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Adsorptive molecular sieving of aromatic hydrocarbons over cyclic aliphatic hydrocarbons via an intrinsic/extrinsic approach†

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Trianglimine (TI) and trianlamine (TA) macrocycles offer an efficient adsorptive molecular sieving strategy to separate toluene (Tol) from an equimolar mixture of Tol and methylcyclohexane (MCH) with 98.3% and 96.4% selectivity, respectively. Selective separation is achieved through the intrinsic cavity or extrinsic channel within the crystalline molecular adsorbents, driven by C–H $\cdots\pi$ and $\pi\cdots\pi$ interactions. Moreover, TI and TA exhibit exceptional recyclability, highlighting their potential for sustainable chemical separation processes.

Cyclic aliphatics, such as cycloalkanes and alkyl-cycloalkanes, are often used as high-performance jet fuels and endothermic fuels to overcome the severe “thermal barrier” issue for hypersonic vehicles.^{1,2} Among them, methylcyclohexane (MCH), a typical hexatomic ring alkyl-cycloalkane with the simplest branched structure, is frequently chosen as a jet-fuel surrogate for many practical fuels.^{3–5} In chemical industry production, MCH is predominantly obtained through the hydrogenation of the corresponding aromatic toluene (Tol), resulting in the presence of unreacted Tol.⁶ The separation of residual Tol from MCH is crucial for producing high grade MCH. However, conventional extraction and distillation methods face significant challenges in the separation of cyclic aliphatic and aromatic hydrocarbons due to their similar physical properties, such as close boiling points (384 K for Tol and 374 K for MCH) and the formation of azeotropes.⁷ Consequently, developing sustainable and efficient technology for separating cyclic aliphatic and aromatic hydrocarbons becomes imperative in addressing these challenges.

Porous materials-based adsorptive separation technology has been recognized as an alternative strategy for the separation of cyclic aliphatic and aromatic hydrocarbons, owing to its high efficiency and low energy consumption.^{8–23} In recent years, various adsorbents such as metal–organic frameworks (MOFs),²⁴ porous organic molecular frameworks (POMFs),²⁵ organic macrocycles,^{26–28} and molecular cages²⁹ have been reported for the separation of MCH and Tol. Typically, these examples showed that MCH and Tol could be selectively adsorbed into the extrinsic void of assembled materials or the intrinsic cavity of macrocycles, depending on the differences in their molecular sizes, conformational structures, and electrical charge distributions. However, different separation mechanisms between the adsorption in the intrinsic cavity and extrinsic void are still unclear at the molecular level. Therefore, understanding the different host–guest complexation modes during separation is essential for developing novel adsorbents and exploring new separation strategies.

Herein, we present that the simple trianglimine (TI) and trianlamine (TA) macrocycles can be used for the separation of MCH and Tol by different adsorption behaviors (Fig. 1). TI exhibits a rigid molecular structure that enables the adsorption of the Tol molecule into its intrinsic cavity, while TA, with a flexible conformation, forms extrinsic channels in the crystalline assembly structure to capture the Tol molecule. Notably, to the best of our knowledge, this is the first example of conformational transitions being introduced to modulate adsorption occurring in the intrinsic cavity and extrinsic void.

TI and TA macrocycles were synthesized using the published methods,^{30,31} respectively, and the purity of products was confirmed through ¹H NMR and ¹³C NMR (Fig. S1–S4†). The crystalline TI and TA materials were obtained through recrystallization of their ethyl acetate solutions, followed by activation at 90 °C under vacuum for 12 hours to remove residual solvent molecules. Thermogravimetric analysis (TGA) and powder X-ray diffraction (PXRD) analysis indicated that both activated TI and TA displayed excellent thermal stability (Fig. S5 and S6†) and persistent crystallinity (Fig. S7 and S8†) after the activation.

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Fig. 1 (a) Chemical structures of TI and TA and their transformation. (b) Schematic illustration of the intrinsic and extrinsic capture approaches of Tol from the mixture of Tol/MCH by TI and TA.

