 mmol, 83 %) potassium-1,3,5-triazine-2,4,6-tricarboxylate dihydrate as colorless needles. Single crystals suitable for single-crystal X-ray diffraction were obtained by repeated recrystallization from aqueous solution at 4 °C.

Elemental analysis (wt. %): N 11.60 (calc. 11.56), C 20.45 (calc. 19.83), H 0.64 (calc. 1.11).

X-ray Structure Determination

Single-crystal X-ray diffraction data of $K_3[C_3N_3(COO)_3] \cdot 2 H_2O$ were collected at 200 K on a Kappa CCD diffractometer using monochromated Mo- K_{α} radiation ($\lambda = 71.073$ pm). The diffraction intensities were scaled using the SCALEPACK software package [32] and no additional adsorption correction was applied. The crystal structure was solved by direct methods using the software package SHELXS-97 [33] and refined against F^2 by applying the full-matrix least-squares method (SHELXL-97) [34]. The hydrogen positions could be determined from difference Fourier syntheses and were refined isotropically using restraints for oxygen-hydrogen distances. All non-hydrogen atoms were refined anisotropically.

CCDC 784049 contains the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

FT-Infrared Spectroscopy

A FTIR spectrum was recorded at ambient conditions between 600 and 4500 cm^{-1} on a Spektrum BX II FTIR spectrometer (Perkin Elmer) equipped with a DuraSampler diamond ATR device.

Thermal Analysis

Thermoanalytical measurements were performed with a Thermoanalyzer TG-DTA92 (Setaram) under inert atmosphere (He). The sample was heated in an alumina crucible from room temperature to 500 °C with a heating rate of 5 °C min^{-1} .

Acknowledgments

The authors thank the Deutsche Forschungsgemeinschaft DFG (project SCHN 377/12) and the Fonds der Chemischen Industrie (FCI) for financial support and Dr. Peter Mayer (Department Chemie, LMU München) for the single-crystal data collection.

Scheme 1. Molecular precursors for carbon nitride networks comprising the *s*-triazine (1) or *s*-heptazine (2) core.

Scheme 2. Multidentate ligands which are commonly employed as linkers in metal organic frameworks.

Figure 1. Representation of one formula unit of $K_3[C_3N_3(COO)_3] \cdot 2 H_2O$. The three triazine tricarboxylate entities present in the crystal structure are labeled A-C. Thermal ellipsoids (except for H) are drawn at the 50 % probability level.

Figure 2. Crystal structure of $K_3[C_3N_3(COO)_3] \cdot 2 H_2O$ representing the layered structure perpendicular to [100]. Thermal ellipsoids (except for H) are drawn at the 50 % probability level.

Figure 3. Crystal structure of $K_3[C_3N_3(COO)_3] \cdot 2 H_2O$ representing the stacked arrangement of the triazine tricarboxylate entities. Crystal water molecules are omitted for clarity. The labels A-C refer to Figure 1, indicating which triazine tricarboxylate unit lies on top of the respective column. Thermal ellipsoids are drawn at the 50 % probability level.

Figure 4. FTIR spectrum of $K_3[C_3N_3(COO)_3] \cdot 2 H_2O$.

Figure 5. TG (solid) and DTA (dotted) curves of $K_3[C_3N_3(COO)_3] \cdot 2 H_2O$, recorded with a heating rate of $5 \text{ }^\circ\text{C min}^{-1}$.

Table 1. Crystallographic data and details of the structure refinement for $K_3[C_3N_3(COO)_3] \cdot 2 H_2O$.

