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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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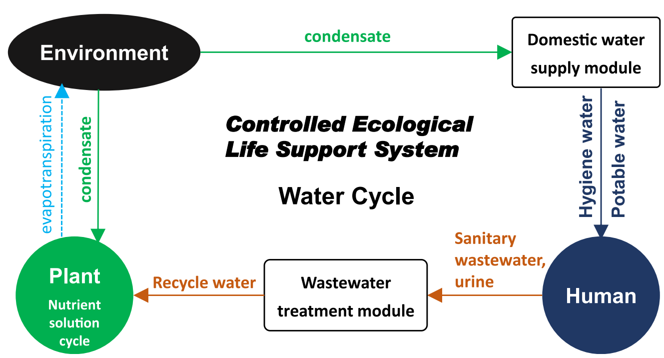
HIGHLIGHTS

- 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

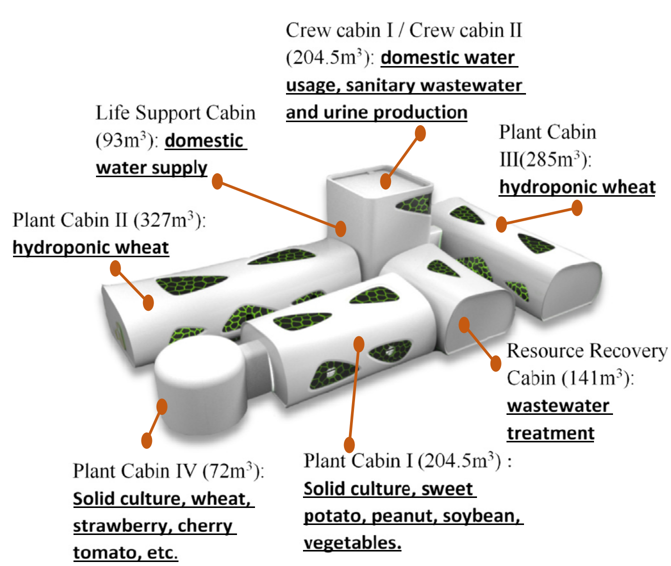

Fig. 1. Cabin configuration of CELSS test base.

located in RCC) consisted of a transition cabin and two airtight gates installed on both sides of the transition cabin. 3. Three transfer windows adopt double-layer sealing window structure to avoid direct gas exchanging during test sample delivering. 4. The other pipeline interfaces were also installed by sealing flange to ensure air-tightness of the entire test base. Before and after the integrated experiment, the method of CO_2 diffusion (~8000 ppm CO_2, longer than 96 h sealing time) was used to test leakage rate of the whole test base. The tested leakage rate was about 0.0284m^3/h, which was at a very low level. Furthermore, we calculated the amount of gas exchange due to the test sample delivering through transfer windows during the whole experiment period, that was about 6.6 m^3 in total. For a test base with a total volume of 1340 m^3, it could be considered to be negligible that the impact of such a gas exchange level on water cycle data.

In the 4 subjects (3 males and 1 female) 180-day CELSS integrated experiment, 25 crops were planted to produce carbohydrate plant oils, plant proteins, fresh vegetables and fresh fruits. The total planting area was around 195 m^2, including a solid cultivation compartment (PC-I 70.14 m^2, PC-IV 13.92 m^2, using vermiculite as solid medium) and a hydroponic cultivation compartment (PC-II 81.9 m^2, PC-III 29.4 m^2). The overall amount of water cycled in the system was about 23 m^3, 92.6% of which was retained in the 4 plant cabins, where cultivation tray, nutrient solution tanks and condensate tanks store water, and the rest of which was retained in the domestic water supply module (DWS) located in LSC and in the wastewater treatment module (WWT) located in RRC. The water distribution in the 180-day experiment (Table 1) indicated that almost 73% of total water was used for hydroponic wheat growth in PC-II and PC-III, and the average water distribution in the hydroponic system was above 140 L/m^2, more than twice the amount of water used in the solid cultivation system.

