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A urine-fuelled soil-based bioregenerative life support system for long-term and long-distance manned space missions

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ABSTRACT

A soil-based cropping unit fuelled with human urine for long-term manned space missions was investigated with the aim to analyze whether a closed-loop nutrient cycle from human liquid wastes was achievable. Its ecohydrology and biogeochemistry were analysed in microgravity with the use of an advanced computational tool. Urine from the crew was used to supply primary (N, P, and K) and secondary (S, Ca and Mg) nutrients to wheat and soybean plants in the controlled cropping unit. Breakdown of urine compounds into primary and secondary nutrients as well as byproduct gases, adsorbed, and uptake fractions were tracked over a period of 20 years. Results suggested that human urine could satisfy the demand of at least 3 to 4 out of 6 nutrients with an offset in pH and salinity tolerable by plants. It was therefore inferred that a urine-fuelled life support system can introduce a number of advantages including: (1) recycling of liquids wastes and production of food; (2) forgiveness of neglect as compared to engineered electro-mechanical systems that may fail under unexpected or unplanned conditions; and (3) reduction of supply and waste loads during space missions.

1. Introduction

Despite the advanced technology available to design long-term manned space missions, the longest space travel that mankind has been able to achieve to date remains the Apollo 11 to the Moon in 1969, for a duration of only 8 days. Since the end of the sixties, advances in technology and space medicine have made possible to bring the crew permanence in low- or micro-gravity up to durations of several months such as on-board the International Space Station in the lower Earth orbit, where permanence has become practical only thanks to the Earth proximity and to periodic shipments of water and food supplies. The key challenge for the long-term man permanence in orbits far from the Earth is still unachieved and solutions to compensate for the distance from supplies are still being sought. Given that the cost of shipment is still valued around $10,000/kg to the low Earth orbit and $300,000/kg to Mars (Massa et al., 2007), periodic supplements of supplies cannot be considered a viable solution. Regenerative life-support systems have therefore become a key objective of technological development to make long-term and long-distance missions possible (Nelson et al., 2009). Regenerative systems have been targeting either the capability to produce edible food such as grains, vegetable, and fibers, or to compost and reuse matter, including water, nutrients and gases, or both (e.g., Verseux et al., 2016). Among regenerative systems, the most promising are those that use porous natural substrates to combine one or more of the above processes, particularly those that use Earth-derived soils and extraterrestrial-derived regolith (Hossner et al., 1991; Salisbury, 1992; Hoehn et al., 2000; Silverstone et al., 2003; 2005; Nelson et al., 2008; 2009; Maggi and Pallud, 2010a; 2010b; Jones et al., 2012)

In earlier studies, Finstein et al. (1998a, 1998b) have tested the composting potential of organic plant residues in a reactor inoculated with soil microorganisms under controlled aeration and self-heating conditions, and showed that such system may be adopted to decompose and recycle matter in a space mission. Hyper-thermophilic bacteria have also been tested more recently to accelerate organic matter breakdown (Kanazawa et al., 2008), while cyanobacteria have been hypothesized to be viable microorganisms to produce food, biofuels, and oxygen, and support nutrient reuse for other organisms including plants (Verseux et al., 2016). Soil-based life support systems are now becoming of particular interest because, as compared to artificial media, they provide a number of additional services including a substrate to grow plants, decompose wastes, recycle water, nutrients and gases, and forgive neglect that would otherwise stall other electro-mechanical systems (Finstein et al., 1998b). Haeuplik-Meusburger et al. (2014) have reported a detailed analysis of features

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and functioning of pilot systems designed since 1971 to grow plants in microgravity, indicating also beneficial psychological effects on the crew.

One of the functions that a bioregenerative life support system may be designed for, is the recycling of human wastes from which nutrients can be extracted and reused (Volk and Rummel, 1987). Human urine is the waste that has the greatest content of nitrogen and contains all elements that are required by soil microorganisms and plants for their biological and physiological functions (Tang and Maggi, 2016). Earlier works on urine-derived nutrients for terrestrial agriculture have shown the potential to satisfy to a large extent the nutrient requirement by various produce plants (e.g., Vinneras, 2001; Pradhan et al., 2007; Mnkeni et al., 2008; Tang and Maggi, 2016). Unlike feces, which can carry bacteria like *E. coli* and other pathogens, urine is sterile in healthy individuals and poses no health risks. This work addresses therefore the design of a urine-fuelled soil-based bioregenerative life support system that can decompose complex substances from the crew's urine and recirculate released nutrients to feed plants for food and fiber production in a closed environment. The system has the potential to recycle water and decrease the energy cost of urine filtration and storage, as well as consumable materials such as filter membranes and artificial porous media subject to microbially-induced clogging (e.g., Maggi and Porporato, 2007). In specific, this work addresses the release rate of bioavailable primary (N, P, and K) and secondary (S, Ca, and Mg) nutrients, the uptake rate by test wheat and soybean crops, and the biogenic production rate of CO_2, NH_3, NO, N_2O, H_2S, and $S_2(g)$ toxic gases. Wheat and soybean crops were chosen after recommendations in Salisbury et al. (1996) and Wheeler et al. (1994). Analyses were performed on nutrient flows through various catabolic biodecomposition reactions and the concentration of microbial functional groups that deintegrate organic compounds from urine, nitrify and denitrify N compounds, and oxidize and reduce various S compounds. The uptake-to-required nutrient ratio by wheat and soybean was also estimated as a function of various urine application modes and rates. All analyses were performed to assess recycling potential (rate and effectiveness) as well as the long-term self-sustainability and health of the proposed system.

