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Aromatic hydrocarbons in a controlled ecological life support system during a 4-person-180-day integrated experiment



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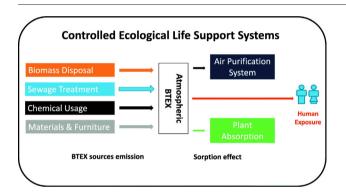
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HIGHLIGHTS

BTEX were monitored in a 4-person-180-day experiment inside an artificial ecosystem.

- The concentrations of BEX experienced exponential decays while toluene's fluctuated.
- Using low-emitting materials/furniture may help lowering BTEX concentration levels.
- CELSS is suitable for humans' long-term living, free of health risks from BTEX.

GRAPHICAL ABSTRACT



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ABSTRACT

Indoor air quality is vital to the health and comfort of people who live inside a controlled ecological life support system (CELSS) built for long-term space explorations. Here we measured aromatic hydrocarbons to assess their sources and health risks during a 4-person-180-day integrated experiment inside a CELSS with four cabins for growing crops, vegetables and fruits and other two cabins for working, accommodations and resources management. During the experiment, the average concentrations of benzene, ethylbenzene, m.p.-xylenes and o.-xylene were found to decrease exponentially from 7.91 ± 3.72 , 37.2 ± 35.2 , 100.8 ± 111.7 and 46.8 ± 44.1 µg/m³ to 0.39 ± 0.34 , 1.4 ± 0.5 , 2.8 ± 0.7 and 2.1 ± 0.9 µg/m³, with half-lives of 25.3, 44.8, 44.7 and 69.3 days, respectively. Toluene to benzene ratios indicated emission from construction materials or furniture to be a dominant source for toluene, and concentrations of toluene fluctuated during the experiment largely due to the changing sorption by growing plants. The cancer and no-cancer risks based on exposure pattern of the crews were insignificant in the end of the experiment. This study also suggested that using low-emitting materials/furniture, growing plants and purifying air actively would all help to lower hazardous air pollutants inside CELSS. Broadly, the results would benefit not only the development of safe and comfort life support systems for space exploration but also the understanding of interactions between human and the total environment in closed systems.

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1. Introduction

Controlled ecological life support system (CELSS) is an artificial closed ecosystem built for long-term space exploration which provides

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humans (astronauts) with enough breathable air, clean water, essential food and safe working-living places. CELSS has a significant material closure and circulation (Nelson et al., 2013) with the help of green plants, including algae or crops, to remove carbon dioxide, produce oxygen and food. Up to now, a variety of closed ecological systems experiments have been conducted, such as Biosphere 2 project (Nelson et al., 1993; Nelson et al., 1991), the BIOS-3 (Salisbury et al., 1997), the Closed Ecological Experimental Facility (CEEF) (Nitta et al., 2000), and the 2-person-30-day CELSS in Beijing (Guo et al., 2015).

Since people spend all day working and living in this closed ecosystem, the indoor air quality affects humans' health directly (Brinke et al., 1998; Salthammer, 2016; Wolkoff, 1995) and plays an important role in evaluating the environmental safety (Liu et al., 2016; Mallach et al., 2017; Pagani et al., 2017). Aromatic hydrocarbons, including benzene, toluene, ethylbenzene, xylenes (collectively BTEX), form an important group of toxic trace gases (Smith et al., 2011; Snyder, 2007), which might pose serious risk on the respiratory system, hematopoietic system and nervous system of human being (Dean, 1978; Ross, 2000; Smith et al., 1989). In CELSS, aromatic hydrocarbons can be emitted from a range of sources including construction and decoration materials (Jones, 1999; Liu et al., 2008a), solvent and chemical usages (Chan et al., 2006; Ilgen et al., 2001; Zhang et al., 2016), biomass burning (Andreae and Merlet, 2001; Li et al., 2009b; Liu et al., 2008b), agricultural soils (Haarstad et al., 2011; Zhao et al., 2016), and human daily activities like cooking (Lee et al., 2001). Thus, it is essential to monitor the concentrations of these aromatic hydrocarbons in case high level concentrations might threaten people's health in CELSS. Furthermore, considering that the CELSS air purification system was designed to reduce trace hazardous air pollutants including BTEX, monitoring the BTEX concentrations also helps in evaluating the effectiveness of air purification system.