Furthermore, the N_2 sorption isotherm at 77 K demonstrated that the activated **TI** and **TA** crystals were not porous to N_2 at 77 K, exhibiting a Brunauer–Emmett–Teller (BET) surface area of $1.68 \text{ m}^2 \text{ g}^{-1}$ for **TI** (Fig. S9[†]) and $6.99 \text{ m}^2 \text{ g}^{-1}$ for **TA** (Fig. S10[†]), respectively.

To investigate the host–guest binding behaviors of guest molecules in **TI** and **TA**, efforts were made to grow single crystals of the macrocycles with **Tol** and **MCH**, followed by single crystal X-ray diffraction (SCXRD) analysis to gain a better understanding of the host–guest interactions. Specifically, by dissolving **TI** in a pure **Tol** solution and allowing it to cool/evaporate at room temperature for several days, colorless cubic crystals of **Tol@TI** were formed. The SCXRD analysis revealed that **Tol@TI** crystallizes in a monoclinic system with a $P2_1$ space group (Table S1[†]). Each asymmetric unit of **Tol@TI** consisted of one **TI** host macrocycle and one **Tol** guest molecule (Fig. 2a and b). The host **TI** molecule exhibited a regular triangular structure with an intrinsic cavity. The guest **Tol** molecule was found to be partially located within the cavity of the **TI** macrocycle, with the methyl group positioned appropriately inside the cavity. Notably, the methyl group of **Tol** formed multiple C–H $\cdots\pi$ interactions (3.025 Å, 3.128 Å and 3.245 Å, Fig. S11[†]) individually with the three benzene rings in the **TI** cavity, and the benzene ring of **Tol** exhibited a $\pi\cdots\pi$ stacking interaction (3.257 Å) with one benzene group in the **TI** macrocycle (Fig. S12[†]). Moreover, the packing arrangement of **Tol@TI** along the crystallographic a axis reveals an inclined 1D packing structure (Fig. S13 and S14[†]). Additionally, from the guest-free single layer 2D packing structure, it clearly shows the guest-accessible voids within the intrinsic cavity of **TI** and their capacity to adsorb guest **Tol** molecules (Fig. 2c).



Fig. 2 (a) Top view and (b) side view of the single crystal structure of the asymmetric unit of **Tol@TI**. Blue dashed lines present the C–H $\cdots\pi$ noncovalent interactions existing between the guest molecule and **TI**. The green dashed line presents the $\pi\cdots\pi$ noncovalent interaction existing between the guest molecule and **TI**. (c) Single layer crystal packing structure along the crystallographic a axis with the contact surfaces of guest-free **TI** showing guest accessible voids within the intrinsic cavities and the complexation to **Tol**.

A single crystal of **Tol@TA** was obtained by the same method. SCXRD analysis revealed that **Tol@TA** crystallizes in an orthorhombic system with a $P2_12_12_1$ space group (Table S1[†]), which consists of three **TA** macrocycles and three **Tol** guest molecules within the asymmetric unit (Fig. 3a and b). In contrast to **TI**, **TA** with a highly flexible conformation exhibited a distorted zigzag structure (Fig. S15[†]), which restricted the volume of guest-accessible voids within its intrinsic cavity and consequently limited its ability to capture guest molecules (Fig. S16[†]). However, in the crystal packing structure, six **TA** macrocycles assembled to form a 1D extrinsic channel along the c axis through host–host C–H $\cdots\pi$ interactions, accommodating all **Tol** guest molecules within these voids (Fig. 3c, S17 and S18[†]). Two of the **Tol** guest molecules (**Tol_I** and **Tol_{II}**) were situated between two adjacent **TA** host macrocycles (**TA₁** and **TA₂**) and stabilized by C–H $\cdots\pi$ interactions between the methyl group of **TA** and benzene of **Tol** (Fig. S19 and S20[†]). The third **Tol** guest molecule **Tol_{III}** was linked by one **TA** macrocycle, as well as connected with the **Tol** guest molecule **Tol_I** (Fig. S21[†]). These host–guest and guest–guest interactions also resulted in the formation of **Tol** channels along the crystallographic c -axis, which is consistent with the extrinsic channels formed by **TA** (Fig. S22[†]).

