Ecological Engineering 90 (2016) 382–386

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng

Short communication

The regulation of CO_2 levels in a BLSS by controlling the solid waste treatment unit

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ARTICLE INFO

Article history:
Received 8 February 2015
Received in revised form
27 November 2015
Accepted 26 January 2016
Available online 20 February 2016

Keywords:
Bioregenerative life support system (BLSS)
Lunar Palace 1
CO_2 concentration regulation
Solid waste bio-convertor

ABSTRACT

A bioregenerative life support system (BLSS) is an artificial closed ecosystem which provides basic human life support for long-duration and far-distance space activities such as lunar bases. "Lunar Palace 1", an experimental facility, was constructed by our team for the integration research of the key technologies in BLSS, and then a continuous 105-day closed integrative BLSS experiment was carried out in "Lunar Palace 1"(Stage I) successfully last year. In such a system, O_2 produced by higher plants is supplied for the breathing of the crew, as well as the respiration of microorganisms which decompose the solid wastes such as inedible plant biomass and human wastes, while CO_2 produced by the crew and microorganisms is provided for plants to grow. In the system, an excessively high CO_2 level can affect plant growth and may harm human health, however, if the CO_2 level is too low, plant growth may also be inhibited. Thus, keeping the balance between CO_2 and O_2 levels is essential to the gas regulation in the system, and is one of the key points for the operation stability of the system. In this study, an efficient and controllable solid waste bio-convertor was built based on the microbial fermentation in "Lunar Palace 1", and the CO_2 generation of the bio-convertor under the optimum fermentation conditions in the 105-day airtight experiment was monitored. Moreover, the changes of CO_2 production along with increasing or reducing the temperature of the bio-convertor from 33 to 45 °C (or from 45 to 33 °C) were also investigated, and a positive correlation between the CO_2 output and the fermentation temperature was obtained accordingly. Therefore, the CO_2 production can be adjusted effectively by changing the temperature of the bio-convertor, which implies that it is feasible to regulate the balance between the CO_2 and O_2 concentrations in BLSS by controlling the fermentation conditions of the solid waste treatment unit. The results of this study could lay a foundation for the following researches conducted in "Lunar Palace 1".

1. Introduction

For deep space exploration, astronauts need to stay for a long time in space. If all necessities required, such as oxygen, water and food, are provided by storage, the weight of spacecraft will be huge and few countries can afford the enormous cost. Therefore the bioregenerative life support system (BLSS) is quite imperative for long-duration and far-distance space activities. BLSS is an independent, integrated and complex artificial ecosystem, in which food production, waste treatment and air and water regeneration are achieved by the activities of biological units including higher plants, animals and microorganisms. By applying BLSS, the material supplement from outside the system and the cost of space activities could be reduced obviously (Kang et al., 2012; Czupalla et al., 2005; He et al., 2010; Liu et al., 2008).

In BLSS, higher plants such as wheat and lettuce can absorb CO_2 and light energy through photosynthesis, and generate O_2 and food. At the same time, human bodies, animals and microorganisms will consume O_2 and food to produce CO_2 through respiration. However, the balance between O_2 and CO_2 might be disturbed under special circumstances, which could spell a disaster for the system (Li et al., 2013b). The concentrations of CO_2 and O_2 are affected by

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http://dx.doi.org/10.1016/j.ecoleng.2016.01.048
0925-8574/

various factors, among which the CO_2/O_2 exchange ratio between autotrophic unit and heterotrophic unit may be the most important one. Unbalanced ratio will inevitably lead to an unstable system and a lack of O_2 or CO_2 (Schneegurt et al., 1996).

Many ways to balance the concentrations of O_2 and CO_2 in BLSS have been studied before, such as changing the crew's diets, modifying the plant composition, incinerating the inedible biomass, culturing microalgae and so on. However, it takes a long time (up to ten days) to recover the balance by changing the crew's diets and even much more time (30–60 days) by modifying the plant composition (Gitelson and Okladnikov, 1996). The recovery time may only be 3 or 4 days by means of microalgae cultivation for the rapid growth. However, it will produce a lot of inedible biomass and increase the load of waste treatment in the system (Li et al., 2013b). Incineration could result in the oxygen insufficiency and produce harmful gases such as NO_x, SO_2, etc. in the system (Fisher et al., 2000). One important way of recycling solid waste in current BLSS is using microbial fermentation to convert solid waste into soil-like substrate (SLS) which is suitable for plants to grow. It could not only transfer N, P and S, etc. from solid waste to the nutrients for plants, but also release CO_2 for plants growth (Trotman et al., 1996, 1997; Strayer et al., 1997; Mackowiak et al., 1996). Therefore, it might be possible to construct a solid waste treatment unit using aerobic fermentation to balance the CO_2 and O_2 concentrations in BLSS, under relatively controllable and mild reaction conditions.

