Life Sciences in Space Research 8 (2016) 14–21

Contents lists available at ScienceDirect

Life Sciences in Space Research

www.elsevier.com/locate/lssr

Advanced nutrient root-feeding system for conveyor-type cylindrical plant growth facilities for microgravity

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ARTICLE INFO

Article history:
Received 12 September 2015
Received in revised form 24 November 2015
Accepted 16 December 2015

Keywords:
Life support systems (LSS)
Plant growth facilities (PGF)
Mineral nutrition system
Artificial soil (AS)

ABSTRACT

A compact and reliable automatic method for plant nutrition supply is needed to monitor and control space-based plant production systems. The authors of this study have designed a nutrient root-feeding system that minimizes and regulates nutrient and water supply without loss of crop yields in a space greenhouse. The system involves an ion-exchange fibrous artificial soil (AS) BIONA-V3^{TM} as the root-inhabited medium; a pack with slow-release fertilizer as the main source of nitrogen, phosphorus, and potassium; and a cartridge with granular mineral-rich ionite (GMRI) as a source of calcium, magnesium, sulfur, and iron. A controller equipped with an electrical conductivity meter controls the solution flow and concentration of the solution in the mixing tank at specified values. Experiments showed that the fibrous AS-stabilized pH of the substrate solution within the range of 6.0–6.6 is favorable to the majority of crops. The experimental data confirmed that this technique allowed solution preparation for crops in space greenhouses by means of pumping water through the cartridge and minimization of the AS stock onboard the space vehicle.

1. Introduction

Expansion of human population to low-Earth orbits, development of technologies for lunar exploration, and space flights to Mars and neighboring asteroids all necessitated complementing life support systems (LSS) with biological subsystems that will enhance autonomy and biological adequacy of the crew environment (Gitelzon et al., 2003, Berkovich et al., 2009). Capability studies of space vehicles designed for remote space missions showed that in the next decade, the only component of LSS bio-subsystem could be a relatively small vegetable or vitamin production plant growth facility (PGF) as a source of natural vitamins and psychological support for the crew (Berkovich et al., 2009). Two PGFs were developed at the Russian State Scientific Center of the Institute of Biomedical Problems (IBMP), namely "Svet" and "Lada," which have flown in space. A new class of cylindrical conveyor-type PGF is presented by several laboratory models that appear to be less demanding in terms of board resources (primarily, electric power and volume). At present, IBMP is engaged in testing a prototype model of vitamin PGF Vitacycle-T designed for incorporation into the Russian segment of the International Space Station.

All designs of vitamin PGFs for different classes of space missions can be classified into two categories depending on key service condition that is decisive for both the facility design and crop cultivation technology, including mineral nutrition supply:

1) Gravity conditions (lunar and planetary bases) and
2) Microgravity conditions (orbital stations and exploration vehicles).

Gravity-specified PGFs are likely to implement some form of hydroponic technique adapted to more rigid power constraints and volume limitations. In a large PGF, water transpired by the crop and then regenerated from air condensate will have to be returned to the nutrient solution preparation system. Thus, in order to provide adequate mineral nutrition to vegetables at the least solution pH, electrical conductivity must be automatically monitored and adjusted (Domingues et al., 2012; Massa et al., 2011), which is done using a conductivity meter; pH is measured using selective silver chloride electrodes. This method produces satisfactory results, as within the range of concentrations of salts suited for crop nutrition solution, conductivity is essentially proportional to total salts concentration. However, hydroponics microgravity application necessitates having no less than three subsystems: to prepare and store mother solutions; to prepare fresh nutrient solutions; and to monitor and adjust nutrient content at the root medium during plant growth. Consequently, the facility will have a cumbersome

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http://dx.doi.org/10.1016/j.lssr.2015.12.002

architecture with excessive equivalent system mass (Drysdale et al., 1999).

In the ISS greenhouse, Lada minerals are provided by granular clay Turface™ with slow-acting fertilizer (SAF) Osmocote 14-14-14™ packed to root module (RM). The amount of SAF is calibrated to provide sufficient minerals for plant growth over planned vegetation. Water pumped into the RM dissolves salts stored in SAF and then, owing to osmotic pressure and diffusion, enriches the entire substrate volume. However, depending on the transpiration rate of plants, soluble salts normally pass from SAF to substrate solution inside the RM within the first 10–15 days, which is long before the end of lettuce vegetation period (20–30 days). Therefore, plants may starve for minerals at the end of cultivation. While increasing SAF dose before sowing inevitably leads to exceeded concentrations of nitrate and nitrite in plant biomass, periodic introduction of new SAF doses before the next sowing is time consuming and endangers cabin air pollution.

