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Analysis and evaluation of strawberry growth, photosynthetic characteristics, biomass yield and quality in an artificial closed ecosystem

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ABSTRACT

Plant cultivation plays an important part in deep space manned mission, and the techniques could be used in ground facility agriculture. The screening of strawberry cultivars and a complete cultivation technique for strawberry are necessary in space life support system. In this work, two strawberry cultivars 'Benihoppe' and 'Frandy' were cultivated under high CO_2 concentration in a closed ecosystem to establish key techniques for strawberry planting for space life support. The main objective of the study is to analyze and evaluate of growth, photosynthetic characteristics, biomass yield and quality of strawberry in a closed ecosystem. Our result showed that the two strawberry cultivars grew well during the 105-day-closed experiment, providing 37.4 g fresh berries every day for the crew in the closed system. The yield, harvest index and sugar content of 'Frandy' were comparatively higher than those of 'Benihoppe', among which the daily dietary allowance of trace elements and amino acids (18 kinds) in the fruits stood out. This study provided experimental support for the cultivation techniques of berry plants both for life support system and ground facility agriculture, and afforded a new perspective and sufficient information about strawberry cultivation and selection under the special condition of closed ecosystem.

1. Introduction

Bioregenerative Life Support System (BLSS) is an artificial ecosystem consisting of complex symbiotic relationships among higher plants, animals, and microorganisms. Biotechnology and engineering control technologies perfectly integrated build the BLSS according to the principles of ecological system (Dong et al., 2014; Gitelson and Lisovsky, 2003). Similar to in the Earth's biosphere, higher plants in BLSS can provide human beings with fresh air, clean drinking water, nutrient-rich food and spiritual consolation necessary, essential to long-term manned space missions (Lasseur et al., 1996; Levine and Paré, 2009).

At present, food crops and vegetable cultivars are the main focus in the study of plant unit in BLSS. Some plant species suitable for the space cultivation have been screened, environmental factors for plant cultivation under controlled conditions (Xu and Liu, 2008; Hu et al., 2011) partially optimized, and meanwhile, the vegetable cultivation system for spacecraft studied (Fu et al., 2013; Hu et al., 2014). As a berry with high nutrition, strawberry is full of vitamins and nutrition elements, and has been widely cultivated under plant factory systems in China and other Asian countries. Besides, strawberry possesses such characteristics as long harvest time and shorter plant height, which meet the criteria of species selection for BLSS (Xu and Liu, 2008). Currently, strawberry has been chosen as candidate crop worldwide in experimental life support system to provide vitamins, mineral elements and improve diet tastes. Although studies for strawberry have been done by NASA and MELISSA in their life-support experiments (Gros et al., 2003; Wheeler and Sager, 2006), strawberry cultivation as a life support system research is still in its infancy with little experimental results. Compared with other food crops, the horticultural operation and daily management of strawberry cultivation are more complex, requiring stringent temperature and humidity control, and strawberry is vulnerable to pathogen infection. Therefore, in life support

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Table 1
The yield per square meter of two strawberry cultivars. Data were calculated from the yield data at each harvest per cultivar.

	Fresh weight (g)	Dry weight (g)	Daily fresh weight (g)	Daily dry weight (g)	Harvest index
Frandy	1701.5	178.41	24.3	2.55	0.32
Benihoppe	916.2	57.33	13.1	0.82	0.18
Total	2617.7	235.72	37.4	3.37	

system a complete cultivation technique for strawberry is needed, where there is relatively high CO_2 concentration and temperature. Some studies done in controlled environments have found that high CO_2 concentration, temperature, and nitrogen conditions would reduce strawberry yield and fruit quality (Konsin et al., 2001; Ledesma et al., 2008), making the screening of strawberry cultivars necessary. Although previous studies have screened some strawberry cultivars for life support system based on the yield and quality in conventional environment (Gros et al., 2003; Wheeler and Sager, 2006), few studies have been done to study the planting and quality characteristics under special environment of an actual life support system.

Lunar Palace 1 is a ground experimental test-bed of bioregenerative life-support system, composed of a comprehensive cabin and one plant cultivation cabins (Fig. S1). As an artificial closed ecosystem, Lunar Palace 1 could provide human with basic living requirements. Oxygen, water and food regenerate through biotechnology, making it possible for human to live for long periods. Lunar Palace 1 is air-tight and composed of a comprehensive cabin and a plant cultivation cabin. The plant cultivation cabin includes two rooms; the environmental conditions within these two rooms were controlled separately according to the growth demands of different plants.