2.2. Overview of water management subsystem

The overall WMS is schematically diagrammed (Fig. 2). The water cycle was chiefly powered by plant transpiration and air evaporation, and water vapor condensation was collected mainly through constant temperature and humidity units (CTHU). All condensate water was collected in the CTHU cooling coils located on the top of cabins, >98% of condensate water was collected from the plant cabins. The remaining 2% was collected from LSC and RRC, and was subsequently returned to the nutrient solution tank. About 94.4% of the condensate water was recycled to the plant nutrient solution tank after UV disinfection, and 5.6% of it was used as influent of DWS. DWS consisted of the hygiene water supply unit and potable water supply unit. The condensate from plant cabins was purified through two-stage membrane bioreactor (MBR) and nano-filtration (NF), and then was provided as hygiene water (for personal hygiene, cleaning of clothes and toilet flushing). The hygiene water was further purified by reverse osmosis (RO), ion exchange (IE) and polyiodide disinfection (PI) to provide potable water for drinking and cooking. To guarantee the crews' health, some mineral elements were added to potable water through edible mineralization column (MC) (Li et al., 2018). Purified water became wastewater after use by the crew. Such wastewater, including sanitary wastewater and urine, was first collected in the wastewater storage tank and then treated by WWT. The WWT module mainly consisted of an anaerobic MBR and an aerobic MBR, where the conversion of organic matter and nitrogen in wastewater was conducted by anaerobic and aerobic microorganisms. The tubular membrane module and the flat sheet membrane module were used in anaerobic MBR and aerobic MBR respectively. During the 180 days experiment, we carried out backwashing or membrane module replacement according to the level of transmembrane pressure to minimize the consumption of membrane module. Regenerated wastewater was used in the nutrient solution water. It was firstly stored in the nutrient solution tanks in the plant cabin, and delivered by pumps to the plant trays and then returned to the storage tank through gravity flow. In the outlet of the cycle pump, the pipeline UV and activated carbon adsorption bed (AC) was mounted if needed. However, during 180-day experiment period, the AC unit was not operated because the recycled nutrient solution was maintained with good quality water. Besides, there were 2 subsystems of nutrient solution self-circulation A and B in each plant cabin (Fig. 2).

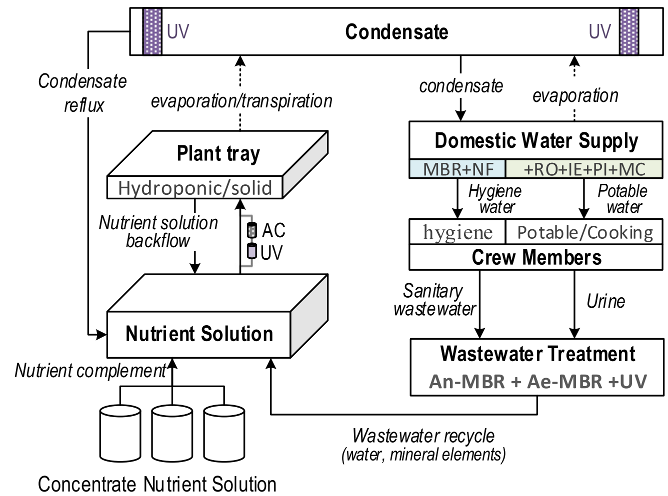

Fig. 2. Overview of water management system in 180-day CELSS experiment.

For adjusting nutrient content of the irrigation water, a concentrate nutrient solution was designed to be pumped into the plants' nutrient solution when necessary. Details of WMS quantity information are shown in Table 2 and Fig. 3.