The distinct host–guest complexation modes of **TI** and **TA** with **Tol** can be attributed to the structural differences between the two macrocycles. Specifically, **TI** with C=N double bonds exhibits a rigid molecular skeleton that enables it to maintain



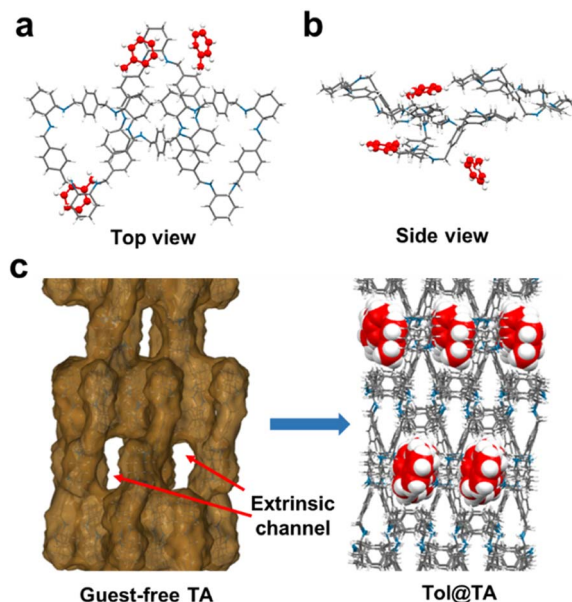


Fig. 3 (a) Top view and (b) side view of the single crystal structure of the asymmetric unit of Tol@TA. (c) Single layer crystal packing structure along the crystallographic *a* axis with the contact surfaces of guest-free TA showing the guest accessible voids within the extrinsic channels and the adsorption to Tol.

intrinsic cavities in the solid packing structure, thereby capturing guest molecules. However, upon reduction to TA, the rigid C=N double bonds are transformed into C-H single bonds, allowing for flexible rotation. As a result, TA adopts a more flexible conformation that makes it difficult to maintain guest accessible voids within its intrinsic cavities in the solid packing structure (Fig. S16†). Nevertheless, TA is more capable of forming extrinsic voids or channels to absorb guest molecules.

Subsequently, attempts were made to crystallize TA and TI with MCH. However, despite using various solvents and methods, all attempts were unsuccessful (Table S2†). This outcome may be attributed to MCH's low electronegativity profile resulting from its non-aromatic structure, which limits its capacity to establish strong host-guest interactions with the host macrocycles (Fig. S39†). Specifically, Tol contains a CH₃ methyl group and an electron-rich benzene ring, which can not only form guest-to-host C-H... π interactions with the benzene rings on TI and TA but also can form additional π ... π interactions and host-to-guest C-H... π interactions. In contrast, MCH solely comprises aliphatic hydrocarbon atoms, which can only form relatively weak guest-to-host C-H... π interactions with the benzene rings on TI or TA.

To further evaluate the potential of TI and TA as candidates for the adsorption of Tol and MCH, solid-vapor sorption experiments were performed on the activated TI and TA upon exposure to the single component of Tol and MCH, as well as their equimolar mixture, respectively. As revealed by ¹H NMR spectroscopy, each TA or TI macrocycle can capture approximately 0.9 molecules of Tol on average after reaching adsorption saturation (Fig. S23–S26†). In contrast, both TI and TA

exhibited negligible uptake after being exposed to MCH vapors (Fig. S27 and S28†). The low adsorption capacity of TI and TA towards MCH explains the challenge in obtaining host-guest single crystals between TA/TI and MCH. Furthermore, PXRD experiments were conducted to investigate the structural changes of TI and TA after the uptake of Tol and MCH. The absorption of Tol molecules with activated TI and TA led to significant guest-induced structural changes, which were consistent with the simulated PXRD patterns of Tol@TI and Tol@TA (Fig. 3a and b). However, there were almost no changes in PXRD patterns for TI and TA after exposure to MCH vapor. Moreover, the different adsorption results were also verified through TGA analysis by comparing the relative weight loss of activated host macrocycles after absorbing Tol and MCH guest molecules, respectively (Fig. S29–S32†). These observations highlight the exceptional selectivity of TI and TA towards Tol over MCH.

