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Modeling gravity effects on water retention and gas transport characteristics in plant growth substrates

T.K.K Chamindu Deepagoda [a,*], Scott B. Jones [b], Markus Tuller [c], Lis Wollesen de Jonge [d], Ken Kawamoto [e], Toshiko Komatsu [e], Per Moldrup [f]

[a] *Dept. of Biotechnology, Chemistry and Environmental Engineering, Aalborg University, Sohngaardsholmsvej 57, DK-9000 Aalborg, Denmark*
[b] *Dept. of Plants, Soils and Climate, Utah State University, Logan, UT, USA*
[c] *Dept. of Soil, Water and Environmental Science, The University of Arizona, 1177 E Fourth Street, Tucson, AZ 85721, USA*
[d] *Dept. of Agroecology and Environment, Faculty of Science and Technology, Aarhus University, Blichers Allé 20, P.O. Box 50, DK-8830 Tjele, Denmark*
[e] *Dept. of Civil and Environmental Engineering, Graduate School of Science and Engineering, Institute for Environmental Science and Technology (IEST), Saitama University, 255 Shimookubo, Sakuraku, Saitama 338-8570, Japan*
[f] *Dept. of Civil Engineering, Aalborg University, Sohngaardsholmsvej 57, DK-9000 Aalborg, Denmark*

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Abstract

Growing plants to facilitate life in outer space, for example on the International Space Station (ISS) or at planned deep-space human outposts on the Moon or Mars, has received much attention with regard to NASA's advanced life support system research. With the objective of in situ resource utilization to conserve energy and to limit transport costs, native materials mined on Moon or Mars are of primary interest for plant growth media in a future outpost, while terrestrial porous substrates with optimal growth media characteristics will be useful for onboard plant growth during space missions. Due to limited experimental opportunities and prohibitive costs, liquid and gas behavior in porous substrates under reduced gravity conditions has been less studied and hence remains poorly understood. Based on ground-based measurements, this study examined water retention, oxygen diffusivity and air permeability characteristics of six plant growth substrates for potential applications in space, including two terrestrial analogs for lunar and Martian soils and four particulate substrates widely used in reduced gravity experiments. To simulate reduced gravity water characteristics, the predictions for ground-based measurements ($1 - g$) were scaled to two reduced gravity conditions, Martian gravity ($0.38 - g$) and lunar gravity ($0.16 - g$), following the observations in previous reduced gravity studies. We described the observed gas diffusivity with a recently developed model combined with a new approach that estimates the gas percolation threshold based on the pore size distribution. The model successfully captured measured data for all investigated media and demonstrated the implications of the poorly-understood *shift in gas percolation threshold* with improved gas percolation in reduced gravity. Finally, using a substrate-structure parameter related to the gaseous phase, we adequately described the air permeability under reduced gravity conditions.

Keywords: Plant growth media; Reduced gravity; Gas diffusivity; Percolation threshold

1. Introduction

The successful landing of NASA's Curiosity Mars Rover on August 2012 in search of microbial life in Martian soils has brought renewed scientific and public interest on space exploration and the establishment of human outposts on

* Corresponding author. Tel./fax: +45 99408493, mobile: +45 52670499.
E-mail address: Chamindu78@yahoo.com (T.K.K Chamindu Deepagoda).

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our Moon and Mars. NASA's future space program envisions revisiting the moon, getting astronauts onto a near-earth asteroid by 2025, and conducting the first-ever manned mission to Mars by the mid-2030s (NASA, 2012). A permanent lunar base and deep-space stations facilitating such long-duration interplanetary space missions have also become key topics among space scientists while a permanent Mars base may mark the culmination of the historical endeavor of space exploration. Despite the profound experience obtained from continuous human presence in short term life-support systems (e.g., on the low earth orbit ISS), the prolonged maintenance of a self-sustaining deep-space human outpost, such as a Mars base, will pose far greater challenges to mankind in the future.

