review article
received: 2011-07-22

UDC: 581.5:524.8

THE CHALLENGING DREAM OF PLANTS IN SPACE

Carmela Rosaria GUADAGNO[1], Amalia VIRZO DE SANTO[2],
Nicola D'AMBROSIO[2]

[1] University of Wyoming, Department of Botany, Wyoming, USA
[2] University of Naples Federico II, Department of Structural and Functional Biology, Complesso Universitario Monte S. Angelo, Napoli, Italy

Corresponding author:
Nicola D'AMBROSIO
University of Naples Federico II, Department of Structural and Functional Biology,
Complesso Universitario Monte S. Angelo, Edificio 7, Via Cinthia 4, 80126 Napoli, Italy
e-mail address: dambrosi@unina.it

ABSTRACT

Plants are essential components of Bioregenerative Life Support Systems (BLSS) because they provide fresh food, produce oxygen, uptake CO_2 *from air and purify waste water via the leaf transpiration processes. In the consideration of long-duration human space missions, the issue of food production is becoming increasingly important. Therefore the possibility of growing plants in space represents the challenge for human space missions on the Moon and Mars and is related to the development of appropriate BLSS. Key issues include food production, nutritional needs, hydroponic techniques, horticultural requirements, waste processing and engineering systems.*

Keywords: *bioregenerative life support system, space plant growth, food production, space constraints*

NOV IZZIV – SANJE O RASTLINAH V VESOLJU

IZVLEČEK

Rastline predstavljajo poglaviten element Sistemov za bioregenerativno podporo življenju (Bioregenerative Life Support Systems ali BLSS), saj nudijo svežo hrano, proizvajajo kisik, absorbirajo ogljikov dioksid iz zraka in čistijo odpadno vodo s pomočjo izhlapevanja skozi liste. Pri obravnavanju dolgotrajnih človeških misij v vesolje, področje proizvajanja hrane postaja vedno pomembnejše. Zato možnost gojenja rastlin v vesolju predstavlja izziv za človeške misije na Luno in Mars, prav tako pa je povezana z razvojem ustreznih sistemov BLSS. Ključna vprašanja se nanašajo na proizvajanje hrane, hranilne potrebe, hidroponične tehnike, hortikulturne zahteve, obdelavo odpadkov in tehnične sisteme.

Ključne besede: *sistem za bioregenerativno podporo življenju, gojenje rastlin v vesolju, proizvodnja hrane, omejitve v vesolju*

INTRODUCTION

During the second part of the last century, space became the so-called last frontier and space exploration started to be seen as a very exclusive research opportunity over the entire world. The scientific community has always auspicated the possibility of growing plants in space because, as photosynthetic organisms, they can play an essential role in the bio-regenerative systems. The initial interest in growing plants in space was mainly focused on air regeneration (O_2 production and CO_2 removal). As the consideration of long-duration space missions increased, the importance of food production became more and more a crucial need for the crew. Since the beginning of this inquiry, all the possible scenarios for long-term space missions and other extraterrestrial structures have involved plants as a human supporting environment. In 1986, Edwards and Pickard proposed for the first time that plants could actually detect and transduce external physical stimuli (Walter, 1987). That substantial evidence gave rise to a series of other experiments aimed at finding out the possible consequences of an alien life for plants. Subsequently, all the European, Asiatic and American space agencies have been putting their effort in involving seeds or previously grown plants in their spaceflights. In fact, even if specific growth facilities have been hypothesized and crafted by different research groups, the actual physiological effects of space environment on plants can only be identified in a weightless environment. Nowadays, the growth of plants in space remains a priority for plans concerning the long-term habitation of space and the media has helped to spread the idea of a possible space farm in the near future. Recently, millions of basil seeds have been put on board the International Space Station (ISS) for a project called Photosynthesis Experiment System Testing and

Operations (PESTO). A certain amount of those seeds will be brought back to Earth and here analyzed and planted in soil; the rest will be kept on board and the crew will try to complete the entire life cycle of the plants from seed to seed. By this time, plants are proper features of the space stations.