"Lunar Palace 1" (stage I), which is an integrative experimental facility for Permanent Astrobase Life-support Artificial Closed Ecosystem (P. A. L. A. C. E), was constructed by our team, and then a 105-day multi-crew closed integrative BLSS experiment was carried out successfully last year (Liu, 2012). During the 105-day experiment, a high-efficient and controllable solid waste treatment unit – a solid waste bio-convertor – was constructed and operated continuously inside "Lunar Palace 1". The inedible parts of plants and human wastes, etc. produced during the experiment were mixed and fermented in the solid waste bio-convertor under aerobic conditions and the generated CO_2 was monitored. Furthermore, the change of the CO_2 generation with different fermentation temperatures was also studied to verify the feasibility of regulating the gas balance in the system through controlling the CO_2 production from the solid waste treatment unit.

2. Materials and methods

2.1. Solid waste materials

The solid wastes including straw and chaff of wheat (*Triticumaestivum L.*) (Dong et al., 2014), frass of yellow mealworm (*TenebrioMolitor L.)* (Li et al., 2013a) and feces of crew produced during the 105-day experiment in "Lunar Palace 1" were processed in this study. The raw materials of straw and chaff were crushed into fragments of 0.5–1 cm with a disintegrator (DF-20, Wenling LINDA Machinery Co. Ltd., China) before fermentation.

2.2. Inoculation

The microbial inoculants of the fermentation which had an efficient ability of cellulose decomposing were selected according to the previous experiments in our group (He et al., 2010).

2.3. The solid waste bio-convertor

In this study, a bio-convertor was placed in the waste treatment room of "Lunar Palace 1" to produce CO_2 for plants growth by processing the solid wastes. As shown in Fig. 1, the solid waste bio-convertor was made of stainless steel and mainly consisted of 17 parts. The solid wastes were put into the fermentor (14) through material inlet (13), mixed completely with the propeller stirrer and then fermented under aerobic conditions. The gases produced in the process of fermentation were exhausted from exhaust air fan (1) after cooling by condensers (11) and deodorizing by deodorant (2). Ceramic heaters were used to maintain the fermentation temperature inside the fermentor (14). The automatic control of the temperature, humidity and aeration rate was achieved through the electric cabinet (8). The basic parameters of the bio-convertor are shown in Table 1.

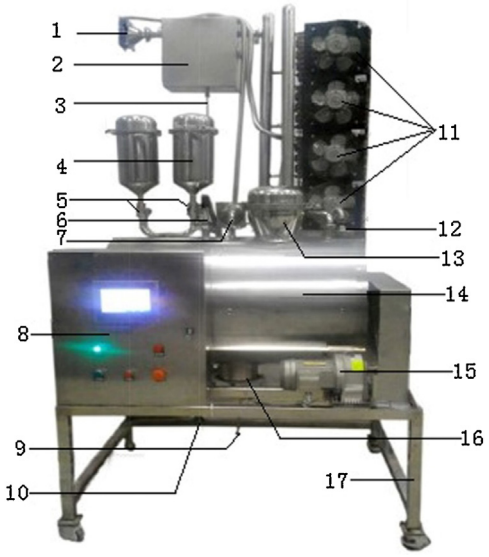

Fig. 1. The photo of the solid waste bio-convertor. (1) Exhaust air fan, (2) box with deodorant, (3) condensate return tube, (4) liquid storage tanks, (5) electromagnetic valves, (6) pressure transducer, (7) air inlet, (8) electric cabinet, (9) condensate outlet, (10) humidity transducer, (11) condensers, (12) temperature transducer, (13) material inlet, (14) fermentor with propeller stirrer, (15) motor, (16) material outlet, (17) base frame.

Table 1
The basic parameters of the bio-convertor.

Parameter	Size
Appearance size	1100 (length) × 750 (diameter of the fermentor) × 2100 mm (height)
Weight	220 kg
Total power	10 kW
Rated capacity	110 L (processing capacity: 50 kg)
Air flow rate	1.8 L/min
Spindle speed range	5–20 r/min

Table 2
The orthogonal test factors and levels according to Taguchi approach.

Factor	Level 1	Level 2	Level 3
Temperature (°C)	40	45	50
Initial moisture (%)	55	65	75
Inoculum density (%)	3	5	7

2.4. The experimental procedures

2.4.1. Fermentation conditions optimizing

In this study, Taguchi approach (Roy, 2001) was used for the optimization of the fermentation conditions including temperature, initial moisture (w/w) and inoculum density. A L9 orthogonal array was arranged as shown in Table 2, and then 9 flask-shaking experiments under different fermentation conditions as listed in Table 3 were operated. The fermentation time of each experiment was seven days. Finally, the weight-loss ratio of each sample was