Growing plants in reduced gravity environments on space outposts may be beneficial for astronauts in two ways; *psychological* and *functional*. Russian cosmonauts witnessed the pleasure they experienced on space missions by growing plants, watering and watching the plants grow (Nechitailo and Mashinsky, 1993), suggesting that plants can provide a significant psychological benefit for the people onboard (Bates et al., 2009; Marquit et al., 2008). Recent studies in space psychology further recognized the *perception of earth* as a key psychological factor for astronauts involved in short-term missions, which was evidenced by the large number of self-motivated photographs of the earth taken aboard the ISS during space missions (Robinson et al., 2011). The conclusions of these studies point to an "intensive feeling of isolation" once the earth is out of view during future extended-duration missions (e.g., Mars exploration), and emphasized the importance of substitute leisure activities for the crew at unscheduled times. Growing and tending to plants can be a promising substitute leisure activity for long-duration missions. The functional benefit of space-grown plants is related to the potential of plants to regenerate air and water and to supply food for self-sustained operation of a remote human base (NASA, 2002). The role of plants in close-loop systems in relation to space-based applications has been discussed in detail in e.g. Wheeler et al. (2003).

Most of the essential needs for successful plant growth on earth (e.g. air, water, and nutrients) are strongly linked to the plant growth substrates (Brady, 1974). Compared to field-grown plants, plants grown in controlled volumes have restricted access to these plant needs due to discontinued boundaries (defined by container size and geometry) for mass transport and root penetration. In space, reduced gravity plays an important but poorly understood role in fluid phase configuration within the root zone, demanding proper characterization of growth media for space-based applications. Air and water supply are particularly crucial, as they compete for the same pore space within the root zone. Potential plant growth substrates for reduced gravity environments have been characterized in previous microgravity research, with a specific focus on air (oxygen), water, and nutrient behavior in the root zone of growth modules (Jones and Or, 1999; Steinberg et al., 2002, 2005; Jones et al., 2003). Despite limited experimental opportunities, many granular growth substrates including balkanine (Ivanova et al., 1997), Zeoponic (Steinberg et al., 2000; Ming et al., 1995), Turface (Blonquist et al., 2006; Jones et al., 2012), and Profile (Blonquist et al., 2006; Jones et al., 2012) have been tested as prospective plant growth media for reduced gravity conditions (e.g., ISS, parabolic flights) and were characterized based on water retention, hydraulic conductivity, and oxygen diffusivity (Heinse et al., 2007). However, time consuming measurements, such as oxygen diffusion under wet conditions (i.e., near gas-percolation threshold), are difficult to perform in reduced gravity (parabolic flight) environments due to insurmountable time restrictions.

Following the concept of in situ resource utilization (ISRU) for construction, energy, and resource recovery in space, native materials mined from the lunar or Martian surface will be preferred plant growth media on a future lunar or Martian base (Yamashita et al., 2012). Based on the soil samples returned from lunar missions, the potential of lunar soil as a plant growth substrate has been examined and is not likely to facilitate adequate aeration for plant growth in reduced gravity-drained conditions due to poor physical structure (Ming, 1989). Further characterization and enhanced management is needed to verify the potential of native materials as plant growth media. Characterization of Martian soils for plant growth is still rudimentary (Yamashita et al., 2005) and awaits further studies following future explorations. Among promising terrestrial analogs for lunar and Martian soils, the JSC-1 lunar simulant and JSC-1 Martian simulant soils have recently gained attention due to their similarity to the native materials. Despite some studies focusing on measuring water characteristics and dielectric properties on simulant soils (e.g. Robinson et al., 2009), little is known about the gas transport characteristics of these soils.

In this study, we discuss the water characteristic and gas diffusivity of six prospective growth substrates, with a main focus on JSC-lunar and JSC-Martian simulant soils. Based on the observations in previous reduced gravity studies, we discuss the possible scaling of the results obtained under full gravity ($1 - g$) to two reduced gravity scenarios, Martian gravity ($0.38 - g$) and lunar gravity ($0.16 - g$). Following a new approach to estimate the gas percolation threshold based on the pore size distribution, we discuss the implications of a shift in the gas percolation threshold in reduced gravity, a difficult-to-estimate parameter under short-term reduced gravity simulations (e.g., 21 s in parabolic flight). Predictions for air permeability measured in four selected substrates will also be discussed with extended scaling to the reduced gravity conditions.

2. Theoretical and modeling considerations

2.1. Gravity and capillary effects

The equilibrium distribution of a liquid in a finite pore domain of a porous medium is mainly governed by the