The unsolved challenges of space biospheres: a research agenda

Original
The unsolved challenges of space biospheres: a research agenda / Scarpisi, F.; Gomez-Fernandez, D.; Pino, P.; Panetta, S.; Rabagliati, L.; Carabellese, D.; Salmeri, A.. - ELETTRONICO. - (2021). ((Intervento presentato al convegno 72nd International Astronautical Congress tenutosi a Dubai (United Arab Emirates) nel 25-29 October 2021.

Availability:
This version is available at: 11583/2973787 since: 2022-12-13T10:18:17Z

Publisher:
IAF

Published
DOI:

72nd International Astronautical Congress (IAC), 25-29 October 2021.

IAC-21-A1, IP20, x66561

The unsolved challenges of space biospheres: a research agenda

Mrs. Floriana Scarpisi [a*], Mr. David Gomez-Fernandez [a], Mr. Paolo Pino [b], Ms. Silvia Panetta[a], Mr. Lorenzo Rabagliati[c] , Mr. Davide Carabellese [d],, Mr. Antonino Salmeri[a], Mr. SGAC Space Exploration Project Group [a]

[a] *Space Generation Advisory Council (SGAC)*
[b] *Politecnico di Torino, Torino, Italy*
[c] *International Master SEEDS, Italy*
[d] *Thales Alenia Space Italia (TAS-I), Italy*
* *Corresponding author florianascarpisi@hotmail.com*

Abstract

An epochal turning point would see the realization of a lunar human settlement, which would require a high degree of autonomy from earthbound services and supplies. In this, a crucial role will be played by the exploitation of local resources and environmental features, as well as by the development and maintenance of bioregenerative ecosystems. The Biosphere Team has been established by the SGAC Space Exploration Project Group, in partnership with the MVA Architecture Working Group, to explore the opportunities presented by the combination of biospherics with the peculiarities of the lunar south pole. This includes the usage of regolith as living soil, customized selection of crops and in situ production and utilization of resources, with the ultimate goal of achieving a maximum degree of biosphere autonomy. This shall also go towards re-creating an environment most similar to Earth and guaranteeing an ideal habitat for the plants, by regulating nutrients, water and daylight supplies. On the other side, the study is designed to explore the disturbance factors deriving from such a strategy, like the presence of metal elements in the soil and the irregular morphology of regolith particles, as both aspects could affect the development of the crops selected. Therefore, delving into these specific aspects would aim in creating and maintaining a well-established ecosystem. The outcome of the work is a multidisciplinary research agenda highlighting the major gaps and needs in research and development required to further advance biosphere technologies towards wider integration with human needs and lunar environments. Please note that this abstract is submitted under the auspices of SGAC, as part of the activities of its Space Exploration Project Group.

1. Introduction

A massive improvement and a crucial milestone for humankind would be the realization of a lunar human settlement. A relevant role would be played by the exploitation of local resources, environmental features, as well as by the development and maintenance of bio regenerative ecosystems. Thanks to the collaboration between SGAC Space Exploration Project Group, and the MVA Architecture Working Group, the Biosphere Team was established in May 2020, which involved the collaboration and efforts of seven professionals specialized in different fields, from Engineering to Pharmaceuticals.

The Biosphere Team has focused their studies mainly in evaluating suitable biosphere structure, promising technologies to bring to the Moon and a customized selection crop which could support the daily nutritional values of the crewmembers.

Overall, this study aims to provide a research agenda by highlighting the major gaps and needs in research and development required to further boost biosphere technologies. Our approach is multidisciplinary, which has led to focus the study on critical issues that involve the exploitation of local resources. Finally, our research will provide promising avenues for further investigation.

Since the dawn of time, people all over the world have been interested in observations and explanations of outer space up to making space exploration possible with cutting-edge technology. Lately, the focus has shifted to the Moon as a result of recent missions that have made possible to establish settlements on the lunar surface. However, we must not overlook that there are several actors involved and there are such numerous decisions on which to reach an agreement at the political level. It should be noted that the development of these lunar settlements would necessitate contributions from a variety of stakeholders and political forces, in addition to the development of advanced technologies and the presence of infrastructure.

Given that the aforementioned scenario will be well supported by the actors involved and critical issues will be resolved, the Biosphere Team has set a goal of analyzing a more detailed proposal for further implementing the lunar habitats by highlighting the limitations and attempting to leverage the aspects that need to be improved and/or strengthened.