2. Methods

2.1. Soil-based cropping unit design concept

While a number of pilot plant growth chambers have been designed and tested in terrestrial and micro gravity (Hossner et al., 1991; Bingham et al., 2000; Haeuplik-Meusburger et al., 2014), we consider in this study a conceptual control volume that includes essential boundary fluxes and internal processes of interest to water and nutrient uptake, and nutrient released by catabolic microbial breakdown of urine. Here, the urine-fuelled soil-based bioregenerative unit is an isolated chamber that receives water and untreated urine to support soil biogeochemical processes and plant growth (Fig. 1). A water injection system maintains the soil water content constant within the soil substrate and facilitates mobility of dissolved aqueous compounds and gases, which become diffusion limited in microgravity (Porterfield, 2002), while nutrient amendments are introduced with injections of untreated human urine from a recycling system.

The atmosphere within the unit is assumed to be maintained at terrestrial composition and total pressure, and at 25 °C temperature, with a constant relative humidity RH% = 50. The soil substrate used in the unit was 20 cm thick over a unit cropping surface area of 1 m^2, which resulted in about 260 kg/m^2 with a mineral soil density of 2848 kg/m^3. Soil was assumed to have clay loam texture with 30%, 40% and 30% fractions of sand, silt, and clay, respectively, porosity $\phi = 0.46$, absolute permeability $k_{abs} = 2.713 \times 10^{-13}$ m^2, and with Brooks–Corey hydraulic parameters $b = 11.65$ and $\psi_s = -4.679 \times 10^2$ m. These define the soil relative permeability to liquids and gases as (Brooks and Corey, 1964)

$$k_{rL} = S^{2b+3}, \tag{1a}$$

$$k_{rG} = (1 - S)^2(1 - S^{2b+1}), \tag{1b}$$

and the water potential as

$$\psi = \psi_s S^{-b}, \tag{2}$$

with S the water saturation. A value $S = 0.5$ was maintained constant with the assumption to be optimal for wheat and soybean plants.

The soil substrate hosts plants that uptake water and nutrients according to evapotranspirative fluxes proportional to their growth stage and the potential evapotranspiration. The potential evapotranspiration

$$ET_0 = f(v)(e_s - e), \tag{3}$$

was calculated as a function of air flow rate $f(v)$, with v the air speed inside the unit, and the water vapour partial pressure deficit $(e_s - e)$, with e_s and e the saturated and actual partial pressures (Brutsaert, 1982). The air flow rate function $f(v)$ was defined using the Penman–Montheit method as (UN-FAO, 1998)

$$f(v) = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}v}{\Delta + \gamma(1 + 0.34v)}, \tag{4}$$

with the slope Δ of the vapour pressure curve over the temperature T in °C defined as

$$\Delta = 4098\frac{0.6108e^{\frac{17.27T}{T+237.3}}}{(T + 237.3)^2},$$

and with R_n and G the net radiation at the crop surface and the soil heat flux density in [MJ/m^2 day], respectively, $\gamma = 0.665 \times 10^{-3}P_a$ the psychrometric constant in [kPa/°C], and $P_a = 101.3$ [kPa] the atmospheric pressure. With e_s estimated as

$$e_s = 0.6108e^{\frac{17.27T}{T+237.3}},$$

the actual e at $T = 25$ °C and RH% = 50 was next estimated as $e = e_s RH$ and used in Eq. (3). With $R_n = 15$ MJ/m^2day and $G = 0$ MJ/m^2day, and for an airflow velocity $v = 0.2$ m/s needed to produce advective flow around leaves and allow plant to exchange photosynthetic gasses in the absence of gravity (Hirai and Kitaya, 2009; Wolff et al., 2013), the potential evapotranspiration in the urine-fuelled soil-based bioregenerative unit was estimated to be $ET_0 = 4.63$ mm/day.

For this study, dwarf wheat and soybean were used as test crops after earlier experiments and recommendations in Salisbury et al. (1996) and Wheeler et al. (1994), respectively. The actual evapotranspiration $ET_c = K_c ET_0$ for dwarf wheat and soybean were calculated with the FAO method using the crop coefficient K_c, which is plant specific and changes over time depending on the growth stage. Stage-dependent K_c values were taken from typical terrestrial plantations (UN-FAO, 1998), but the life cycle of these test plants were shortened to about 70% (Table 1) under the hypothesis that engineered species for space agriculture may be developed to complete a growing season in a shorter time while retaining yield, and primary (N, P and K) and secondary (S, Ca and Mg) nutrient requirements as in typical terrestrial crops (Table 2) (Nelson et al., 2009). Under these hypotheses, the actual evapotranspiration ET_c was calculated over the full growing period (Fig. 2), and was used to condition the boundary water flow to maintain constant water content in the soil substrate. More likely, however, changes in physiological requirements caused by microgravity may lead to different evapotranspiration or nutrient requirements, or both, thus K_c values typical of terrestrial agriculture may have to be reassessed for use in extraterrestrial agriculture as discussed in Section 3.2.