The concentrations of aromatic hydrocarbons have been previously determined in controlled ecological environment within durations of 10 days inside closed ecology experiment facilities (Tani et al., 2002) and 33 days inside a CELSS (Guo et al., 2015). However, the emission and variation of these aromatic hydrocarbons inside CELSS were not fully understood. In this study, we collected air samples during the 4-person-180-day integrated experiment inside a CELSS, and measured BTEX for their trends inside the CELSS, their possible emission sources and their health risks as well. The study aimed to provide valuable information for better air quality management inside CELSS to lower crews' personal exposure to hazardous air pollutants like BTEX.

2. Methods

2.1. Description of the 4-person-180-day CELSS integrated experiment

The 4-person-180-day experiment was conducted inside the controlled ecological life support system (CELSS) in Shenzhen, China: four researchers lived in this closed ecosystem for 180 days from 17 June to 14 December 2016. As shown in Fig. 1, the CELSS was comprised of six cabins. Twenty-five kinds of plants were planted in four plant cabins (CPs; cabin volumes ranging from 72 to 327 m³) to absorb carbon dioxide (CO₂) and produce oxygen and food though photosynthesis: Cabin Plant 1 (CP1; 204.5 m³) grew leafy vegetables; Cabin Plant 2 (CP2; 285 m³) grew wheat and leafy vegetables; Cabin Plant 3 (CP3; 327 m³) grew wheat; and Cabin Plant 4 (CP4; 72 m³) grew leafy vegetables and fruits. More details about plants growing are given in Table S1 in the supplementary materials. Cabin Crew & Life Support (CC; 274 m³) were used for crew's daily activities like working, cooking and sleeping, while Cabin Resource (CR; 141 m³) was used to dispose the non-edible portion of plant and produce CO₂. The temperature, relative humidity and CO₂ mixing ratio in each cabin during the experiment are given in Table S2.

The indoor air of each cabin was not ventilated in most time during the experiment. Air-lock rooms (2–5 m³) between conjoint cabins (Fig. 1) were normally close to reduce air exchange and pollutant dispersion through passageways, where crews must stay for at least 10 min before they move from one cabin to another. When the mixing ratio of oxygen in CC was lower than 19.0% (the threshold value for possible symptoms of anoxia; Schaefer, 1981) or the mixing ratios of CO₂ in CP 1–4 were lower than 500 ppm (a relatively high CO₂ mixing ratio to promote photosynthesis rates; Rosenberg, 1981), the ventilation among plant cabins (CP 1–4) and non-plant cabins (CC and CR) would activate automatically to balance the needs of oxygen and CO₂. Otherwise the ventilation among cabins was off. To build a livable ecosystem for crews with approximately 100% closure of carbon and oxygen, the air purification modules, water management systems and the solid waste disposal units worked well under the control of automatic feedback programs.

2.2. Air sampling

During the 180-day CELSS experiment, air samples were collected every 30 days in each cabin. Sampling inlet (8 mm I.D.) of polytetrafluoroethylene was obligated in advance outside of each

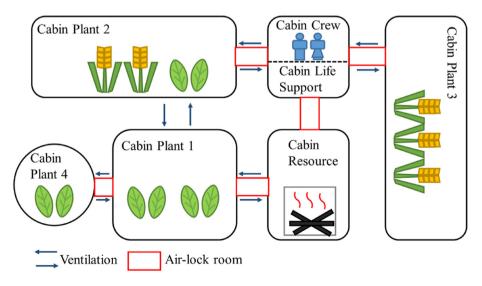


Fig. 1. Six cabins in 4-person-180-day CELSS experimental platform.

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