From our standpoint, a more convenient way to supply plants with mineral nutrients in microgravity is to use a fibrous ion-exchange resin substrate (FIERS) loaded with plant nutrition elements. Water potential control in the root zone can be adjusted by negative pressure maintaining inside water-filled porous tubes immersed in the substrate (Berkovich et al., 2002, 2003). FIERS is particularly good for microgravity as its capillary-porous structure is unaffected by microgravity and does not pollute the cabin. The main disadvantage of FIERS is small mineral content per volume unit that dictates the necessity of relatively large volumes of the store available onboard the space vehicle. For instance, in order to ensure the specified annual Vitacycle-T biomass production, the stock of FIERS BIONA-V3™ should amount to 18 kg, which will occupy approximately 150 dm^3, a volume exceeding the PGF dimensions. In order to minimize the FIERS stock, we designed a mineral nutrition system with FIERS and enrichment pack (column) with granular mineral-rich ionite (GMRI) mounted onto the PGF water-feeding system. If a space greenhouse requires growing plants for 2–3 months or longer, it will make sense to use an SAF column as the main source of quickly consumed elements such as nitrogen, potassium, and phosphorus (Berkovich et al., 2013).

The aim of the effort was to test the new nutrient root-feeding system integrated into a conveyor-type PGF for leaf vegetables.

2. Methods

2.1. Mineral nutrition system

Functional diagram of the root-feeding system is presented in Fig. 1. The system consists of 10 RMs filled by FIERS BIONA-V3™, an enrichment column with GMRI BIOINA-312™, and an additional column with SAF Osmocote 14-14-14™. The GMRI is the main source of slowly consumed elements (e.g., calcium, magnesium, sulfur, iron, and microelements); the SAF column is the key supplier of nitrogen, phosphorus, and potassium, which are in particular demand for growing plants. Separate storage of the two types of nutrients is of fundamental importance as their mineral gradients differ in both the way they dissolve and the time course of their entry into the solution.

In the proposed system, water runs through the GMRI column into the mixing vessel with a conductivity meter inside, and then into RMs. On receiving the signal of least-acceptable conductivity from the meter, the controller engages the pump to keep on forcing water into the bypass line and the mixing vessel via the SAF column till conductivity in the mixing vessel reaches a specified value.

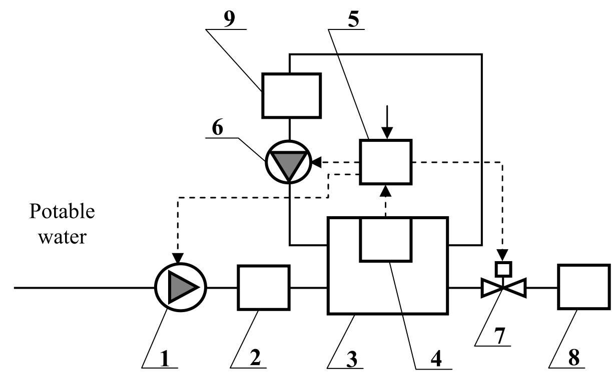

Fig. 1. Block diagram of a designed mineral nutrition system for PGF Vitacycle-T. 1, 6 – peristaltic pumps; 2 – enrichment column with GMRI BIONA-312™; 3 – mixing vessel; 4 – conductivity meter; 5 – regulator; 7 – electric valve; 8 – root module with FIERS BIONA-V3™; 9 – enrichment column with SAF Osmocote 14-14-14™.

2.2. Calculation of the mass and volume of the enrichment column

Volumes of both enrichment columns and dry mass of nutritional substrates were calculated on the assumption that:

1. Mineral flux is sufficient to grow the desired crop;
2. Certain time is needed for water to contact with substrate in the column; and
3. In the output solution, each element must be present in at least its minimal acceptable concentration.

Calculations were made using the following expressions:

$$M \geq (mC_i)/(k_i \cdot d_i); \quad (1)$$

$$M = W/V_{crit}; \quad (2)$$

$$V = T_{cont} \cdot w/P, \quad (3)$$

where M – mass of the column with nutritional substrate; m – expected plant biomass at the end of specified time of PGF operation; C_i – weight content of the ith element in biomass; k_i – weight content of the ith element in a unit of nutritional substrate mass; d_i – portion of the ith element available to plants; W – total volume of water passing through the enriching column during PGF operation; V_{crit} – specific critical water volume equal to the volume that, when running through 1 g of substrate, produces output mineral concentrations no less than minimal acceptable values; V – column volume; w – water flow through the column; P – nutritional substrate porosity; T_{cont} – required time of water contact with the nutritional substrate.

Reduction (due to washout) of mineral nutrients with the crop was calculated using the Domingues et al. (2012) approach. Weight contents of nutrients in mass units of FIERS, GMRI, and SAF were taken from manufactures' technical data. Total plant biomass was determined based on the specification for the PGF Vitacycle-T, according to which this PGF must operate 72 days continuously with the average output of 60 g/day.

Time of contact between water and GMRI was determined as the time for establishing nitrate-anion equilibrium concentration in the solution in the course of BIONA-312™ moistening. It was assumed that, as a rough approximation, this time is the same for all other elements. In this study, patches of dry GMRI with a mass of 3 g were moistened with water, covering the GMRI layer with a thickness of 1.0–1.5 mm, and exposed to 30 °C in a thermostat for 4 days to stabilize ion-exchange resin granules. On the fifth day, the resulted equilibrium solution was removed and the same volume of fresh water, heated to 30 °C, was added to the sediment that was thereafter again installed in the thermostat. For the