In order to screen out a suitable strawberry cultivar and establish a complete cultivation technique for strawberry for space life support system, two strawberry cultivars 'Benihoppe' and 'Frandy' were cultivated in the plant cabin of Lunar Palace 1, when three volunteers lived in this closed system for a 105-day period. The cultivation technologies for strawberry with inorganic matrix as growing media and water supplied by the negative pressure of porous tubes were established. The main objective of this study is to analyze and evaluate of growth, photosynthetic characteristics, biomass yield and quality of strawberry for screening out suitable strawberry cultivar for life support system by actual planting in simulated life support system environment. This study provided experimental support for the cultivation techniques of berry plants both for life support system and ground facility agriculture, and afforded a new perspective and information about strawberry cultivation and selection under the condition of artificial closed ecosystem.

2. Materials and methods

2.1. Plant material and cultivation conditions

In Lunar Palace 1, plants were grown in plant cultivation racks designed by our team. Plant racks were divided into three layers, each having a separate light board and cultivation tank. The so-called "Soil" was a kind of inorganic matrix "vermiculite" determined by a special screening, and nutrient solution supplied by the negative pressure of the porous tubes. This cultivation method in low gravity of the lunar-base is still feasible, as well as the microgravity conditions in space station. Seedlings were cultivated first in plastic pots with nutrient solution for one week in an artificial climate chamber, and then transplanted into the plant compartment in Lunar Palace 1. The cultivation condition in artificial climate chamber and Lunar Palace 1, such as light intensity, photoperiod, temperature, relative humidity and nutrient solution were similar, while the CO_2 level in the artificial climate chamber was atmospheric level.

The strawberry cultivars were 'Benihoppe' and 'Frandy', two widely cultivated cultivars in China with high yield and good disease resistance. The planting acreage was 0.5 m^2 for each seedling and planting density was 10 seedlings. The planting matrix was medium-grained vermiculite supplied with Hoagland nutrient solution. LED lights with full spectrum were used as light source, and the light intensity was 500 μmol m^{-2} s^{-1} with a photoperiod of 12/12 h light/dark. The CO_2 level was in a dynamic range of 500–5000 ppm in the closed ecosystem. The relative humidity (RH) was maintained at 55 ± 4.6%, with a temperature of 21 ± 1.3 °C during daytime and night.

The Hoagland nutrient solution (Hoagland and Arnon, 1950) included: $Ca(NO_3)_2 \cdot 4H_2O$, 945 mg/L; KNO_3, 607 mg/L; $NH_4H_2PO_4$, 115 mg/L; $MgSO_4 \cdot 7H_2O$, 493 mg/L; Fe-EDTA, 30 mg/L; $MnSO_4 \cdot H_2O$, 2.13 mg/L; $CuSO_4 \cdot 5H_2O$, 0.08 mg/L; $ZnSO_4 \cdot 7H_2O$, 0.22 mg/L; $(NH_4)_6Mo_7O_{24} \cdot 4H_2O$, 0.02 mg/L; H_2BO_3, 2.86 mg/L, and the pH was 6.0.

Seedlings needed regularly pruning of old yellow leaves after planting, and thinning the flowers timely after the inflorescence appeared. Generally 3–5 flowers were reserved per inflorescence. The weight of all these wastes was recorded and added into the weight of inedible weight. After flowering, the flowers were pollinated artificially.

2.2. Yield and physiological analyses

2.2.1. Photosynthesis related indicators

Net photosynthesis rate (Pn) of leaves of two cultivars was measured using the LI-COR portable infrared CO_2 gas analyzer (LI-6400 XRT portable photosynthesis system, LI-COR Biosciences, Lincoln, NE, USA). Block temperature was kept at 22 °C during all measurements (registered leaf temperatures ranging 21–22 °C) vapor pressure deficit (VPD) at around 1.5 kPa (Peng et al., 2009; Yang et al., 2008), and each plant were determined with fully expanding leaves in the same position. As the CO_2 concentration changed dynamically, the Pn is measured only when the CO_2 concentration was relatively stable. The concentration was: 500 ppm, 1500 ppm, 2000 ppm. Other experimental conditions such as PPFD, air temperature, and relative humidity (RH) were set as 500 μmol m^{-2} s^{-1}, 21 °C, and 55% respectively. After each determination of Pn, Photosynthetic pigment content was extracted by acetone from the leaves (fully expanded, exposed) of 10 plants at a similar position for each treatment. The optical density was measured with a UV-1200 spectrophotometer (SP-75, Shanghai spectrum instruments co., LTD, China) at 663 nm (OD_{663}) for chlorophyll *a* (Chl. *a*), and 645 nm (OD_{645}) for chlorophyll *b* (Chl. *b*) (Hartmut, 1983).

2.2.2. Biomass yield and quality analyses

Strawberry seedlings flowered on the 10th day after planting (DAP) into the closed system, and strawberry were harvested at a 7-day interval per cv., starting from 30 DAP, when fruit turned to red. Harvest was staggered in order to simulate the typical situation in BLSS where fruit storing space is limited and a sustainable work load for astronauts is needed. At each harvest, yield data (fresh weight and dry weight of fruits) were determined per cultivar (edible biomass). At the end of the harvest, plants were collected to