The main themes that will be explored during the evaluation include the following proposals:

- Structure concept
- Crop selection and key factors
- Daily Nutritional values
- Equivalent System Mass assessment

2. Structure concept

The Biosphere is designed within a hollow pit over the Moon surface that already exists or is excavated. The biosphere is covered by four petal-shaped dome hatches covered with filled or 3D printed regoliths to improve isolation and it can be opened/closed during daytime, nighttime, or under any other event. Then the center of the biosphere has a semi-buried habitat to improve shelter conditions [1] [2] . The habitat is surrounded or encircled by an artificial greenhouse shown in Figure-1. Comprising a place for plantation of crops. Further, the greenhouse is surrounded by regolith walls using 3D printed and additive technology [3], and glass panels at the inner walls. A side view and a complete scheme of the parts of the biosphere are shown in Figure-2**.**

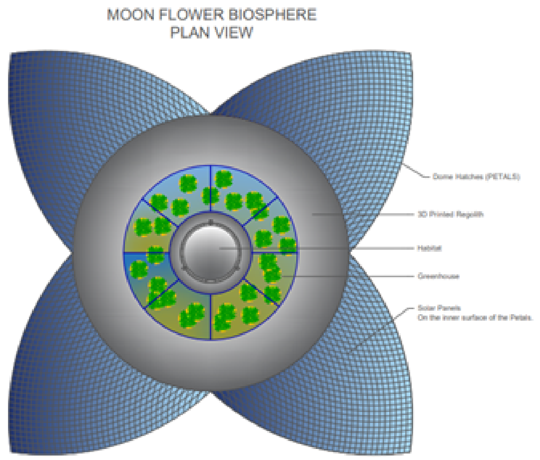


Fig. 1. Biosphere concept plan view

2.1 Operation of the Dome under different scenarios

During maintenance operations, thermal adjustments or under any other event the petal-shaped dome hatches get folded and closed to isolate the complete biosphere (both greenhouse and habitat). Due to the shielding nature of the dome hatches (filled with lunar regoliths), it protects the entire biosphere from exposure to harmful surface radiation.

The dome system can be used during the 14-days period of daytime that takes place at any location of the moon once per month in regions distant from the poles, to simulate a day-night cycle for stimulating plants and crops in a more natural or Earth-like way. Further, the inner surface of the dome is equipped with solar panels to enhance power production and to take advantage of sun rays when dome hatches are open. When the dome is closed it contributes to balance the thermal conditions inside the greenhouse. The above mentioned follows the principle of some terrestrial flowers. Hence, the biosphere concept is named as "The Moon Flower Biosphere".

The opening and closing cycles during this 14-day light period also have a positive psychological impact on the crew, allowing the establishment of light-dark cycles analogous to those on the Earth, contributing to circadian rhythms.

During the 14-day dark period, when temperatures are lower for a longer time, the dome can be kept closed to ensure correct thermal conditions inside and to improve the energy efficiency of the greenhouse during such a cold cycle.

Dome system also allows the crew to protect the habitat and subsequently themselves under a micrometeoroid impact event [4].

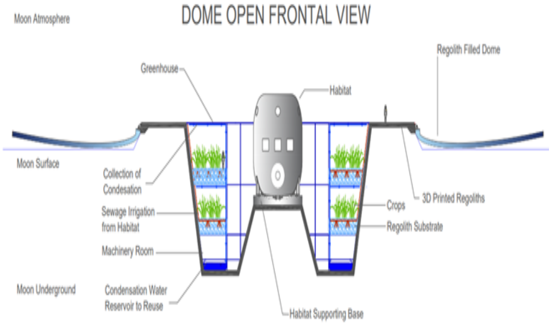


Fig. 2. Biosphere concept side view - Open

2.2 Design Overview of Moon Sub-surface Habitat

The proposed habitat is ovoid to retain adequate pressure within it. Then the habitat is integrated into a supporting base with seismic bearings to compensate for the impact of the seismic effect imposed over the structure by the moonquakes. Then the supporting base is fixed over a 3D printed regolith floor shown in Figure 2. The dome structure is to improve the extent of isolation of the habitat against radiation and to mitigate micrometeoroid impacts [4], as shown in Figure 3.

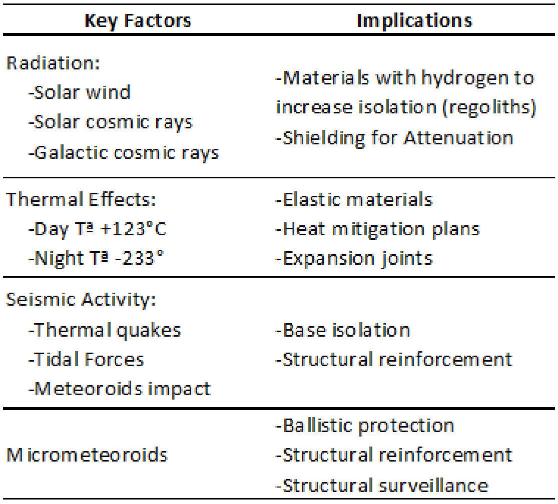
2.3 Justification of the Moon Semi-Buried Habitat

