Human lunar base: "Lunar Palace 1" team of Beihang University unveils China's "Lunar Palace" plan

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Recently, the "Lunar Palace 1" team of Beihang University, China, in response to the long-term habitation and healthcare of humans on the Moon, released the "Lunar Palace" plan through the official account "Beihang University" on WeChat's video platform. With the development of crewed deep-space exploration, human permanent residence on the Moon is no longer an unattainable dream but an anticipated future. Humans on the Moon will live in a Lunar Palace equipped with a bioregenerative life support system (BLSS), creating an Earth-like environment, much like the Lunar Palace 1 facility on Earth. The system will cultivate grain, vegetables, and fruits, breed edible insects, and recycle waste for further plant cultivation. Urine and graywater will be purified for plant irrigation, and the condensed water will be purified for human consumption. Oxygen produced through plant photosynthesis will support the respiration of humans, insects, and microorganisms, which will conversely produce carbon dioxide for plant photosynthesis. Harvested grain, crops, vegetables, fruits, and processed insects will be available for human consumption. Life in the Lunar Palace will resemble life on the Earth (Figure 1).

The future development trend of crewed deep-space exploration will follow a trajectory of crewed lunar exploration, establishing lunar bases, and eventually visiting Mars. The Moon serves as the initial destination for human space missions beyond low-Earth orbit. Based on the principles of ecosystems, the integration of biotechnology and engineering control technologies is essential for constructing an artificial ecosystem composed of plants, animals, and microorganisms, known as BLSSs. This system is considered as the optimal approach to ensuring human long-term residence, survival, and health on the lunar surface.[1,2] Through biological processes, the BLSS regenerates essential resources for human survival such as food, oxygen, and water, minimizing the need for supplies from the Earth. Simultaneously, it provides a living environment like the natural terrestrial ecosystems on the Earth. After more than a decade of theoretical research and key technology breakthroughs, Beihang University's Lunar Palace 1 team integrated atmospheric management, advanced plant production, insect cultivation, waste recycling, and water treatment technologies in 2013. They developed an Earth-based comprehensive experimental BLSS facility called Lunar Palace 1, consisting of a four-biological chain loop of "plants-animals-microorganisms-humans." Between 2014 and 2018, the team completed successive Earth-based BLSS experiments known as "Lunar Palace 105"[1] and "Lunar Palace 365."[2,3] These experiments marked significant milestones in advancing the understanding and application of BLSSs, laying the foundation for sustainable human habitations in extraterrestrial environments.

In BLSSs, the cultivation of higher plants plays a crucial role, including the production of food, absorption of CO_2, release of O_2, circulation and purification of water, and regulation of the physical and mental health status of the crew.[1] Efficient plant cultivations are directly related to the system's construction and stable operation. The feeding of animals (edible insects) transforms the inedible parts of plants into edible animal protein while also releasing CO_2 and consuming O_2 through metabolism.[1] Microorganisms in the BLSS play essential roles in degrading solid waste (plant inedible biomass, human and animal feces), purifying organic compounds in water, promoting higher plants growth (plant probiotics), and improving human physical and mental health (intestinal probiotics, mental probiotics, etc.)[4] (Figure 1). Hence, in a BLSS, it is not only necessary to control harmful microorganisms but also to utilize and regulate microorganisms. During the 370-day Lunar Palace 365" experiment, the dynamically stable matching between the four biological chain loops of plants, animals, microorganisms, and humans was maintained. The efficiency of plant production completely meets the crew's demand for vegetative food. The concentrations of O_2, CO_2, and trace harmful gases within the system are controlled at levels suitable for human health and plant cultivation. And the entire system has achieved a closure rate of 98.2% and demonstrated strong robustness, responding to disturbances such as crew rotations with different basal metabolic rates and short-term interruptions in energy supply by self-adjusting rapidly, minimizing the impact of disruptions, and gradually restoring a stable state.[2] Furthermore, crewmembers showed neither behavioral disturbance nor psychological distress during the 370-day period of mission confinement. Comprehensive data analysis suggested that the cultivation of higher plants and the human gut microflora might be the potential contributors to support crews' physical and mental health.[3]