2.3. Data acquisition method

Water quality parameters are analyzed following APHA Standard Method (APHA, 1998). Total organic carbon (TOC) was analyzed by total organic carbon analyzer (TOC-4200, Shimadzu); NH_4^+-N was determined by colorimetric method using a UV/Visible spectrophotometer (UV 2450, Shimadzu), following the methods outlined in Standard Method; Na^+ was determined by ICP-MS (NEXION350X, PerkinElmer); Cl^- was determined by Ion chromatography (ICS-5000+, ThermoFisher); and pH was measured using a pH meter (P33A1NN, HACH). On day 10 of each phase, water samples were withdrawn and subject to be analyzed. Each sampling event was recorded in detail for regulating the water cycle cloture. All the analysis tests were carried out in duplicate and repeated 5 times. The Student's *t*-test was used to statistically evaluate the significance of a difference of two data sets. A confidence level of 95% was used to determine the critical value of the *t*-distribution.

And water quantity data was obtained through online measurements, the flowmeters and methods were all calibrated before the experiment to ensure the relative standard deviation of water quantity <5%.

Table 1
Water distribution, fluxes, and residence times in 180-day CELSS integrated experiment.

Reservoir	Volume (L)	% of total water	Typical water flux (L/d)	Residence time (d)
PC-I	4087.5	17.7	249	16.4
PC-II	11,528	50.0	455	25.3
PC-III	5303	23.0	131	40.5
PC-IV	455.2	2.0	69.3	6.6
LSC	376.7	1.6	50.6	7.4
RRC	284.8	1.2	51.4	5.5
Atmosphere	14	0.06	917.1	0.37 h
Plant straw	1017.1	4.4	8.7	116.9

Table 2
Characteristics of water cycle in 180-day CELSS integrated experiment in the dynamic balance period.

Water category	Quantity (L/d)	Water quality (mg/L)	
		Concentration range	Average concentration
PC-I condensate	249	TOC: 1.7–18.7; pH: 5.9–8.2 NH_4^+-N: 0.7–15.8	TOC: 8.2 ± 4.8; pH: 6.7 ± 0.9 NH_4^+-N: 7.1 ± 3.1
PC-II condensate	455	TOC: 3.9–53.9; pH: 5.7–8.4 NH_4^+-N: 0.5–8.8	TOC: 6.8 ± 13.9; pH: 6.9 ± 0.9 NH_4^+-N: 2.0 ± 1.7
PC-III condensate	131	TOC: 4.2–31; pH: 5.8–8.3 NH_4^+-N: 2.8–12.9	TOC: 6.7 ± 7.0; pH: 6.6 ± 1.0 NH_4^+-N: 4.7 ± 2.4
PC-IV condensate	69.3	TOC: 0.6–18.6; pH: 5.7–8.2 NH_4^+-N: 0.6–7.2	TOC: 2.5 ± 5.8; pH: 6.9 ± 0.7 NH_4^+-N: 1.3 ± 1.7
LSC condensate	7.1	TOC: 107–288; pH: 5.8–8.4 NH_4^+-N: 25–50	TOC: 134 ± 46.9; pH: 6.5 ± 0.7 NH_4^+-N: 37 ± 7.2
RRC condensate	5.7	TOC: 20–890; pH: 5.9–8.1 NH_4^+-N: 50–422	TOC: 265 ± 259.6; pH: 6.8 ± 0.6 NH_4^+-N: 195 ± 92.9
PC-II-A nutrient solution[a]	9500 L	TOC: 13.9–40 NH_4^+-N: 0.3–2.2	TOC: 25.7 ± 6.8 NH_4^+-N: 0.65 ± 0.58
PC-II-B nutrient solution[a]	1900 L	TOC: 6.8–43 NH_4^+-N: 0.2–2.0	TOC: 30.1 ± 9.1 NH_4^+-N: 0.66 ± 0.54
PC-III-A nutrient solution[a]	2500 L	TOC: 16.4–40.7 NH_4^+-N: 0.4–1.9	TOC: 20.9 ± 7.3 NH_4^+-N: 0.37 ± 0.52
PC-III-B nutrient solution[a]	2600 L	TOC: 24.4–40.7 NH_4^+-N: 0.2–2.0	TOC: 30.1 ± 6.6 NH_4^+-N: 0.28 ± 0.14
Potable water	10.9	TOC: <0.5; pH: 5.4–8.2 NH_4^+-N: <0.02 EC: 3.2–12.2 μS/cm	TOC: <0.5; pH: 6.7 ± 0.7 NH_4^+-N: <0.02 EC: 4.8 ± 2.6 μS/cm
Mixed wastewater	51.4	TOC: 50–1200; pH: 8.0–10.7 NH_4^+-N: 650–1550	TOC: 685 ± 265.7; pH: 9.05 ± 0.9 NH_4^+-N: 1054 ± 245.9
Recycle water/treated wastewater	51.37	TOC: 7.8–65; pH: 6.2–7.9 NH_4^+-N: 0.88–439	TOC: 19 ± 3.1; pH: 7.3 ± 0.9 NH_4^+-N: 62.7 ± 17.8[b], 329 ± 117.5[c]

