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Editorial: Bioregenerative life-support systems for crewed missions to the Moon and Mars

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Editorial on the Research Topic
Bioregenerative Life-Support Systems for Crewed Missions to the Moon and Mars

The present decade may see the beginning of a sustainable human presence on the Moon; the next may be that of humankind's first steps on Mars. Such at least is the goal of the leading space agencies (ISECG, 2018), and private companies—most publicized, SpaceX—have stated related objectives (Musk, 2017).

Humans, of course, need a habitable environment and a wealth of consumables to survive: food, water, oxygen and possibly medication, to name a few. As missions get longer and more remote, providing all these consumables from Earth becomes unrealistic: launch costs, travel times, and risks of failure are critical obstacles. Bioregenerative life-support systems (BLSS) are a highly promising way of addressing this limitation, even more so if they can be combined with *in situ* resource utilization (ISRU). In the present Research Topic, this is illustrated by Berliner et al., who argue for an integrated biomanufacturing plant for resource production and recycling on Mars. They also present associated challenges, goals, and example systems.

Despite extensive research performed over the last few decades, no BLSS project has reached enough maturity to significantly increase the autonomy of even a small-sized base on the Moon or Mars. Experience gained from long-running BLSS projects (e.g., ESA's MELiSSA project; Lasseur et al., 2010; Walker and Granjou, 2017) shows that their development is a long-term process. Pragmatic efforts are thus needed presently for BLSS to be ready when Moon and Mars missions would benefit from them. This Research Topic aimed at stimulating such efforts.

Lunar and Martian BLSS will most likely include plants, which are necessary for food production. In addition, they provide air revitalization and water purification capabilities (e.g., Wheeler, 2010), and could be used for other functions including, for instance, pharmaceutical production (McNulty et al., 2021). Accordingly, nine contributions to this

Research Topic focus on plant cultivation. Johnson et al. review NASA's work toward the development of plant chambers for supplemental, fresh food production in space. Such chambers could be used in early missions, before on-site production covers the crewmembers' entire nutritional needs. Another facility, this one at the University of Naples, is described by Pannico et al. (with a higher focus on its atmosphere control system): the Plant Characterization Unit, an environmentally-controlled chamber for investigations on BLSS higher plant compartments. Poulet et al. describe major challenges for space crop production, as identified by the Kennedy Space Center, as well as NASA's efforts to overcome them. Medina et al. and Schuerger each focus on one of these challenges. Medina et al. give an overview of the available knowledge, and its gaps, on the influence of gravity levels below 1 g on the early development of plants. Schuerger argues that pests and phytopathogens, common in terrestrial agriculture, will be a concern in plant-supported missions to the Moon and Mars; he therefore outlines a first-order integrated pest management program. Tack et al. introduce an additional challenge: their results suggest that average ionizing radiation levels at the surface of Mars could reduce plant productivity (but not germination), although technical difficulties made conclusions hard to draw. Handy et al. describe, rather than challenges, some opportunities: those brought by plant growth promoting bacteria. They identify promising ones, isolated from a crop production system aboard the ISS. Finally, two articles pertain to the use of lunar and Martian regolith as plant growth substrates. In the first, Duri et al. describe regolith simulants previously used for cultivation experiments, review these experiments, and discuss solutions aimed at improving the suitability of simulants (and, possibly, of actual lunar and Martian regolith) for agriculture. In the second, Peyrusson presents preliminary results which suggest that hydrogels could improve the water retention of Martian regolith, thereby fostering germination and growth under low irrigation regimes.

Whether or not they are directly associated with plants, microorganisms are other likely components of lunar and Martian BLSS. The roles they could fulfill include waste processing, food production, atmosphere regeneration, the production of drugs, fuels, biomaterials and various industrially useful chemicals, metal leaching, and food processing for taste improvement (e.g., Hendrickx and Mergeay, 2007; Horneck, 2008)—in some cases after genetic engineering (see for instance Cockell, 2011; Montague et al., 2012; Menezes et al., 2014; Verseux et al., 2016). A number of microbial species have been proposed and the complexity of the targeted applications, as well as the variety of microbial metabolisms, make it hard to select rationally the microorganisms to be used. Averesch provides insights: he compares microbial systems which could be suitable for ISRU on Mars and sketches some classification schemes. He suggests, for instance, that microbial systems can be sorted based on carbon conversion: on whether carbon is directly converted from an inorganic state to end products, or first fixed by primary producers and then used as a substrate for secondary producers. An example of the latter case is provided by Cestellos-Blanco et al. They present a process aimed at producing PHB (a biodegradable polyester whose material properties resemble that of polyethylene, and which can be 3D-printed) from Mars's atmospheric CO_2 in two steps, each carried by a separate bacterium: CO_2 is first used as feedstock to generate acetate, which then serves as a substrate for PHB production.