Roles of plants in space

For the first space researchers one of the first matters was to provide life support during space missions. The easiest and most used solution is an initial launch mass with periodic resupplies of consumables. Unfortunately, since from the beginning it was quite clear that it could become very expensive and wasteful on a long time scale as the stowage increases linearly as mission duration or distance from the Earth. In the late 80s, the idea of a Bioregenerative Life Support Systems (BLSS) for providing sustained life support during space missions was raised for the first time (Olson et al., 1988). In this prospective, vegetal systems play an important role for sustenance, producing food for the crew (Figure 1). Moreover, plants regenerate the air by removing CO_2 and producing O_2, and they purify water through transpiration. Another important aspect to be underlined is the psychological support that living organisms can give to the astronauts (Wheeler et al. 1996; De Micco et al. 2009). In regards to the food production, the human diet seems to require about 15 species of plants which must be grown on each space mission to ensure a complete, balanced diet (Olson et al., 1988). The ideal space-plant would have short stalks to save room, would have few inedible parts, would grow well in low light, and would be resistant to microbial diseases. The most efficient designs of regenerative life support systems combine both physicochemical and plant-based systems. In this case, food and waste processing, and temperature control can be accomplished with physicochemical systems beside the use of plants. Early studies of bioregenerative life support focused on algal systems, but converting the algae to useful and palatable food proved difficult (MacElroy and Bredt, 1984). Some algae are very rich in protein and are not appropriate for a balanced diet, moreover they may contains indigestible cell wall materials. Several studies focused on what crops might be the best candidate for the BLSS taking into consideration the nutritional needs and also the best harvest index (ratio of edible to total biomass). Research was aimed at choosing varieties of wheat, rice, lettuce, potatoes and other plants that meet these criteria. Many studies have highlighted growing more conventional crops using hydroponics to eliminate water and nutrient stress (Resh, 1989). Soilless culture has many advantages in cultivation of plants in space, such as no use of soil, reuse of water in the plant system, best control of nutrient levels and reduced risk of weeds. Moreover because the candidate crops are all C3 photosynthetic type elevated carbon dioxide concentrations and high light levels were applied to enhance growth rates and yields (Bugbee and Salisbury, 1988; Wheeler and Tibbitts, 1997). On ground extensive experiments were conducted to test crop responses to mineral nutrition, humidity, temperature, humidity, photoperiod and even light spectral quality. Currently, the possibility of growing plants in space is a requirement for the realization of long-duration manned missions.

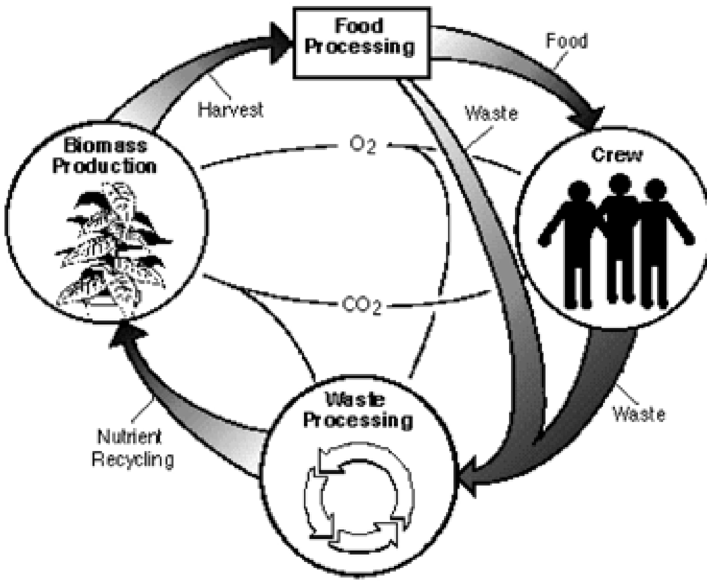

Figure 1: The fundamental relationships among plants, animals and humans within Bioregenerative Life Support Systems. A continuous supply of food, oxygen and clean water is available for the crew, while products of waste processing and CO_2 are reutilized by plants.

Space constraints for plants

The space environment that includes such factors as altered gravity and cosmic rays may affect plant growth and fitness in various aspects, but even today, there are few answers to these questions. The efficient development of plants in space is constrained by: a) the same environmental factors as the Earth, such as temperature and light (Zimmermann et al. 1996); b) the new space factors such as microgravity and ionizing radiation; c) the interaction of usual and new factors that modify the availability of resources. Our knowledge on plant growth response to the microgravity environment of low Earth orbit comes from experiments performed mainly aboard Space Shuttles, Mir and the International Space Station. The challenge of using plants as bioregenerative life support systems in space is the management of water, nutrient and light delivery. Nutrient delivery and water recycling will be most difficult in systems operated in microgravity. Technological advances are promising areas for enhancements in long-term space research. Improvements in lighting efficiency and the genetic engineering of crops that are better suited to a spaceflight environment such as dwarf crops, or of plants with high light harvesting indexes that can grow in artificial light or elevated CO_2 conditions, have been the aims of space researchers during the last years. The light system is one of the most important and critical components for growth of plants in a BLSS. The requirement to reduce power needs have brought to use lamps with narrow spectra (blue and red light) or light emitted diodes (LEDs). Some BLSS researches include the developments of a particular plant growth unit to be used on the surface of the Moon or Mars, such as an inflatable greenhouse that relies on direct photosynthetically active radiation (PAR) to irradiate crops. In this case transparent films would be required to withstand large external temperature gradients, strong cosmic-galactic and UV radiation, micrometeorite impacts and low atmospheric pressure.