The habitat is semi-buried in order to improve shelter conditions [5], such as tangential radiation at poles and tangential ballistic projections coming from other human activities such as construction and space mining. The habitat has a configuration of three floors, first and second floors, where laboratories and sleeping rooms for the crew are located, are completely underground to assure protection. Third floor, where spare areas for leisure time are located, is at surface level, it allows the crew to relax, enjoying the lunar landscape and the views towards the Earth through the windows [6], also to control and monitor the activities that astronauts are developing outside the biosphere.

2.4 Environmental considerations to take into account when designing a lunar settlement

There are a few critical external factors to take into account when designing infrastructures on the Moon. The main ones are summarized in Table 1 together with their implications in the structure and in the materials to be chosen.

Table 1. Design key factors



Key Factors	Implications
Radiation: -Solar wind -Solar cosmic rays -Galactic cosmic rays	-Materials with hydrogen to increase isolation (regoliths) -Shielding for Attenuation
Thermal Effects: -Day Tª +123°C -Night Tª -233°	-Elastic materials -Heat mitigation plans -Expansion joints
Seismic Activity: -Thermal quakes -Tidal Forces -Meteoroids impact	-Base isolation -Structural reinforcement
Micrometeoroids	-Ballistic protection -Structural reinforcement -Structural surveillance

2.5 Biosphere and Habitat Features

- Ensures isolation against the hostile environment.
- Effective against recurrent micrometeoroid impact events.
- Effective against surface radiation and seismic effects of moonquakes.
- Enhances thermal stability of habitat and greenhouse when needed.
- Afford a favourable environment for the growth of life forms.
- Effective for retaining optimal pressure and atmosphere.
- Affords fresh breathable air and food, retro alimentation habitat-greenhouse.
- Promotes sustainable habitation.

2.6 Biosphere proposed materials

Many building materials can be sources in situ through ISRU, namely:

- 3D printed regoliths through sintering (perimetral walls, foundations and isolation)
- Loose regoliths (cultivation area and isolation)
- Solar panels manufactured from regolith sand (energy caption system)
- Water & Oxygen extracted during excavation (greenhouse air).
- Intelligent glass panels manufactured from regolith sand (greenhouse envelope).

Whereas some other materials will need to be imported from Earth initially, i.e.:

- Aluminum (greenhouse and habitat structures. Isolation)
- Steel reinforcements (3D printed walls strengthening)
- Anti-radiation painting to improve isolation (inner face of 3D printed walls and habitat)
- Water irrigation pipes for water distribution.
- Equipment (water pumps, water tanks, air pumps)

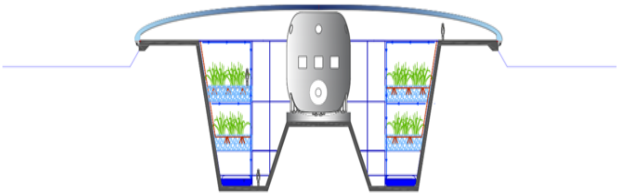


Fig. 3. Biosphere concept frontal view - Closed

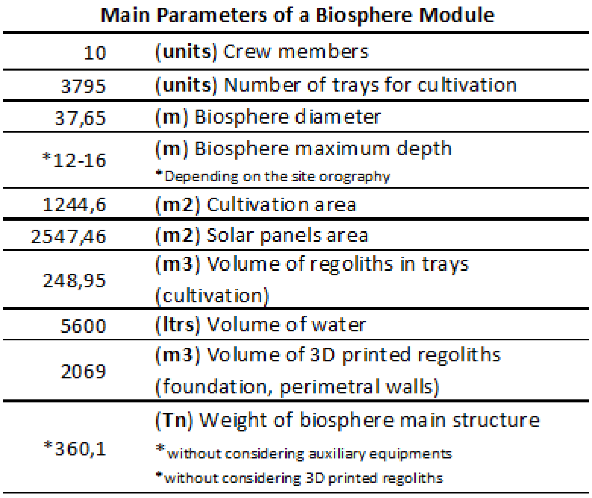
2.7 Biosphere main parameters

The biosphere module has been designed to have enough space and plantation area to sustain up to 10 crew members together with crops and small animals, like chickens and rabbits, in a balanced way. The plantation area is divided in two different floors, acclimatized with two different temperatures to fit the optimal development temperature of the crops, 22ºC and 27ºC. It has been designed in such a way that the size expansion of the biosphere is simple, the modules can be linked to each other up to an amount of 5 by placing then together enough and by installing the connection pipes for the air and water recirculation systems between modules, in such a way to ensure a correct functioning of both air and water cycles within the biosphere, simulating those existing on Earth, thus ensuring the purification of both fluids in a more natural way.