[a] A and B represent the two independent systems of nutrient solution circulation in the same PC, and the value behind is the total amount of nutrient solution.
[b] The average of the first 100 days.
[c] The average of the next 80 days.

3. Results

3.1. Quantitative features of the water cycle

In the 180-day CELSS integrated experiment, crops were planted in successional batches to lower volume fluctuations of circulated water due to the variation of photosynthesis and transpiration at different crops' growth stages. When all the planting areas were planted, food production and photosynthesis achieved a relatively stable level and crop transpiration also reached a steady state. The quantitative features of overall water cycle during the steady state in the 180-day experiment are shown in Fig. 3. Water in solid, liquid, and gaseous form circulated by processes including plant growth, evapotranspiration, condensation, human metabolism, solid waste conversion, and wastewater treatment.

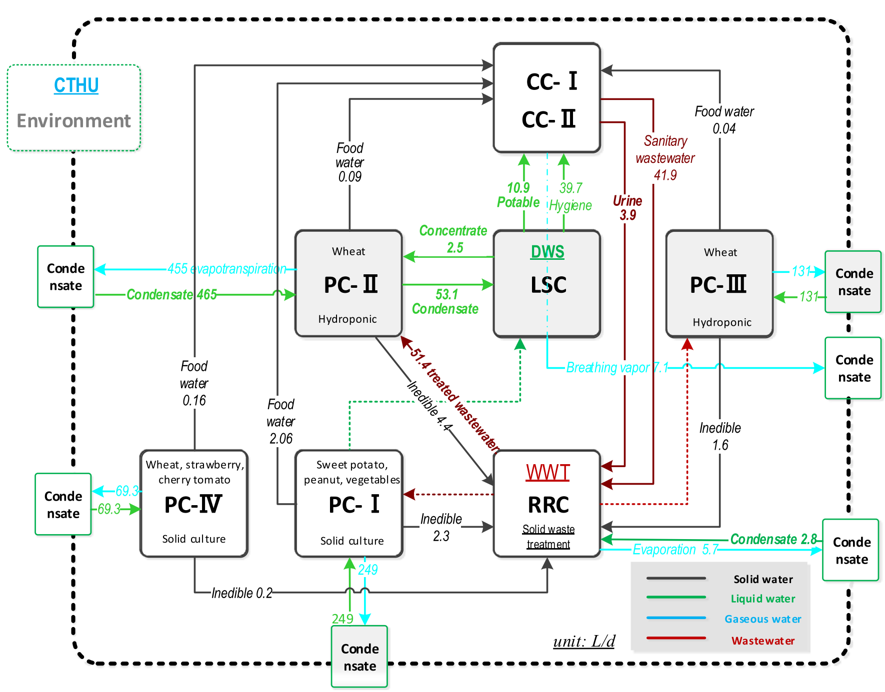

Fig. 3. Typical quantitative model of water cycle in 180-day CELSS integrated experiment in the dynamic balance period. The self-circulation of plant nutrient solution in PCs, and the water transportation, which produced during inedible plant treatment (drying, biological or chemical oxidation), between the solid waste treatment module and WWT in RRC, were not shown.

