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Short communication

The fluxes of carbon, nitrogen and water in the multibiological life support system

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ABSTRACT

To establish bioregenerative life support systems (BLSS) on lunar or mars bases, firstly, it is necessary to conduct BLSS experiments including humans and various kinds of creatures on the ground. Carbon and nitrogen balances as well as water cycle are the important subjects that need to be studied. To provide basis for establishing a manned BLSS, a multibiological life support system composed of lettuce, silkworm and algae was set up in this study to carry out gas exchange investigation between humans and the system. During this process, the production rate and quality of condensate, substance flows of lettuce, silkworm and algae in and out of the system as well as carbon and nitrogen contents of these substances were studied. Results showed water was completely cycled in the system and condensate quality was relatively good, certain amounts of carbon and nitrogen were accumulated in the system and existed in the form of microorganisms.

1. Introduction

In bioregenerative life support systems applied during long-term deep space exploration with long distance, basic living materials must be self-sufficiently provided, i.e., the system must possess relatively high closure degree (Bartsev et al., 1996; Bartsev, 2003; Morowitz et al., 2005). Besides, environmental engineers can establish small-scale closed ecosystem including several biological units similar to bioregenerative life support systems on the ground to study mass circulation and migration as well as transformation principles of the natural ecosystem (Toscano et al., 2009; Kotti et al., 2010). Therefore, it is necessary to investigate the balance of main elements in the system (Tong and Liu, 2011; Tong et al., 2011).

In Russian BIOS-3 experiments with humans, researchers processed drinking water and sanitary water in the higher plant and algae cultivation units via ion exchange and carbon filter. Through detecting COD, pH and mineral element (Na^+, K^+, Ca^{2+}, Mg^{2+}, etc.) contents of the above water, it is found that water in the system is conformed to the sanitary standard and can be utilized as potable water. The dynamics of nitrogen and phosphorous is controllable and balanced in the system (Гительзон et al., 1975).

In CEEF system, researchers monitored condensate production rates; meanwhile, condensate was reused as transpiration replenisher of hydroponic nutrient liquid. Abandoned nutrient of growing rice and other crops were reused in the system after microfiltration and reverse osmosis membranes processes (Abe et al., 2005; Tako et al., 2008).

Biological units and operation methods of different life support systems are distinct from each other, so element flow, water cycle and condensate quality of the systems were different (Nelson et al., 2009; Tako et al., 2001). Therefore, it is necessary to study the above problems of the multibiological life support system established in this study to provide some experimental basis for establishing life support system in the future.

2. Materials and methods

2.1. Integrative experimental system

An integrative experimental system (IES) composed of a CICS (Tong et al., 2011) and a Plate Photo-Bioreactor (PPB) was established. The PPB includes an automatic control system and a flat algae bioreactor with two LED panels as light source.

In the system, lettuce and *Chlorella vulgaris* were cultivated to satisfy humans' O_2 requirement, silkworms (*Bombyx Mori* L.) regarded as animal protein source for astronauts were cultivated in a conveyer-type manner to study gas exchange between humans and the multibiological system.

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2.2. Biological units in the system

2.2.1. Lettuce cultivation

In the plant cultivating chamber (PCC), five batches of red leave lettuce (*Lactuca sativa* var. capatata L.) with four-day growth interval were cultivated hydroponically (Tong et al., 2011).

2.2.2. Animal breeding

Every day, mulberry leaves and stem lettuce leaves were transferred into the animal breeding chamber (ABC) through mass exchange chamber to feed the silkworms (*Bombyx Mori* L.) from the 1st instar to the 3rd instar and the silkworms from the 4th instar to the 5th instar, respectively (Tong and Liu, 2011; Tong et al., 2011).

2.2.3. Chorella vulgaris cultivation

According to the biomass increment rate of the microalgae, certain amount of algae liquid was carried out from PPB, meanwhile, certain amount of nutrient liquid was supplemented.

2.3. Rules of gas exchange between humans and the system

Metabolic levels of four healthy male testers without smoking habit were normal. During the experiment, they did not take up any medicine (Tong et al., 2011).

