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Water management in a controlled ecological life support system during a 4-person-180-day integrated experiment: Configuration and performance

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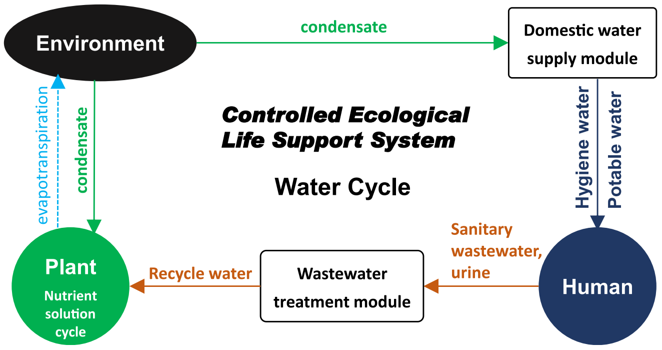
HIGHLIGHTS

- A 100% water closure was obtained in CELSS during the whole time of 4-person-180-day integrated experiment.
- The water quantitative model of water cycle was established.
- The safety of water quality was guaranteed by domestic water supply module and wastewater treatment module.
- An upgraded water cycle system for the larger-scale and longer-term CELSS was proposed.

GRAPHICAL ABSTRACT



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ABSTRACT

Water management subsystem (WMS) is a major component of the controlled ecological life support system (CELSS). For guaranteeing the water requirement of crop growth and crewmember's daily life, a WMS was established in a 4 person 180-day integrated experiment (carried out in Shenzhen, China, 2016) to maintain a closed cycle with a total water amount of ~23 m^3. The design and operation of the WMS was summarized as follows: (1) Collection and allocation of condensate water. About 917 L/d condensate water (>98% was from plants' evapotranspiration) was collected, and ~866 L/d of which was reused as plant nutrient solution after ultraviolet (UV) disinfection, and 50.6 L/d was used as the raw water for the domestic water supply module (DWS). (2) Domestic water supply. The condensate water from the plant cabin was purified through the DWS, a modified membrane bioreactor (MBR) system, and then provided hygiene and potable water to 4 crewmembers with different water quality standards. (3) Wastewater recovery. 51.4 L/d wastewater from urination and personal hygiene were treated together via a biological wastewater treatment process to complete the conversion of nitrogen and organic matters, and then recycled to plant nutrient solution. (4) Nutrient solution recycling. In the overall water cycle process, the plant nutrient solution was continuously self-circulated and the water quality of which was maintained at a relatively stable level with total organic carbon of 20–30 mg/L and NH_4^+-N < 1.0 mg/L. The 180-day continuous operation demonstrated that a 100% water closure was achieved. Based on the results of this study, an upgraded water cycle system for larger-scale and longer-term CELSS has been proposed.

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1. Introduction

Controlled ecological life support system (CELSS) is an artificial ecosystem aiming to continuously provide humans with clean air, essential water and food during long-term space exploration (Guo et al., 2017). Previously, a number of closed ecological system experiments, including Biosphere 2 project (Nelson et al., 1993; Nelson et al., 1992), the BIOS-3 facility (Salisbury et al., 1997), the Closed Ecological Experimental Facility (CEEF) (Nitta et al., 2000), the 2-person-30-day CELSS in Beijing (Guo et al., 2015) and a 105-day experiment in Lunar Palace 1 (Dong et al., 2017), have been conducted.