Moreover, to investigate plant behavior in space, the effects of ionizing radiations have been studied since last century. For this purpose, ground-based experiments have been performed with particles of different charge and energy (as X- or γ-rays) (Durante and Cucinotta 2008). The aim of this space research is not only to identify qualitatively and quantitatively the effects of ionizing radiations but also to define countermeasures to mitigate these effects.

Studies on space effects on plants

A comparison of various studies has clarified how space effects are deeply influenced by plant characteristics (e.g. species, cultivar, stage of development, tissue architecture and genome organization) (Holst and Nagel 1997). In relatively short-term space-flight experiments, it has been pointed out the space environment causes chromosome aberration and changes in the cell cycle of plant cells. This may be due to either microgravity or increased cosmic rays in space or resulting from unfavorable growing conditions in the plant growing unit. Structural and functional changes in the DNA molecule are responsible for most of the damage expressed after exposure to ionizing radiations, at both the cellular and the systemic levels. DNA modifications range from single base alterations, base substitutions, base deletions, chromosomal aberrations to epigenetic modifications. In general, radiation exposure can induce both negative and positive effects on plants, and the mutations at the base of these effects can also be transmitted to the progeny (Mei et al. 1998; Yu et al. 2007). Apart from reduced germination, among the detrimental effects, there is often reference to embryo lethality, dwarf architecture, modification of floral morphology with altered occurrence of fertile floral elements (Kranz 1986; Sah et al. 1996). On the other hand, stress conditions, like the exposure to ionizing radiations, can have stimulatory effects on specific morphological parameters and can increase the yield of the plants in terms of growth, reproductive success and ability to withstand water shortage (Maity et al. 2005; Yu et al. 2007; Melki and Dahmani 2009). A few space-flight experiments have attempted to test the effects of the space environment on plant reproduction. For instance, *Arabidopsis thaliana* and wheat plants were grown in space for different durations (Mashinsky et al., 1994; Salisbury et al., 1995).

They were found to produce and develop flowers, but the flowers produced more sterile seeds than did ground control plants. These experiments could not specify the cause for such failure in seed production.

CONCLUSIONS

For space research, it is mandatory to understand how our planet supports all of us, and somehow replicate the parts that are necessary so that we can have affordable and even doable long-term space missions. A bioregenerative life support system will probably never fully replace the mechanical one on the International Space Station but with the help of plants and microbes, future space stations will truly become worlds unto their own.

REFERENCES

Barnes, C., & Bugbee, B. (1992). Morphological responses of wheat to blue light. Journal of Plant Physiology, 139, 339–342.

Bingham, G. E., Jones, S. B., Or, D., Podolski, I., Levinskikh, M. A., Sychev, V., et al. (1997). Microgravity effects on water supply and substrate properties in porous matrix root support systems, Reprint IAF/IAA-97-G.3.03, 48th International Astronautical Congress, Turin, Italy, October 6–10.

Boston, P. J. (1981). Low-pressure greenhouses and plants for a manned research station on Mars. Journal of British Interplanetary Society, 54, 189–192.

Britz, S. J., & Sager, J. C. (1990). Photomorphogenesis and photoassimilation in soybean and sorghum grown under broad spectrum or blue-deficient light sources. Plant Physiology, 94, 448–454.

Bugbee, B. (1999). Engineering plants for spaceflight environments. Gravitational Space Biology Bullettin, 12, 67–74.

Bugbee, B., & Salisbury, F. B. (1998). Exploring the limits of crop productivity. I. Photosynthetic efficiency of wheat in high irradiance environments. Plant Physiology, 88, 869–878.

De Micco, V., Aronne, G., Colla, G., Fortezza, R., & De Pascale, S. (2009). Agro-biology for bioregenerative life support systems in long-term space missions: general constraints and the Italian efforts. Journal of Plant Interaction, 4, 241–252.

Dreschel, T. W., & Sager, J. C. (1989). Control of water and nutrients using a porous tube: a method for growing plants in space. Horticultural Science, 1989, 24, 944–947.

Durante, M., & Cucinotta, F. A. (2008). Heavy ion carcinogenesis and human space exploration. Natural Review of Cancer, 8, 465–472.

Galston, A. W. (1992). Photosynthesis as a basis for life support on Earth and in space: photosynthesis and transpiration in enclosed spaces. Bioscience, 42, 490–493.

Goins, G. D., Yorio, N. C., Sanwo, M. M., & Brown, C. S. (1997). Photomorphogenesis, photosynthesis, and seed yield of wheat plants grown under red light-emitting diodes (LEDs) with and without supplemental blue lighting. Journal of Experimental Botany, 48, 1407–1413.