molar mass / g mol ⁻¹	363.41
crystal system	triclinic
space group	$P\bar{1}$ (no. 2)
T / K	200
diffractometer	Nonius Kappa-CCD
radiation, λ / pm	Mo-K α , 71.073
<i>a</i> / pm	696.63(14)
<i>b</i> / pm	1748.5(3)
<i>c</i> / pm	1756.0(3)
α / deg	119.73(3)
β / deg	91.96(3)
γ / deg	93.84(3)
<i>V</i> / 10 ⁶ pm ³	1847.6(8)
<i>Z</i>	6
calculated density / g cm ⁻³	1.960
crystal size / mm ³	0.70 x 0.07 x 0.05
absorption coefficient / mm ⁻¹	1.150
diffraction range	$3.26^\circ \leq \theta \leq 27.54^\circ$
index range	$-8 \leq h \leq 9, -22 \leq k \leq 22,$ $-22 \leq l \leq 22$
parameters / restraints	577 / 16
total no. of reflections	14291
no. of independent reflections	8452
no. of observed reflections	5617
min./max. residual electron density / 10 ⁶ pm ³	-0.679/ +0.984
GooF	1.047
final R indices [$I > 2\sigma(I)$]	$R1 = 0.0513, wR2 = 0.1068$ [a]
final R indices (all data)	$R1 = 0.0868, wR2 = 0.1228$ [a]

[a] $w = [\sigma^2(F_o^2) + (0.0389P)^2 + 1.6956P]^{-1}$, with $P = (F_o^2 + 2F_c^2)/3$

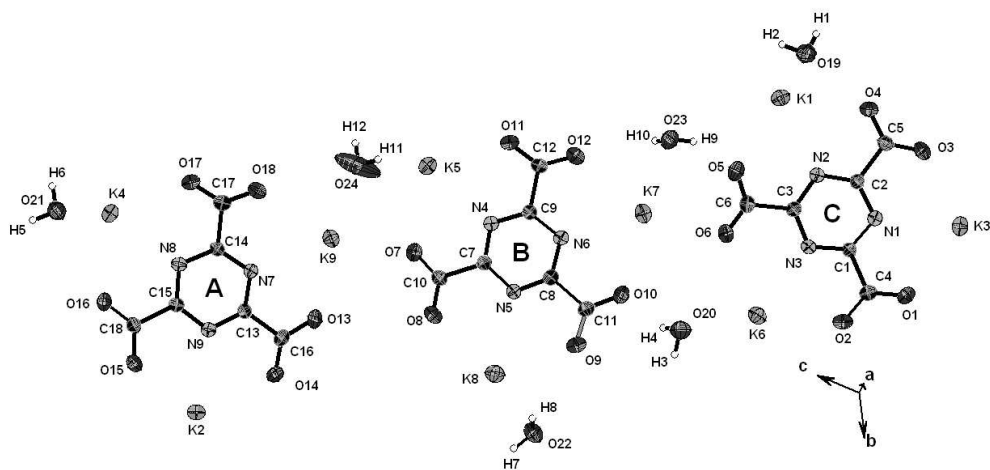
Table 2. Selected bond lengths (in pm) and angles (in deg) in $K_3[C_3N_3(COO)_3] \cdot 2 H_2O$, standard deviations in parentheses.