Despite these varying driving forces, a safe and stable water cycle in the CELSS was established.

The quantitative characteristics of the water cycle of the CELSS can be divided into four categories.

1) Condensate collection and distribution. The total collected condensate water in the whole CELSS was 917 L/d, and most of the condensate of all the cabins was produced in PC-II, 455 L/d. The condensate production rates of PC-I, PC-II, PC-III, and PC-IV was 3.75 $L/m^2/d$, 5.33 $L/m^2/d$, 5.86 $L/m^2/d$ and 5.05 $L/m^2/d$, respectively, indicating that evapotranspiration by grain food crops was greater than that of vegetable crops. Almost all condensate generated from PCs returned into their own nutrient solution tanks after UV disinfection, excluding 53.1 L/d condensate produced from PC-II, which was delivered to the DWS. The crew members' humidity condensate with an average of 7.1 L/d (1.78 L/CM-d) was collected in LSC and then transported to PC-II to enter the nutrient solution circulation. This amount was smaller than that of 2.27 L/CM-d reported by NASA in 1991 (Hanford, 2008), which was a result of crew members doing work in other cabins. The humidity condensate collected from the wastewater treatment process and solid waste (feces and inedible plant) treatment process was first collected in RRC and averaged 5.7 L/d, and then preferentially passed through WWT, subsequently being discharged into PC-II.
2) Domestic water supply and wastewater treatment. The average daily domestic water supply was 50.6 L/d, including 10.9 L of potable water and 39.7 L of hygiene water. Compared to normal requirements, the average daily hygiene water was relatively lower in this experiment. This might be because 2 crewmembers took waterless showers instead of normal water showers during the 180-day test. When taking waterless shower, crewmembers only use about 150 mL of water to dissolve the special cleaning agents for the body and hair cleaning, that was one of valid ways to save water consumption in manned space flight missions (Li et al., 2018). Wastewater from different sources, including urine, sanitary wastewater, condensate of solid waste treatment, was mixed together in the wastewater storage/regulate tank, then treated by WWT, and subsequently pumped into the nutrient solution tank of PC-II with an average water flow rate of 51.4 L/d. Urine and sanitary wastewater was collected and moved to WWT in the RRC, with an average production rate of 3.9 L/d and 41.9 L/d, respectively. Compared with the urine amount of 1.2–1.5 L/CM-d reported in earlier research (Hanford, 2008), 0.98 L/CM-d in our experiment was lower. This might be attributed to the crew's individual differences caused by dietary structure and metabolic levels.
3) Water allocation between cabins. As shown in Fig. 3, under normal operations, PC-II was the primary center of the whole water cycle, and also the intake of domestic water as well as the returning port for treated wastewater. However, several factors disturbed water equilibrium among cabins, e.g. plant harvest, the required ventilation between cabins for CO_2 or O_2 transfer, and crew members' movement among different cabins. If the normal water equilibrium was disturbed, there would be potential water transfers which might lead to an excess or shortage of cabin water. Under normal water cycles, the water balance of each cabin could be estimated by a water cycle flow model, and the predicted deviation was as +6.3 L/d in PC-II, −4.3 L/d in PC-I, −1.6 L/d in PC-III, and − 0.4 L/d in PC-IV. Based on the predictions, to restore water equilibrium, two pre-arranged ways of water cycle regulation were designed as follows: 1. treated wastewater would be pumped to PC-I and PC-III as shown by the dotted red line. 2. the DWS would take raw water from the PC-I' condensate as a water source as shown in the dotted green line (Fig. 3). During the whole actual experimental operation, there were only two times that these mode switches were needed and the total runtime under normal mode was used for >170 days of the experiment.
4) Water residence time. The results from Biosphere 2 demonstrated that biogeochemical cycles of closed ecological systems are greatly accelerated compared to such cycles in natural systems. For example, atmospheric water turnover (~4 h) in Biosphere 2 was accelerated by a factor of ~54 compared to that in the global biosphere (~9 days) (Nelson et al., 2009). In our 180-day experiment, the overall atmospheric water residence time of ~0.37 h was around 11 times and 584 times faster than that of Biosphere 2 and the global biosphere respectively. The water cycle in PC-III had the longest residence time of 40.5 d among the 4 plant cabins. In response to the entire water cycle of "plant-environment-DWS-crewmember-WWT-plant", the circulation rate was equal to that of the domestic water supply, because it was the slowest link in the whole cycle. Hence, the total water circulating period in our CELSS was calculated as ~466 d.