Hepler, P. K., & Wayne, R. O. (1985). Calcium and plant development. Annual Review of Plant Physiology, 36, 397–439.

Holst, R. W., & Nagel, D. J. (1997). Radiation effects on plants. In: Wang W., Gorsuch JW., Hughes JS. (Eds), Plants for environmental studies (pp 37–81). Boca Raton, FL: Lewis Publishers.

Kranz, A. R. (1986). Genetic and physiological damage induced by cosmic radiation on dry plant seeds during space flight. Advances in Space Research, 6, 135–138.

Krizek, D. T., Mirecki, R. M., Britz, S. J., Harris, W. G., & Thimijan, R. W. (1998). Spectral properties of microwave-powered sulfur lamps in comparison to sunlight and high pressure sodium/metal halide lamps. Biotronics, 27, 69–80.

MacElroy, R. D., & Bredt, J. (1984). Current concepts and future directions of CELSS. Advances in Space Research, 4, 221–229.

Maity, J. P., Mishra, D., Chakraborty, A., Saha, A., Santra, S. C., & Chanda, S. (2005). Modulation of some quantitative and qualitative characteristics in rice (Oryza sativa L.) and mung (Phaseolus mungo L.) by ionizing radiation. Radiation Physical Chemistry, 74, 391–394.

Mashinsky, A. L., Ivanova, I., Derendyaeva, T., Nechitailo, G. S., & Salisbury, F. B. (1994). From seed-to-seed experiment with wheat plants under space-flight conditions. Advances Space Research 14, 13.

Mei, M., Qiu, Y., Sun, Y., Huang, R., Zhang, Q., Hong, M., et al. (1998). Morphological and molecular changes of maize plants after seeds been flown on recoverable satellite. Advances in Space Research, 22, 1691–1697.

Melki, M., & Dahmani, T. H. (2009). Gamma irradiation effects on durum wheat (Triticum durum Desf) under various conditions. Pakistan Journal of Biological Science, 12, 1531–1534.

Olson, R. L., Oleson, M. W., & Slavin, T. J. (1988). CELSS for advanced manned missions. Horticultural Science, 23 (2), 275–286.

Pickard, B. G. (1985). Early events in geotropism of seedling shoots. Annual Review of Plant Physiology, 36, 55–75.

Pickard, B. G. (1985). Roles of hormones, protons and calcium in geotro-pismo In Encyclopedia of Plant Physiology, (N S), Hormonal Regulation of Development. III. Role of Environmental Factors, ed. R. P. Pharis, D. M. Reid, 1 1 : 1 93–28 1. Berlin/Heidelberg/NY: Springer-Verlag.

Resh, H. (1989). Hydroponic Food Production, edn 4. Santa Barbara, CA: Woodbridge Press.

Sah, N. K., Pramanik, S., & Raychowdhuri, S. S. (1996). Peroxidase change in barley induced by ionizing and thermal radiation. International Journal of Radiation Biology, 96, 107–111.

Salisbury, F. B. (1999). Growing crops for space explorers on the moon, Mars, or in space. Advances Space Biology Medicine, 7, 131–162.

Salisbury, F. B., Bingham, G. E., Campbell, W. F., Carman, J. G., Bubenheim, D. L., Yendler, B., et al. (1995). Growing super-dwarf wheat in svet on Mir. Life Support and Biosphere Science, 2, 31.

Schwartzkopf, S. H. (1997). Human life support for advanced space exploration. Advanced Space Biology Medicine, 6, 231–253.

Walter, H. U. (1987). Fluid Sciences and Materials Science in Space: A European Perspective. Edited by Walter H.U. Berlin: Springer-Verlag.

Wheeler, R. M., Mackowiak, C. L., Stutte, G. W., Sager, J. C., Yorio, N. C., Ruffe, L. M., et al. (1996). NASA's biomass production chamber: a testbed for bioregenerative life support studies. Advances in Space Research, 18, 215–224.

Wheeler, R. M., & Tibbitts, T. W. (1997). Influence of changes in day length and carbon dioxide on the growth of potato. Annals of Botany, 79, 529–533.

Yu, X., Wu, H., Wei, L. J., Cheng, Z. L., Xin, P., Huang, C., et al. (2007). Characteristics of phenotype and genetic mutations in rice after spaceflight. Advances in Space Research, 40, 528–534.

Zimmermann, M. W., Gartenbach, K. E., Kranz, A. R., Baican, B., Schopper, E., Heilmann, C., et al. (1996). Recent results of comparative radiobiological experiments with short and long term expositions of Arabidopsis seed embryos. Advances in Space Research, 18(12), 205–213.