K1 - O4	292.6(3)	K3 - O16	281.0(3)	K5 - N4	278.2(3)	K8 - O8	284.0(3)	N3 - C3	132.9(4)	N2 - C2 - C5	117.9(3)
K1 - O5	281.7(3)	K3 - O16	283.7(3)	K6 - O2	278.6(3)	K8 - O9	296.2(3)	C4 - O1	123.9(4)	N2 - C3 - C6	118.2(3)
K1 - O14	279.1(3)	K3 - O21	282.2(3)	K6 - O6	287.2(3)	K8 - O22	278.2(3)	C4 - O2	125.0(4)	N3 - C3 - C6	117.3(3)
K1 - O14	284.6(3)	K3 - N1	279.7(3)	K6 - O18	280.0(3)	K8 - N5	279.7(3)	C1 - C4	153.0(4)	O1 - C4 - O2	127.5(3)
K1 - O19	280.3(3)	K4 - O1	287.5(3)	K6 - O18	293.0(3)	K9 - O7	274.4(3)	C2 - C5	154.2(5)	O4 - C5 - O3	127.8(3)
K1 - N2	278.6(3)	K4 - O9	276.9(3)	K6 - O20	285.4(4)	K9 - O13	274.0(3)	C3 - C6	153.0(5)	O6 - C6 - O5	128.5(4)
K2 - O4	286.3(3)	K4 - O16	290.3(3)	K6 - O24	284.7(4)	K9 - O18	297.1(3)	C2 - N1 - C1	115.4(3)	O1 - C4 - C1	117.5(3)
K2 - O12	281.2(3)	K4 - O17	286.5(3)	K6 - N3	279.3(3)	K9 - O20	275.7(3)	C2 - N2 - C3	115.4(3)	O2 - C4 - C1	115.0(3)
K2 - O14	284.4(3)	K4 - O21	273.4(3)	K7 - O6	277.8(3)	K9 - O24	274.0(4)	C3 - N3 - C1	115.7(3)	O3 - C5 - C2	115.2(3)
K2 - O15	283.0(3)	K4 - O22	279.3(3)	K7 - O10	276.2(3)	K9 - N7	281.8(3)	N3 - C1 - N1	124.3(3)	O4 - C5 - C2	117.0(3)
K2 - O19	275.7(3)	K4 - N8	281.8(3)	K7 - O12	291.8(3)	N1 - C1	133.8(4)	N2 - C2 - N1	124.7(3)	O5 - C6 - C3	115.3(3)
K2 - O23	273.4(3)	K5 - O1	280.5(3)	K7 - O19	295.5(3)	N1 - C2	133.4(4)	N3 - C3 - N2	124.5(3)	O6 - C6 - C3	116.1(3)
K2 - N9	280.7(3)	K5 - O7	291.3(3)	K7 - O23	285.2(3)	N2 - C2	133.1(4)	N1 - C1 - C4	117.9(3)		
K3 - O1	287.6(3)	K5 - O11	277.1(3)	K7 - N6	279.1(3)	N2 - C3	133.9(4)	N3 - C1 - C4	117.8(3)		
K3 - O3	281.1(3)	K5 - O24	280.0(5)	K8 - O4	278.7(3)	N3 - C1	133.6(4)	N1 - C2 - C5	117.4(3)		

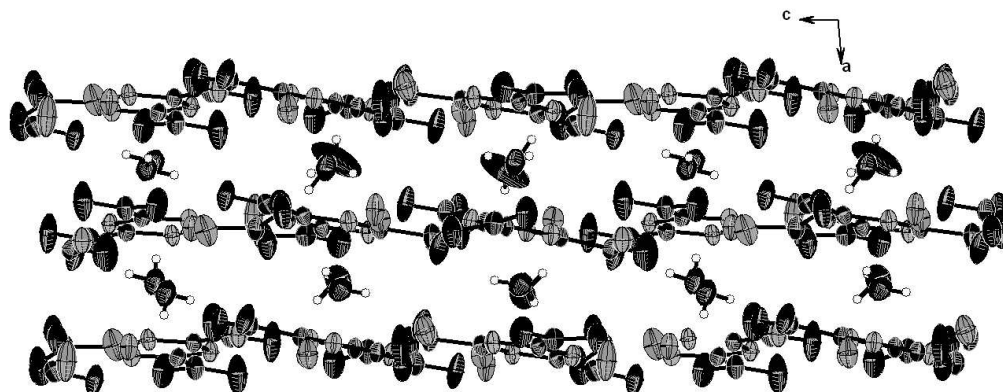
Table 3. Donor-acceptor distances and donor-hydrogen-acceptor angles (in pm / deg) for the hydrogen bonding network in $K_3[C_3N_3(COO)_3] \cdot 2 H_2O$.

D-H...A	D...A	<D-H...A	D-H...A	D...A	<D-H...A
O19-H1...O8	283.9	154.79	O22-H7...O15	266.5	173.09
O19-H2...O5	272.0	159.35	O22-H8...O11	292.8	176.50
O20-H3...O2	277.5	152.52	O23-H9...O13	269.0	157.25
O20-H4...O10	279.6	166.63	O23-H10...O8	290.1	167.27
O21-H5...O3	270.6	160.13	O24-H12...O17	266.6	155.49
O21-H6...O11	281.4	169.61			