The water cycle is important and challenging for any CELSS, because there are some specific organisms (such as higher plant, algae, insect, microbe, etc.) living in it (Nelson et al., 1999; Nelson et al., 2013). Water management subsystems (WMS) of CELSS should meet the water requirements of both humans and other organisms in the system. The first advanced bioregenerative closed system including humans was the Bios-3 facility built in Krasnoyarsk, Russia in 1972 (Gitelson et al., 1989; Salisbury et al., 1997). This 315 m^3 facility supported 12 food crops grown hydroponically, and 2–3 person living for closure experiments of up to 6 months between 1972 and 1984. In Bios-3, the water cycle was designed to be closed and recirculating. Condensate water evapotranspired from the plants in the three plant growth areas was an important part of the water collection and redistribution system. Most of this water was reused for the hydroponic nutrient solution. Water allocated for human use in washing and cleaning was boiled, and potable water was further purified by ion-exchange filters. The wastewater recovered from feces and urine was used as an additive to the hydroponic crop irrigation for wheat during the experiments conducted in Bios-3. This led to an increase in sodium in water and plant tissue, but not to unhealthy levels (Salisbury et al., 1997). Engineering Biosphere 2, the first multi-biome closed ecological system with a total airtight footprint of 12,700 m^2 and a combined volume of 200,000 m^3 and a total water capacity of some 6×10^6 L, created by far the largest artificial closed ecosystem. It included human inhabitants, their agricultural and technical systems, as well as five analogue ecosystems ranging from rainforest to desert, freshwater to saltwater ecosystems like mangrove and mini-ocean coral reef ecosystems. Between 1991 and 1994, Biosphere 2 crewed with eight people (Allen et al., 2003; Marino and Odum, 1999), succeeded in achieving a relatively complete water recycling and purification system predominantly using the pathways of evapotranspiration, condensation, and constructed wetland wastewater treatment. Disinfection of condensate water for potable water use was achieved through use of hydrogen peroxide and wastewater was treated with UV (Nelson et al., 2009). Mechanical assistance to recovery of condensation used fan-driven air movement to bring humid air to cooling coils, and pumping to deliver water to usage points. Algal turf scrubbers and protein skimmers helped remove nutrients from the marine ecosystems' water (Nelson et al., 2009). A bioregenerative life support systems “Lunar Palace 1” with a volume of 308 m^3 was established in 2014, in which a 105-day crewed closed integrative experiment was conducted (Fu et al., 2016). The WMS of Lunar Palace 1 consisted of three units, a humidity condensate water processing unit, a sanitary wastewater treatment unit, and a urine treatment unit. The humidity condensed water generated from the plant cabin and the comprehensive cabin was collected and then pumped through water purification equipment (activated carbon adsorption combining ultrafiltration and UV disinfection) (Xie et al., 2017). Most of the purified water was used for plant nutrient solution preparation, and the rest was served for drinking and sanitary water for the crew. Urine was treated with low-pressure distillation to regenerate water and part of the nitrogen it contained. The regenerated water was mixed with sanitary wastewater before going through a biologically activated carbon membrane reactor for purification. The purified water was then collected into a gray-water tank before being pumped into the nutrition tank for the preparation of plant nutrient solution. The residual semi-solid urine obtained from distillation was collected, then stored, and periodically sent out of the system (Fu et al., 2016).

Though there are some differences in the configuration and size of WMS in response to different ecological life support systems, the functions and objectives of WMS should be the same. A WMS should maintain balance in the water cycle, maintain required water quality, and achieve a virtually closed water cycle with minimum replenishment and consumption. Achieving water quality required for different uses is the biggest challenge, since such factors as air quality, plant metabolism, solid waste recycle, microbe growth, material surface dissolution and nutrient elements addition, affect it. Once water quality deteriorates, the health of crewmembers and the equilibrium of ecosystems are all threatened.

In order to further investigate methods to achieve a stable water cycle in CELSS, a closed ecological-cycle integrated ‘4 Crews 180 Days’ experiment ‘SPACEnter’ was conducted in Shenzhen, China (Dai et al., 2018; Zhang et al., 2018). The configuration and operation of the WMS of ‘SPACEnter’ focused on the safe production of domestic water to guarantee crew's daily living requirements, stable water quality of the hydroponic nutrient solution, and the integrated water balance of the entire system.

2. Methods

2.1. Cabin configuration and water distribution

An airtight facility with the intention of experimenting with controlled ecological life support was established in Shenzhen, China, in 2015. This CELSS test base was constructed of stainless steel covered with a insulation layer for temperature control, and consisted of 8 individual cabins, including 4 Plant Cabins (PC), 2 Crew Cabins (CC), 1 Life Support Cabin (LSC), and 1 Resource Recovery Cabin (RRC), with a total volume of around 1340 m^3. The configuration of the base was shown in Fig. 1, LSC and the 2 CCs shared the same atmospheric environment, as did the PC-I and PC-IV.

The following construction processes was adopted to ensure good air tightness of the test base. 1. Firstly, the main structure of the platform is made of stainless steel, and all the 8 cabins and 4 transition cabins were combined together into a whole structure by argon arc welding process (Fig. 1). 2. Four emergency escape gates to the outside (located in PC-1, plant cabin PC-3, RRC and CC-1) connected to the cabin by flange with silicone sealing rings, and the main entrance gate (that

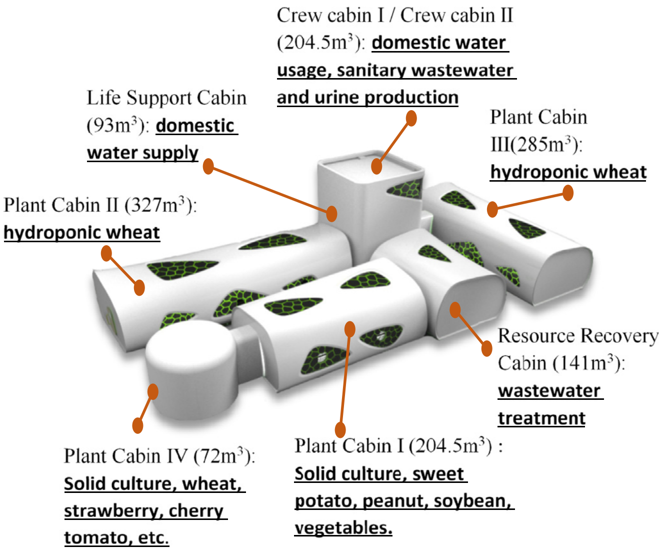

Fig. 1. Cabin configuration of CELSS test base.