Subsequently, equimolar mixtures of Tol and MCH were used to evaluate the separation performance of TI and TA. The results showed that the uptake of Tol in TI and TA increased over time and reached saturation within 20 h and 10 h, respectively (Fig. 4c, d, S33 and S34†). In contrast, MCH absorption was almost negligible throughout the entire experimental period for both TI and TA. Additionally, the PXRD patterns of TI and TA upon

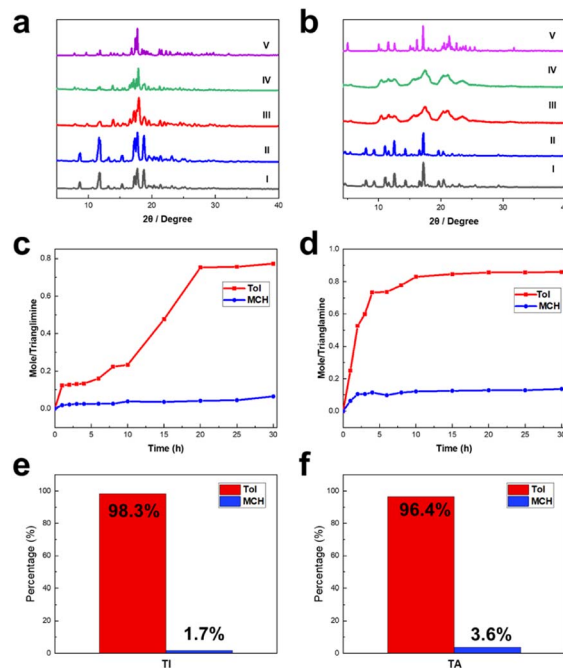


Fig. 4 (a) PXRD pattern of TI: (I) pure activated TI, (II) after absorption of MCH, (III) after absorption of Tol, (IV) after absorption of the Tol/MCH mixture, and (V) simulated from the single crystal structure of Tol@TI. (b) PXRD pattern of TA: (I) pure activated TA, (II) after absorption of MCH, (III) after absorption of Tol, (IV) after absorption of the Tol/MCH mixture, and (V) simulated from the single crystal structure of Tol@TA. (c) Time-dependent solid-vapor sorption curve of TI with a mix component of Tol/MCH. (d) Time-dependent solid-vapor sorption curve of TA with a mix component of Tol/MCH. (e) Relative uptakes of Tol/MCH in TI after saturated absorption. (f) Relative uptakes of Tol/MCH in TA after saturated absorption.



adsorption of **Tol/MCH** equimolar mixture vapor were in complete agreement with the patterns of **TI** and **TA** upon capturing **Tol** vapor and those simulated from **Tol@TI** and **Tol@TA** (Fig. 4a and b), respectively, implying the phase transformation from **TI** and **TA** into **Tol@TI** and **Tol@TA**. Furthermore, gas chromatography confirmed the high selectivity for **Tol** over **MCH**, with the proportion of **Tol** adsorbed in **TI** and **TA** reaching 98.3% and 96.4%, respectively (Fig. S35 and S36†).

In practical applications, the recyclability of absorbents is a crucial aspect that influences their potential use. For **TI** and **TA**, regeneration was achieved by heating the saturated samples at 90 °C under vacuum for 12 hours. Remarkably, the restored **TI** and **TA** samples maintained their selectivity towards **Tol** without any performance loss even after undergoing five cycles (Fig. S37†).

Conclusions

In conclusion, we have investigated the potential of **TI** and **TA** for the separation of aromatic **Tol** from aliphatic cyclic **MCH**. Both **TI** and **TA** exhibited high selectivity towards **Tol**, with adsorption capacities of 98.3% and 96.4%, respectively. Crystal structure analysis revealed that **TI**, with its rigid structure, could capture **Tol** through its intrinsic cavities, while the flexible conformation of the reduced product **TA** was able to assemble into extrinsic channels for absorbing guest molecules. This study demonstrates that altering the structure of a macrocycle can induce conformational changes to regulate intrinsic and extrinsic voids for separation. We expect that this research will not only provide a new strategy for designing novel absorbents but also inspire the application of supramolecular macrocycles in energy-intensive separation.

Conflicts of interest

There are no conflicts to declare.

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