A small amount of water can be initially sent from Earth in order to have a guaranteed supply during the very beginning of the implantation phase, but in the long term and in order to reduce the dependance from Earth it is proposed to take advantage of the water present in the regoliths [8], by melting it during the excavation and sintering processes to be done while construction activities are developed.

Main parameters of a biosphere module are summarized in Table 2.

Table 2. Parameters of a biosphere module



Main Parameters of a Biosphere Module	
10	**(units)** Crew members
3795	**(units)** Number of trays for cultivation
37,65	**(m)** Biosphere diameter
*12-16	**(m)** Biosphere maximum depth *Depending on the site orography
1244,6	**(m2)** Cultivation area
2547,46	**(m2)** Solar panels area
248,95	**(m3)** Volume of regoliths in trays (cultivation)
5600	**(ltrs)** Volume of water
2069	**(m3)** Volume of 3D printed regoliths (foundation, perimetral walls)
*360,1	**(Tn)** Weight of biosphere main structure *without considering auxiliary equipments *without considering 3D printed regoliths

3. Crop selection

Plants are crucial to the operation of many ecosystem processes not to mention the vast number of properties that a human being can benefit from. For this reason, we have considered a range of 14 plants which will provide a good nourishment in terms of nutritional intake and properties. The crop selection evaluated has been selected according to these criteria [9]:

- Plant cultivation aspects (e.g.required height, harvest number)
- Human factors (e.g. if the plant is edible, taste)
- Nutrition values

The following table (Table 3) is an overview of the selected plants for the proposed Biosphere structure:

Table 3. Crop selection and their nutrition values

Raw crop 100 g	**Protein [g]**	**Carbohydrates [g]**	**Fats [g]**	**Dietary Fibres [g]**	**Water content [%]**
Arugula*	2,6	3,7	0,7	1,6	91,70
Basil fresh	3,2	2,7	0,6	1,6	92,06
Batavia lettuce	1	2	0	1	95
Cherry tomatoes	0,88	3,92	0,2	1,2	95
Chives	3,3	4,4	0,7	2,5	90,65
Cucumber	0,7	3,6	0,1	0,5	96,4
Mizuna	2,6	5,6	0,7	3,8	91,8
Fresh parsley	3	6,3	0,8	3,3	87,71
Radish	0,68	3,4	0,1	1,6	94,94
Swiss Chard	1,83	4,1	0,11	2,1	92,66
Orange tomatoes	1,2	3,2	0,2	0,9	94,78
Peas (split, mature seeds harvested, raw natural)	24,55	60,37	1,16	25,5	11,27
Peas (split, mature seeds harvested, boiled, cooked, without salt)	8,34	21,1	0,39	8,3	69,49
Kale (raw natural)	4,28	8,75	0,93	3,6	84,04
Kohlrabi	1.9	3.7	0.2	3,6	91

This study has taken into consideration the deficiencies which may affect a crewmember of a lunar settlement subject to a new environment adaptation but above all to a lack of fresh food diet from which to obtain essential vitamins and nutrients to support human metabolic activities.

Thus, it is important to highlight that this study aims to raise the crucial role of introducing fresh food in the diet in order to increase the intake of nutrients which could improve the health of the crewmembers. In fact, it is highly noted that in microgravity environments, proper nutrition can combat the resulting degradation of bones and muscles. For this reason, we have considered the above plants which contain vitamins D, K and C will trigger the processes in synthesizing calcium into bone. Therefore, combining exercise with a daily intake of these vitamins will help astronauts in retaining bone and muscle strength against the deleterious effects of microgravity. Another possible health issue which may face the crew members could be the sight which could be reduced along the mission due to the environmental condition.

To counter this possible damage we have included in our selection Mizuna, which is a plant with promising health benefits. In fact, it has been proven that this plant boasts lutein and zeaxanthin, two antioxidants important for eye health[] These compounds have been shown to protect the retina from oxidative damage which will be a great improvement for the well-being of the crew members who will take part in long missions.

In addition, it has been shown that a crucial element has been played by a specific element, which is magnesium. In fact, a shortage of this component in our diet could damage body functions due to the fact that it is involved in more than three hundred enzymatic reactions like synthesis of DNA and RNA, carbohydrates, and lipids, and also it is essential for nerve conduction and muscle contraction.