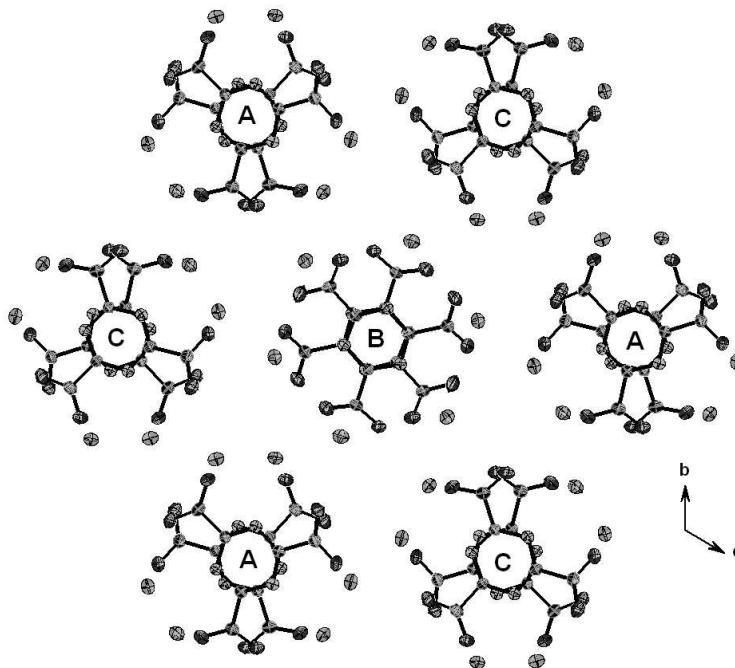
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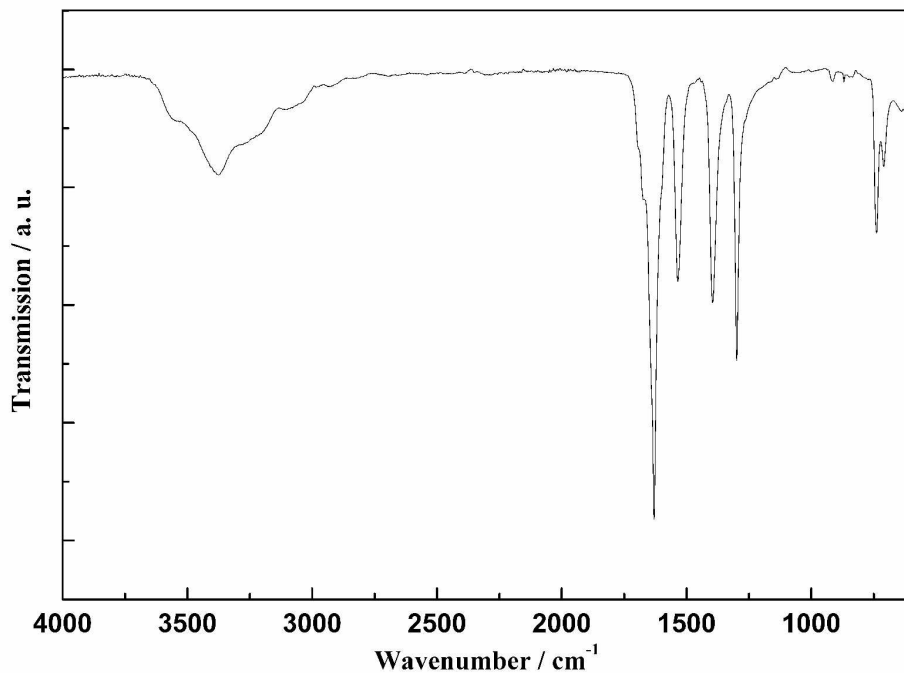
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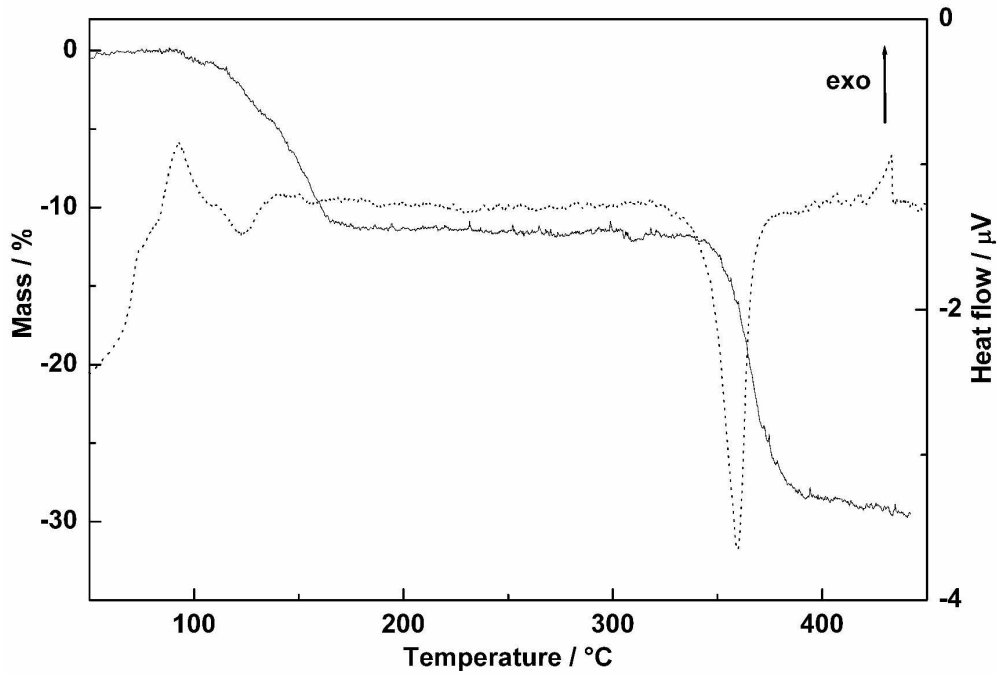
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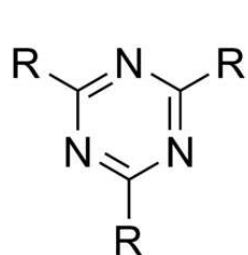
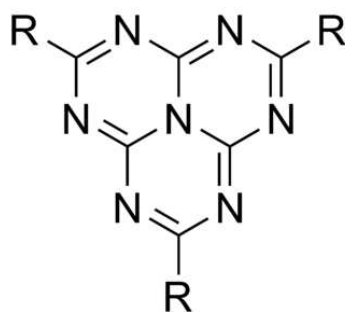