3.2. Qualitative features of the water cycle

Water quality is very significant the CELSS operation. When water quality deteriorates, this affects water closure, and could threaten human health and plant growth. There were five kinds of water in our 180-day experiment, including 1) condensate from air evaporation and plant transpiration, 2) nutrient solution of hydroponic plant system, 3) potable water, 4) mixed wastewater and 5) recycle water (treated wastewater). The water quality could be influenced by several factors, such as plant growth, atmosphere environment, cabin ventilation, human metabolism and water treatment technologies used in the subsystem. The overview of water quality in the dynamic balanced period is shown in Table 2.

Table 2 shows that condensate water quality collected in PCs was good. The average concentration of total organic carbon (TOC) and ammonia nitrogen (NH_4^+-N) were both below 10 mg/L. Among all 4 PCs, the water quality in PC-I was the worst, which might be due to the ventilation between PC-I and RRC. Compared to condensate in the PCs, the condensate collected in LSC or RRC had much poorer water quality, especially in RRC with the average concentration of TOC and NH_4^+-N up to 265 mg/L and 195 mg/L, respectively. This difference of the water quality between the cabins was caused by two factors. On the one hand, much more pollutants were produced from crew members' daily use of water in CC1/CC2/LSC (i.e. cooking, dining, physical exercise, medical checks, washing, urination) and waste treatment process in RRC (including defecation, solid waste treatment, wastewater treatment, etc.) are released into the atmosphere and then absorbed into the condensate. On the other hand, the amount of condensate quantity was much less in LSC and RRC than that of in PCs, which would increase the pollutants' concentration. However, the comprehensive water quality of condensate collected in this CELSS was much better than the ersatz humidity condensate with design TOC concentration of 51.4 mg/L in the early planetary base designed by Verostko et al. (2004).

There was no obvious difference in nutrient solution quality among the four systems, and the pollutant concentration range was stable within a TOC of 20–30 mg/L and NH_4^+-N < 1 mg/L (Text S1, Fig. S1). Compared with the condensate produced from the plant cabins, more organic substance and less ammonia were obtained in the nutrient solution, which might be attributed to plants absorbing NH_4^+ and simultaneously releasing organic compounds through their root systems (Beck and Gilmour, 1983; Coskun et al., 2017). Though the TOC concentration of nutrient solution should be continuous increasing theoretically because of the continuously treated wastewater recharge, the actual slight change of TOC (Fig. S1) during the whole 180 days experiment we think may be due to the effects of microbial degradation, root decomposition and radicular system absorption in the nutrient solution. Unlike TOC, the accumulation of NaCl in PC-II-A nutrient solution was high, with concentration of Na^+ and Cl^- reaching 197 mg/L and 167 mg/L, respectively, because of the continuous recirculation of treated wastewater into the nutrient solution. Nevertheless, the wheat yield of PC-II-A was not affected by this NaCl accumulation during the entire 180 day experiments.

Potable water was purified from PC condensate by DWS, and its quality maintained stable during the whole experimental duration. The water simultaneously met both China's national standards (Standards for Drinking Water Quality, GB 5749-2006) and the medical standards developed in this experiment (Li et al., 2018).