3.1 Key factors

For the implementation of the greenhouse, it has been considered the following factors in order to obtain sufficient edible mass for each crewmember on a daily basis []:

- Water pH
- Humidity
- Temperature
- Partial pressure Carbon dioxide

It is crucial to understand the pH and alkalinity of irrigation water since it may have a negative impact on the fertility of the plants in the greenhouse. As a result, we must consider pH and alkalinity when determining the suitability of water for irrigating the crop selections evaluated for the greenhouse. For the reason above, it is recommended to check the pH and alkalinity of the water before using it for irrigation. The alkalinity test is essential for determining the concentration of bicarbonates, carbonates, and hydroxides in water. The results of tests are typically expressed in parts per million of calcium carbonate ($CaCO_3$) and the optimal values for most plants have a level of $CaCO_3$ between 30 and 60 ppm. Furthermore, for irrigation water, the ideal range is 0 to 100 ppm $CaCO_3$ [10].

Water with a high pH (7-8) and low alkalinity is commonly used in irrigation systems (less than 100 ppm $CaCO_3$).

The second factor evaluated is humidity, which should be 60-80 percent roughly in order to allow plant transpiration. The last one is extremely important in order to guarantee two primary functions: cooling the plant and pumping water and minerals to the leaves for photosynthesis.

The third factor is the temperature, which has been set at 18-27 degrees Celsius.

Finally, but not least is the pressure, which should be 101 kPa.

3.2 Crop fertility

One of the main factors which could affect the growth of plants could be the pH of the soil. The study of soil pH is critical in agriculture because soil pH regulates plant nutrient availability by controlling the chemical forms of the various nutrients and also influences their chemical reactions. As a result, soil and crop productivity are related to soil pH. For most agricultural crops, the ideal range is between 5.5 and 7.5. Some crops, however, have adapted to thrive at soil pH levels outside of this optimum range. On this matter, the United States Department of Agriculture's National Resources Conservation Service categorizes soil pH values as follows: extremely acidic (3.5–4.4), very strongly acidic (4.5–5.0), strongly acidic (5.1–5.5), moderately acidic (5.6–6.0), slightly acidic (6.1–6.5), neutral (6.6–7.3), slightly alkaline (7.4–7.8), moderately alkaline (7.9–8.4), strongly alkaline (8.5–9.0), and very strongly alkaline (8.5–9.0)[11].

In fact, over time, soil scientists who focus on soil fertility have been trying to manage nutrients to improve crop production by using composts, commercial fertilizers, waste products, and manures to add nutrients and organic matter to the soil. It has been demonstrated that the technique to add chemicals or components might change the pH to a more optimum level for nutrient availability to plants.

3.3 Positive effects on crop fertility

As previously stated, soil and crop productivity are linked to soil pH value.
Crop growth and development are influenced by both acidic and alkaline soils. Agricultural crops grown in acid soils, for example, may be subjected to stresses such as aluminum, hydrogen, and manganese toxicity, as well as calcium and magnesium nutrient deficiencies. Strong alkaline soils such a regolith soil on the other hand, have slow infiltration, low hydraulic conductivity, and poor soil water retention capacity, causing crop water stress.

Because agricultural crops vary in their suitability for soil pH ranges, pH adjustment is critical for crop performance.Using finely ground agricultural lime, the pH of acidic soil can be raised (limestone or chalk). Other additives that can be used include wood ash, industrial calcium oxide (burnt lime), magnesium oxide, basic slag (calcium silicate), and oyster shells.
Alkaline soils, on the other hand, can have their pH reduced by using acidifying fertilizers such as ammonium sulphate, ammonium nitrate, and urea or organic materials, for instance, peat or sphagnum peat moss [12].
Another factor to consider is the possibility of increasing plant productivity via the photosynthetic route: a mixture of aliphatic alcohols (C-24 to C-34) known as “Mixtalol”. The treatment was found to increase root length and number of laterals, shoot fresh weight, and shoot and root dry weight of various crop plants significantly. Mixtalol foliar application on vegetables (tomato, beans, cauliflower etc.) resulted in significant yield increases [13].