2.4. Water cycle in the system

When there was only lettuce cultivated in the system, certain amount of deionized water was supplemented to the plant cultivation chamber through mass exchange chamber according to biomass increment and water content of lettuce taken out of the system. When the biggest lettuce were carried out of the system and the smallest lettuce were transferred into the system every four days, light expanded clay aggregate (LECA) used as growing substance of the biggest batch of lettuce was taken out of the system. Meanwhile, dry LECA of the smallest batch of lettuce was put into the plant chamber. Because certain amount of water was taken out of the system along with the biggest batch of lettuce, this part of water should be supplemented after harvest every four days. When lettuce and algae were simultaneously cultivated in the system, water was replenished according to water content of algae liquid and lettuce carried out. Besides, no other water was replenished; therefore, self-circulation of water in the system was realized.

Condensate firstly flew into 0.008 m^3 of tank under the temperature and humidity regulating chamber of CICS, and then flew into nutrient liquid storage tank under the plant cultivation chamber. Thus, the complete water cycle was realized.

2.5. Condensate quality measurement

pH, total organic carbon (TOC), total dissolved solid (TDS) and volatile organic carbon (VOC) of condensates produced in the system under different running conditions were tested with pH meter (USA, Thermo Orion, 868), TOC analyzer (Japan, SHIMADZU, V-CPH SB-005), electroconductivity meter (Italy, Hanna, HZ8733) and gas phase-liquid chromatography (USA, Agilent, GC6890-MS5973).

2.6. Carbon and nitrogen measurement

Carbon and nitrogen contents of the substance in the system were measured with an element analyzing equipment (Germany, Elementar Vario, EL).

3. Results and discussion

3.1. Water cycle in the system

When only lettuce was cultivated in the system, production rate of evapotranspiration water returned to the plant nutrient liquid tank in the form of condensate was 0.61 L/d. When lettuce and algae were cultivated simultaneously in the system, production rate of the evapotranspiration water from vapor released by the plant and algae via respiration and evaporation was 1.28 L/d which is about two times as much as that when only lettuce was cultivated. This phenomenon might be caused by the fact that the testers' respiration frequency in Phase 2 was two times as much as that in Phase 1. Therefore the amount of carbon that was exhaled by humans through respiration and transported into the system was increased, promoting the physiological reactions including respiration and evapotranspiration of the plants, then vapor released by them was also increased.

When lettuce, algae and silkworm were cultivated together, evapotranspiration water production rate was 1.23 L/d. When determining the number of silkworms which can be fed in ABC, half amount of oxygen produced by autotrophic creatures in Phase 2 was distributed to provide oxygen for the insects in Phase 3. Therefore, the total amount of carbon received by the autotrophic creatures in this phase is similar to that of Phase 2 when only human provided carbon for the autotrophic creatures. So the amount of evapotranspiration water of Phase 3 mainly produced by the higher plants is similar to that of Phase 2.

In the closed BIOS-3 system including humans, plants received water from the following sources: the condensate of transpirational moisture in the phytotrons and the moisture produced by humans in the living compartment; hygiene wastewater after taking a shower, washing, etc. (upon rough filtering); and human liquid waste as an additional source of water for wheat (Гительзон et al., 1975). Compared with this system, the system established in this study was simpler.

Almost all water was circulated in the CEEF. Condensate collected in the plant module was sterilized via UV and recycled as replenishing water compensating transpiration loss of nutrient solution. In addition to recycling of transpired water, waste nutrient solution from crops other than rice was also recycled after filtration and adjustment by addition of depleted nutrients. The waste nutrient solutions from rice and other crops were processed through micro filters (MFs) separately (Nitta, 1999; Nitta et al., 2000; Nitta, 2003; Tako et al., 2008). Similarly, certain amount of nutrient salts and deionized water were replenished every day in this study.

3.2. Condensate quality of the system under different running conditions

Table 1 shows evapotranspiration condensate qualities of the system under different running conditions (only lettuce cultivated, lettuce and algae cultivated together and lettuce, algae and silkworm cultivated simultaneously). It could be seen that the condensate qualities were generally in accordance with Chinese national potable water standard (GB5749-2006) except that total dissolved solid contents were a little low and TOC contents were a little high. When TDS content is lower than 300 mg/L, water taste is very good. However, if it is too low, it will taste insipid; therefore it is necessary to detect mineral element contents of the water. When the condensate is used as potable water, it is necessary to replenish mineral elements to it according to drinking water standards of astronauts and process it via membrane filter, disinfection and so