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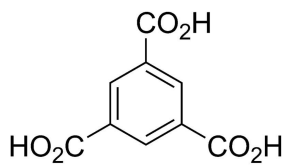
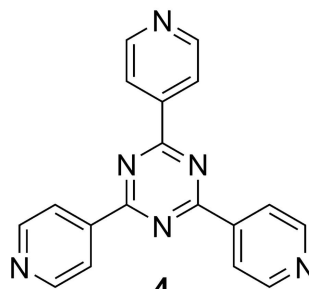
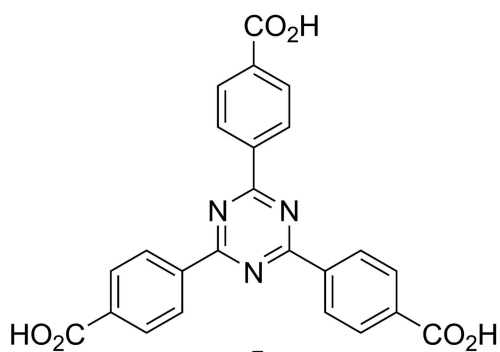
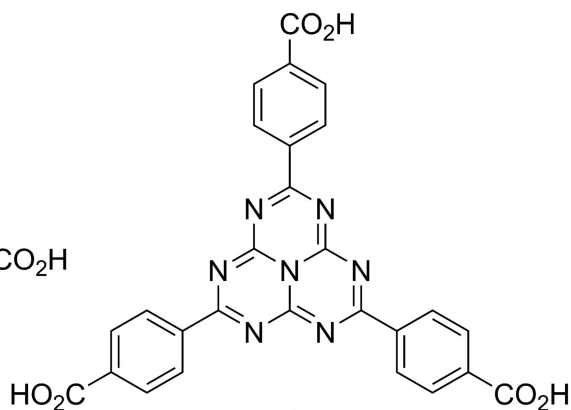


326x227mm (537 x 537 DPI)

**1****2**

- a** R = NH₂
- b** R = OH
- c** R = Cl
- d** R = N₃
- e** R = CN
- f** R = COOH

39x15mm (600 x 600 DPI)

**3****4****5****6**

123x105mm (600 x 600 DPI)