3.4 Negative effects on crop fertility

Environmental conditions can influence the production and development of plant growth regulator factors such as auxins,gibberellins and cytokinins. In fact, several studies have demonstrated that complex protein structures are destroyed or denatured at high temperatures, and biological reactions are hampered. Low temperatures, on the other hand, can limit biological reactions because water is unavailable and the available energy is insufficient. Another import factor to denote is the scarcity of nutrients. In fact, nutrient deficiencies are one of the factors that can contribute to low plant productivity. There are 17 plant nutrients that are required and they are divided into macronutrients, micronutrients and beneficial. The first category comprises nitrogen, phosphorus, potassium, calcium, magnesium and sulfur, which are required in large quantities. The second one includes iron, manganese, zinc, boron, chlorine, nickel, copper and molybdenum, instead, they are considered necessary in small amounts, and beneficial elements (silicon, cobalt and sodium) are required by some plants but not all.
It is important to shed light on another aspect, water stress has well-documented effects on plant growth. Water scarcity causes plants to overproduce reactive oxygen species (ROS) such as hydrogen peroxide (H2O2) and superoxide anion radicals (O2), which inhibits growth, decreases photosynthetic functions, lipid peroxidation, and increases the frequency of programmed cell death processes.It is worth noting, however, that in order to adapt to water stress, plants have evolved numerous acclimation mechanisms, such as osmotic adjustment and antioxidant defense systems, which improve their ability to grow and develop under drought conditions. Soluble sugars and proline accumulate under water stress conditions to serve as osmolytes in various plants, aid in membrane protein stabilization, and ultimately increase plant resistance to water stress. Furthermore, ROS-scavenging enzymatic antioxidants such as superoxide dismutase (SOD), peroxidase (POD), catalase (CAT), glutathione reductase (GR), and ascorbate peroxidase (APX) can be activated to remove excess ROS. Modifications in the activities of these enzymes are most likely the primary mechanism by which plants tolerate water stress [14].

4. Equivalent System Mass Assessment

The ability of the biosphere to ensure long-term sustainability has been preliminarily assessed through the Equivalent System Mass (ESM) approach [15].
This approach allows us to estimate the overall mass that would need to be shipped to the Moon in order to establish and sustain continued presence and operations throughout the entire mission duration. Some of the main factors impacting the ESM are hardware mass, power requirements, resupplies, and crew time. The extent to which these elements influence the ESM depends on the technologies being used. For instance, bio-regenerative life-support systems allow to significantly decrease the need for resupplies with respect to non-regenerative systems, which translate into much larger ESM savings over the long term, in spite of a higher starting ESM due to the larger hardware mass required. This tool is therefore very important to inform long-duration mission planning and systems design.
For the present study, a coarse ESM model has been adopted to compare three different scenarios for the biosphere and identify the most pressing research and development needs.

1. **Scenario N.1: “Melissa-like”**. A biosphere concept based on ESA’s Melissa system is taken as a reference case for comparison. Here, the biosphere is not explicitly designed to leverage environmental features, such as crater slopes and illumination patterns, and does not make use of ISRU or in-situ manufacturing for water provision and fabrication of structural parts. Similar concepts are meant to be an all-in-one solution that can rapidly enter operational status. Plants are grown using hydroponics. The biosphere is able to recover a large amount of water, similar to the International Space Station [16]. Half of the crew tasks are automated.
2. **Scenario N.2: “Biosphere-1”.** The biosphere described in the above sections is deployed and operational. The biosphere recovers most of the water used, and sources the remainder from a local water extraction system. The water extraction system is based on architecture previously described in the literature [17][18]. Briefly, a regolith excavation system is deployed in the permanently shadowed area inside the Shackleton Crater. Here, ice-rich regolith is collected and delivered to a regolith transport system, which feeds a plant tasked to separate water from dry regolith. Indicatively, about 2 kg of hardware mass are required to produce 1 kg of water. 30% of the biosphere mass is constructed in situ leveraging specialized machinery [19]. It has been assumed that regolith sintering would be the manufacturing technique of choice for the production of structural parts. The manufacturing system is assumed to have a 2.5 tonnes mass. Two systems are deployed for construction. Regolith is also used as cultivation soil, replacing hydroponics. This determines an overall 50% decrease in food productivity which creates the need for additional cultivable area [20]. Half of the crew tasks are automated.
3. **Scenario N.3: “Biosphere-2”.** Biosphere-2 is an evolution of Biosphere-1, bringing several improvements under key areas. Up to 70% of the biosphere is now built in-situ out of lunar materials. These include foundations and retaining regolith walls, roof shields and glass panels. Improvements have been made in food production with lunar soil, for instance through the addition of organic matter, microbes, or regolith pre-treatments, bringing a 20% improvement with respect to the previous scenario. Advancements in robotics and AI allow for a 70% automation of crew tasks. 99% of the water is recovered, while the rest is obtained locally.

A summary of the key traits in the three scenarios is presented in the Table below:

Table 4. Scenarios for ESM determination.

Parameters	Reference Case	Biosphere-1	Biosphere-2
Water recovery	94%	94%	99%
In-Situ Water Production	0%	100%	100%
In-Situ Construction	0%	30%	70%
Food productivity	100%	50%	70%
Automation	50%	50%	70%

Some baseline assumptions have been made for all cases. The ESM penalty for crew time has been set to 0,465 kg/hr-CM [21], with the crew working 6,5 hrs/day. The excess oxygen produced by plants in order to meet the entire nutritional needs of the crew is used to burn waste biomass and generate CO_2 for plant growth. The graph below shows the evolution of ESM over a 4 years timespan.