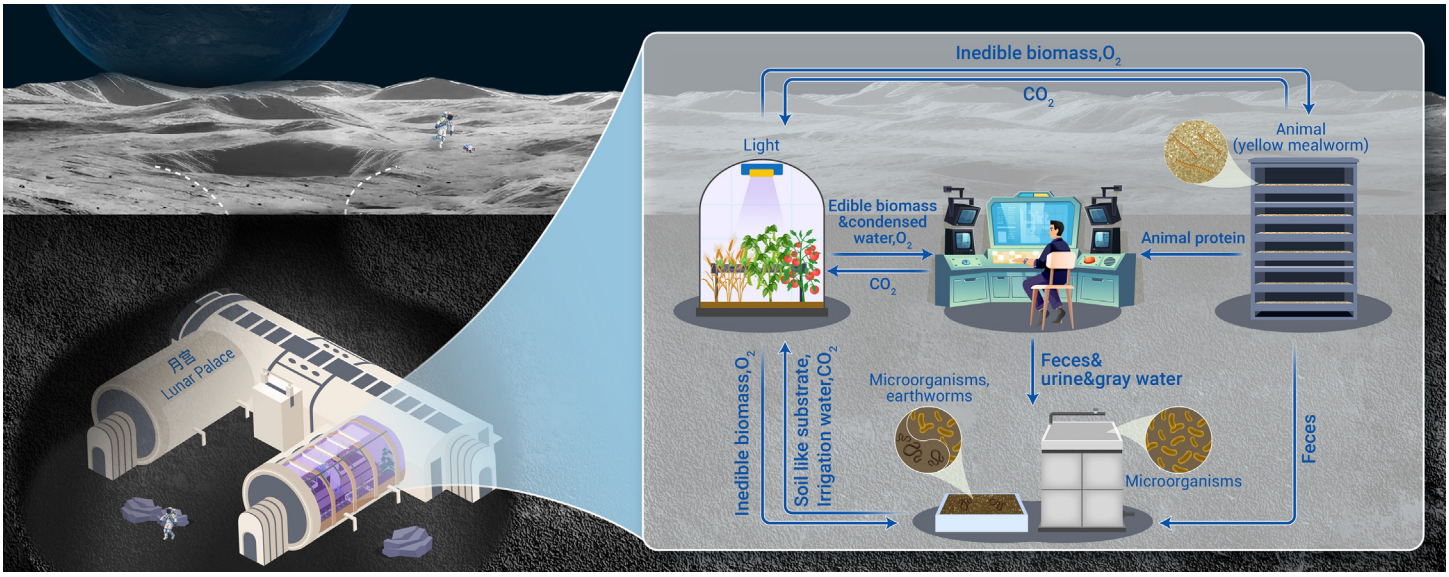

Figure 1. Concept of a crewed lunar base presented by the "Lunar Palace 1" team of Beihang University in Beijing, China

Due to the high cost of transporting materials from the Earth to the Moon, it is essential for the BLSS to fully utilize *in situ* resources. Lunar soil (or say regolith) stands out as the most abundant *in situ* resource on the lunar surface. It has low biological toxicity, holding significant potential as a substrate for plant cultivation. Research has been conducted with both real lunar soil and simulated lunar soil on the Earth, confirming the feasibility of using lunar soil to cultivate plants. However, having never experienced the bioweathering process like the Earth's soil, lunar soil's bioavailability is low, generating some limitations such as low bioavailability of mineral components, lack of organic matter, poor water holding capacity, and so on. In view of these challenges, various methods (biological, physical, or chemical) need to be employed to modify its physicochemical properties to meet the needs of plant cultivation. Imitating the bioweathering process, the Lunar Palace team improved the bioavailability of lunar soil simulant by mixing and co-fermenting it with BLSS's organic solid waste (composed of plant residues, human feces, and microbes).[5] This study brings confidence to future lunar soil utilization programs.

Together, there are still some challenges in building a human lunar survival base like the Lunar Palace 1 on Earth, such as geographical location selection; development and utilization of *in situ* resources; construction of airtight and space-radiation-free cabins; environmental control such as temperature, humidity, and light; the response and adaptation of organisms to space special gravity, magnetic field, and radiation environment; and efficient cultivation of organisms, as well as the technical specifications for the BLSS on the lunar surface. To achieve the construction and application of lunar-surface BLSSs, scientists are actively utilizing lunar-environment simulation platforms, low-Earth orbit space stations, and real lunar environmental conditions to conduct research on lunar life/ecology sciences, related technology, and hardware equipment.

In the near future, it is believed that BLSSs will provide crucial survival and health support for human lunar residency (Figure 1).

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DECLARATION OF INTERESTS

The authors declare no competing interests.