The pollutant of the mixed wastewater consisting of urine, sanitary wastewater and RRC condensate, with an average concentration of TOC 685 mg/L and NH_4^+-N 1054 mg/L, was a little higher than that of simulated early planetary base wastewater, in which TOC was 631 mg/L and NH_4^+-N was 852 mg/L (Hanford, 2008; Verostko et al., 2004).

Most of the organic matter and part of ammonia in the wastewater were converted by the biological processor WWT to avoid its negative impact on plants (Table 2). In the final effluent of the treated wastewater, the TOC concentration was maintained at a low level during the whole experiment. While the NH_4^+-N concentration was controlled at two levels; with <65 mg/L in the first 100 days and >200 mg/L in the last 80 days. Though there was great changes of NH_4^+-N in the final effluent of treated wastewater, NH_4^+-N concentration in PC-II-A nutrient solution was always maintained below 3 mg/L, which further demonstrated that wheat had good NH_4^+-N absorption (Dai et al., 2003).

4. Discussion

A water cycle management subsystem is necessary and critical to space flights (i.e. transit vehicle, space station, et al.) and planetary bases (i.e. lunar base, Mars base, et al.). But for planetary bases, due to the introduction of higher plants into CELSS, the amount of cycled water is much more than that in space flights, consequently a more complicated water management subsystem should be installed in CELSS. The primary purpose of WMS is to keep water cycle healthy and to reduce the need for water supplements. This can be achieved by maintaining the water amount balances among different biomes or locations of water storage and usage, and ensuring the delivery of waters of appropriate water qualities for different uses. The whole experimental results described above demonstrates that water distribution among all six cabins reached overall balance, and water quality of nutrient solution and potable water was maintained in a stable and healthy manner. There was no water supplement or discharge needed during the whole experimental time, excluding 1.86% of total water used for research samples. We conclude that a 100% water closure was obtained in this experiment.

As shown in Table 2, water quality of evapotranspiration condensate collected in the plant cabins was much better than expected, so the process of DWS could be simplified. But, some kinds of C_4–C_9 organic substances was observed in nutrient solution (data not shown), indicating that some kinds of root exudate had been released. Hence, in order to ensure the nutrient solution security in the longer-time experiments, some new purification processes should be added for nutrient solution recirculation. For the same reason, a condensate purification process should be added in condensate reflux to reduce condensation organic matter entering into the nutrient solution. Since organic matters was the main pollutants of plant nutrient solution and condensate, according to the treatment performance of WWT in this experiment, we considered that biological treatment technologies could be selected to purify these two wastewaters, and because of lower energy consumption, anaerobic biological process will be preferred.

As crew members' daily necessities, NaCl was supplied continuously and excreted in crews' urine, and then subsequently accumulated in nutrient solution recharged by the wastewater in this study (~8.6 mM at the end of the experiment), since NaCl could not be degraded by WWT and assimilated by crops. For avoiding the adverse effect of NaCl or other potential substance accumulation on the crops in much longer-time or permanent manned CELSS base, a dedicated urine

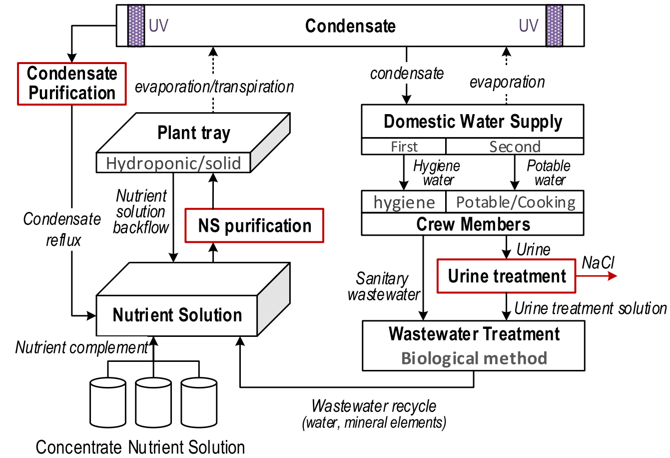

Fig. 4. Overview of suggested water subsystem for longer time or permanent CELSS base.