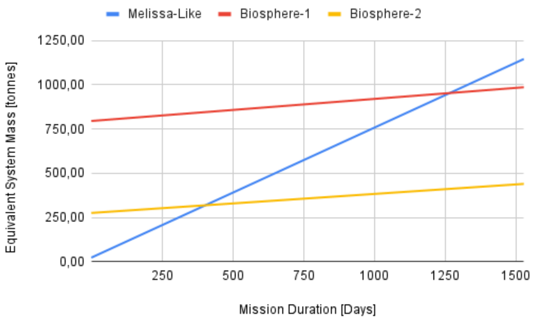


Fig. 4. ESM evolution for the three scenarios.

As can be noted, the Melissa-like curve has the highest steepness, i.e. the related ESM tends to grow faster with respect to the other two cases. This makes this approach particularly convenient for relatively short-duration missions, where mass - and cost as a consequence - are the lowest. According to this model, it takes slightly more than four years (1531 days) for the Biosphere-1 concept to break even and become more convenient. In the case of Biosphere-2, however, the same result is achieved in less than two years (478 days). This is largely driven by the possibility to in-situ manufacture structural parts, which are by far the heaviest component of the architecture. This factor contributes about 66% to the decrease in break-even time. However, the magnitude of the improvement in in-situ manufacturing is higher than that in regolith utilization for agriculture. In practice, the ESM shows comparable sensitivity to equal variations in these two key drivers. This is due to the fact that the dimensions of the greenhouse - and hence the building mass to be manufactured - are here assumed to scale linearly with the cultivable area, which is in turn affected linearly by variations in food productivity. Future studies shall investigate the actual relationship among these factors, but it can be clearly understood that enhanced food productivity impacts ESM mostly by decreasing the size of the structures to be realized. On the other side, the replacement of traditional agricultural soil with regolith seems to only allow for a 5% reduction of ESM. Using regolith can however be truly advantageous to scale up the cultivated areas upon further colonization and growth of the human settlement, as this would surely simplify the logistics and the need for terrestrial support. Finally, automation and water extraction play a negligible role within the timespan considered.

These preliminary finding show how a consistent leap in next-generation biospherics should be searched both inside and outside ECLSS technology: on one side, research efforts should concentrate on manufacturing techniques to enable rapid, reliable and scalable production of walls, berms, shields and pads; on the other side, food productivity is key and using regolith as cultivation soil offers some interesting perspectives, especially in sight of future missions in more remote places of the solar system. This latter idea holds numerous technical challenges though that should be incorporated into a research agenda. One of these is the enhancement of regolith fertility. Literature studies have shown that Moon simulants yield lower edible mass compared to their martian counterparts and to Earth’s soil, even after addition of organic substances [20]. Finding an optimal mixture composition can therefore bring further improvements, but other strategies shall be pursued as well, such as introduction of supporting microorganisms, optimization of atmospheric composition, genetic modification of crops, or chemical pretreatment of regolith for pH adjustment. Furthermore, no research is available on the impact of regolith particle size and shape on plant growth: can the sharp and abrasive particles damage plant tissues? Other issues concern irrigation water recovery and filtration.

5. Conclusions

In conclusion, the Biosphere team has identified a number of items for a research agenda focused on biosphere advancements, below are listed the main points:

- The need to improve the production of off-Earth glass and light-weight metal alloys
- Study and testing of ballistic protection systems against micrometeorites and other ejectable particles coming from landing pads, and other works and activities developed in the lunar surface such as construction of human settlements and lunar mining.
- The need of improving dust mitigation techniques outside the biosphere to prevent clogging and deposition of dust on the surfaces of solar panels and greenhouse glass panels in order to maintain the efficiency of the systems.
- The need of improving dust mitigation techniques inside the biosphere in order to prevent crew poisoning by deposition of moondust particles in the lungs.
- Optimize the processes for extracting water, oxygen and nitrogen from lunar regoliths in order to reduce the costs of creating an appropriate environment and atmosphere inside the biosphere. Thus reducing the amount of these compounds to be sent from Earth.
- Improve settlement master planning to take advantage of natural formations, craters for semi-buried biospheres, hills and lunar mountains to act as natural protective barriers against radiation and ballistic activity.
- Expanding crop selection and improving agricultural techniques to capitalize on plant benefits and improve the crew's quality of life

References

[1] M. K. Biswal M, D. Gómez Fernández, N. Basanta Das, e R. N. Annavarapu, «Conceptual Design of Mars Sub-Surface Habitat for Sustaining Thermal Stability», pag. 1280, mar. 2021.