While in the example given above the carbon fixer is an acetogen, most microbial primary producers under consideration are photosynthetic. Six articles of the present Research Topic treat of such organisms. Fahrion et al. review experiments performed with photobioreactors, over the past three decades, in view of developing BLSS for human space exploration. They also identify gaps in knowledge. Two articles focus on *Limnospira indica* (formerly *Arthrospira* sp. PCC8005), the cyanobacterium included in MELiSSA (Hendrickx et al., 2006). In the first, Poughon et al. describe a mass-balanced mechanistic model which can describe and predict its growth in photobioreactors of various scales. In the second, Sachdeva et al. compare the effects of three different nitrogen sources (nitrates, and the prominent nitrogen forms in non-nitrified urine: urea and ammonium) on its oxygen production rates, in a ground demonstrator where the cyanobacterium revitalizes the air breathed by a mouse. Results should help in assessing whether the nitrification of urine fed to cyanobacteria can be skipped, which could reduce the complexity of the MELiSSA loop. Detrell writes on the potential of the eukaryotic microalga *Chlorella vulgaris* (recently sent to the ISS for experiments on life support; Detrell et al., 2020) as a BLSS component for food production and air revitalization, as well as on the associated challenges. Cycil et al. exposed five microalgal species, considered for food production and air revitalization, to low total pressures (down to 80 hPa) of high-CO_2 atmospheres. The goal was to compare the organisms' tolerance for hypobaric conditions: relying on lower-than-ambient pressures in photobioreactors could help relax engineering constraints, and consequently the costs, of microalgal cultivation on the Moon or Mars (Kanervo et al., 2005; Verseux et al., 2021). Finally, Matula et al. assess the impact of rapid temperature variation on the oxygen production of temperate and psychrotolerant microalgae. Results will help in assessing the feasibility of using culture media as a heat sink in crewed spacecraft, thereby coupling air revitalization with temperature control.

While carbon is certainly central to BLSS, as illustrated by the many articles in this Research Topic which focus on organisms capable of its fixation, nitrogen is another key element (see, e.g., Loader et al., 1997). Its recycling will most likely require microorganisms, and so may its fixation from Mars's atmospheric N_2: though abiotic fixation with the Haber-Bosch process is being considered as well, the associated upmass and energy consumption are high. Three articles address this theme.

One is that of Sachdeva et al., already mentioned above. Another is that of Langenfeld et al., who review approaches considered for nitrogen fixation and recycling in BLSS. The third is that of Verbeelen et al., who discuss nitrogen recovery from urine waste streams (the main source of nitrogen in BLSS waste) and detail the compartment which, within MELiSSA, performs such functions.

Microbial capabilities on the Moon and Mars can go beyond basic life support. In addition to the PHB production process described by Cestellos-Blanco et al., this is exemplified by Kozyrovska et al.: they discuss potential applications of kombucha microbial communities beyond Earth that range from the synthesis of health-promoting compounds to the production of clothing materials.

Plants, bacteria and microalgae are not the only organisms considered for lunar or Martian BLSS. Examples of proposed elements include fungi (Cortesão et al., 2020), insects (Li et al., 2015), and fish. Przybyla addresses the last. He discusses the prospects of space aquaculture, reviews experiments with fish in low Earth orbit, and describes Lunar Hatch: a project whose contributors assess the feasibility of sending fish eggs to the Moon for on-site hatching.

A number of concepts for BLSS elements have been described, here and elsewhere, and promising proofs-of-concept have been obtained. The next steps are highly challenging. Efforts are nonetheless underway to test the integration of different elements, or to assess the cost-efficiency of maturing BLSS technologies. Garcia-Gragera et al., for instance, report recent results from MELiSSA's Pilot Plant, a ground-based demonstrator whose focus is currently on the integration of three elements: a nitrifying packed-bed bioreactor, an air-lift photobioreactor for *L. indica*, and an animal isolator with rats as a mock-up crew. McNulty et al. present an assessment, based largely on equivalent system mass (a single metric accounting for mass, volume, power, cooling and crew-time requirements; Levri et al., 2003), of different strategies for the purification of monoclonal antibodies. More broadly, they discuss paths toward the development on-site pharmaceutical production systems, as well as approaches to their evaluation. Finally, Irons and Irons propose a framework to quantify the sustainability of BLSS, after pointing out that, while BLSS are often seen as enablers of sustainability beyond Earth, ways of formally quantifying sustainability are lacking.

When proposing this Research Topic, we hoped that it would both provide an overview of the field and lessons from past efforts, as well as introduce innovative concepts and new results that may find their way into mission designs. Thanks to the enthusiasm of our colleagues who submitted manuscripts, and to the diligence of the solicited reviewers, we hope that readers from the broader scientific community will find that these objectives have been met.

Author contributions

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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