treatment module should be set up in the water cycle system. As for wastewater treatment, the final NH_4^+-N effluent concentration can be elevated to higher than 329 mg/L, since NH_4^+-N is effectively absorbed by hydroponically grown wheat in a CELSS. So the nitrification capacity in the WWT can be lowered to reduce energy required for aeration, hydraulic retention time, and the reactor volume of WWT. Based on an optimization analysis, the suggested water cycle subsystem for much more longer-time or permanent CELSS with the same configuration in this research is shown in Fig. 4. As for the wastewater biological treatment technology mentioned in the figure, we still suggested the combination process of anaerobic MBR and aerobic MBR, which was developed from WWT process of this experiment after doing possible improvement (such as the utilization of biofilm process, etc.) to enhance the membrane fouling resistance. The excess sludge generated in the biological treatment process could be concentrated and mixed with biomass solid waste (feces, plant inedible parts, etc.), and then converted into organic fertilizer through the solid waste fermentation process.

Energy consumption is critical to the sustainability of CELSS, although the main purpose of this paper was to verify the feasibility of water cycle technologies, the energy consumption and composition of this experiment was also monitored and investigated. The power source of this CELSS test base consisted of the municipal electricity supply and the solar photovoltaic power (SP) system that was installed on the roof of the experimental building. And the SP system contributed 3.3% of the total power demand, most of the power requirement was supplied through the municipal electricity during the experimental period. As for the WMS, the energy consumption mainly included, 1) plant nutrient solution recirculation, 2) domestic water supply, and 3) wastewater treatment, and the power was mainly used for water transportation and oxygen supply. Table 3 shows the energy consumption statistics of WMS, and the total WMS power was approximately 1.0 kW, and the module of WWT had the highest energy consumption, accounting for 53% of WMS. For the longer and larger 100% water closure system, the following methods might be effective to improve the energy efficiency, 1) Using low-oxygen aeration technology to reduce energy

Table 3
Energy requirement of WMS in 180-day CELSS integrated experiment.

Items	Averaged energy requirement (W)	Proportion (%)
Plant nutrient solution recirculation	244	24
Domestic water supply	233	23
Wastewater treatment	532	53
Total of the water cycle management	1009	100

consumption of biological water purification, 2) Introducing anaerobic biological treatment technology to deal with organic matter pollution in nutrient solution, 3) Developing nutrient film technique to reduce power demand for plant nutrient solution circulation.

Moreover, according to the research results of Ewert et al. (1996), for a CELSS base established on Lunar surface and powered by SP power generation with regenerative fuel cell for power storage, the required energy equivalent mass would be as high as 749 kg/kW. So, from an engineering perspective, nuclear propulsion and nuclear power for CELSS base may be more potential to provide the required power at an acceptable cost (Hanford, 2008).

5. Conclusion

In the 180-day CELSS integrated experiment, a balanced water management subsystem was established to meet the water requirements of 25 crops and 4 crewmembers. Water allocation among the different cabins was maintained in a relatively balanced state and the water quality of different kinds of waters was maintained within health standards. As a result, all the water was regenerated to supply in situ during the whole 180 days and reached a 100% water closure in this experiment. Plant evapotranspiration was the main driving force of the water cycle in this CELSS, and plant transpiration condensate was reused as water source of DWS to provide water for the crew. The modules of DWS and WWT were the key functional units which ensured water quality was maintained within safety ranges. UV disinfection module was used to ensure the microbial safety of the entire water system. For longer term or a permanent CELSS base, some further purification processes, such as plant nutrient solution purification and independent urine treatment module, should be employed to ensure the water quality of the plant nutrient solution.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2018.10.080.

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