[2] C. Nast, «Gallery: Concept for underground Mars habitat marks dawn of Martian mole-people», *WIRED UK*, set. 06, 2013. https://www.wired.co.uk/gallery/underground-mars-habitat-gallery (consultato set. 30, 2021).

[3] M. Yashar *et al.*, *Project Olympus: Off-World Additive Construction for Lunar Surface Infrastructure*. 2021.

[4] V. Vanzani, F. Marzari, e E. Dotto, «Micrometeoroid impacts on the lunar surface», vol. 28, pag. 1481, feb. 1997.

[5] D. C. Fernández-Remolar *et al.*, «Underground Habitats in the Río Tinto Basin: A Model for Subsurface Life Habitats on Mars», *Astrobiology*, vol. 8, n. 5, pagg. 1023–1047, ott. 2008, doi: 10.1089/ast.2006.0104.

[6] R. Lewis, «Human Integration Design Handbook», *NASA*, mar. 04, 2015. http://www.nasa.gov/feature/human-integration-design-handbook (consultato set. 30, 2021).

[7] T. Owen, H. Niemann, e P. Mahaffy, «Nitrogen on the Moon: What Does it Tell Us?», in *Earth-Moon Relationships*, Dordrecht, 2001, pagg. 343–350. doi: 10.1007/978-94-010-0800-6_28.

[8] E. Ethridge e W. Kaukler, «Microwave Extraction of Water from Lunar Regolith Simulant», vol. 880, gen. 2007, doi: 10.1063/1.2437523.

[9] «(1) (PDF) From ice to space: a greenhouse design for Moon or Mars based on a prototype deployed in Antarctica». https://www.researchgate.net/publication/341437540_From_ice_to_space_a_greenhouse_design_for_Moon_or_Mars_based_on_a_prototype_deployed_in_Antarctica (consultato set. 30, 2021).

[10] admin, «Water Quality for Crop Production», *Center for Agriculture, Food, and the Environment*, apr. 13, 2015. https://ag.umass.edu/greenhouse-floriculture/greenhouse-best-management-practices-bmp-manual/water-quality-for-crop (consultato set. 30, 2021).

[11] «Soil Survey Laboratory Methods Manual, Soil Survey Investigations Report No. 42, Version 4.0 (2004)», pag. 736.

[12] S. O. Oshunsanya, *Introductory Chapter: Relevance of Soil pH to Agriculture*. IntechOpen, 2018. doi: 10.5772/intechopen.82551.

[13] K. K. G. Menon e H. C. Srivastava, «Increasing plant productivity through improved photosynthesis», *Proc. Plant Sci.*, vol. 93, n. 3, pagg. 359–378, lug. 1984, doi: 10.1007/BF03053089.

[14] Y. Sun, C. Wang, H. Y. H. Chen, e H. Ruan, «Response of Plants to Water Stress: A Meta-Analysis», *Front. Plant Sci.*, vol. 11, pag. 978, 2020, doi: 10.3389/fpls.2020.00978.

[15] J. A. Levri, A. R. Centel, M. Field, A. E. Drysdale, M. K. Ewert, e J. S. Centel, «Advanced Life Support Equivalent System Mass Guidelines Document», pag. 47, 2003.

[16] «New Brine Processor Increases Water Recycling on the Station | NASA». https://www.nasa.gov/feature/new-brine-processor-increases-water-recycling-on-international-space-station (consultato set. 30, 2021).

[17] «Paper information (50220) — IAF». https://iafastro.directory/iac/paper/id/50220/summary/ (consultato set. 30, 2021).

[18] P. Guardabasso *et al.*, *Lunar Outpost Sustaining Human Space Exploration by Utilizing In-Situ Resources with a Focus on Propellant Production*. 2018.

[19] T. Nakamura e B. Smith, «Solar Thermal System for Lunar ISRU Applications: Development and Field Operation at Mauna Kea, HI», in *49th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition*, American Institute of Aeronautics and Astronautics, 2011. doi: 10.2514/6.2011-433.

[20] G. W. W. Wamelink, J. Y. Frissel, W. H. J. Krijnen, e M. R. Verwoert, «Crop growth and viability of seeds on Mars and Moon soil simulants», *Open Agric.*, vol. 4, n. 1, pagg. 509–516, gen. 2019, doi: 10.1515/opag-2019-0051.

[21] P. Zabel, «Influence of crop cultivation conditions on space greenhouse equivalent system mass», *CEAS Space J.*, vol. 13, n. 1, pagg. 3–15, gen. 2021, doi: 10.1007/s12567-020-00317-5.